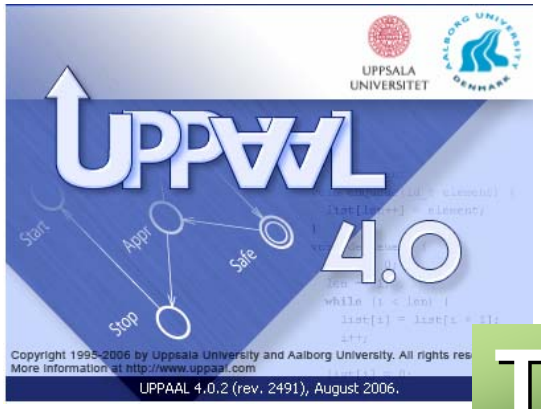

TRON

Real Time Testing

using UPPAAL

With

Mariius Mikucionis, Brian Nielsen, Arne Skou, Anders Hessel, Paul Pettersson

AALBORG UNIVERSITY DENMARK

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Overview

- Introduction
- Conformance for Real-Time System

- Off-line Test Generation
  - Controllable Timed Automata CLASSIC CORA
  - Observable Timed Automata TIGA

- On-line Test Generation TRON

- Conclusion and Future Work

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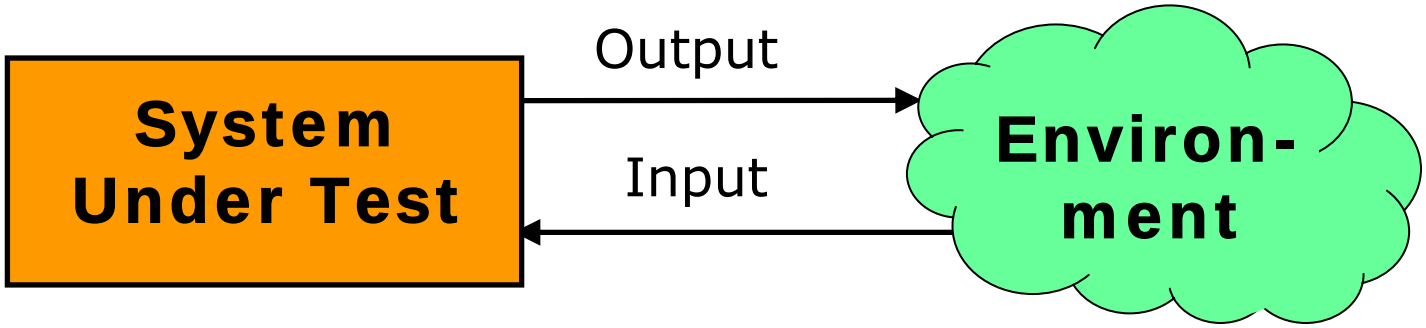
Testing

- Primary validation technique used in industry
  - In general avg. 10-20 errors per 1000 LOC
  - 30-50 % of development time and cost in embedded software
- To find errors
- To determine risk of release
- Part of system development life-cycle



- Expensive, error prone, time consuming (for Real-Time Systems)
- UPPAAL model can be used to generate test specifications

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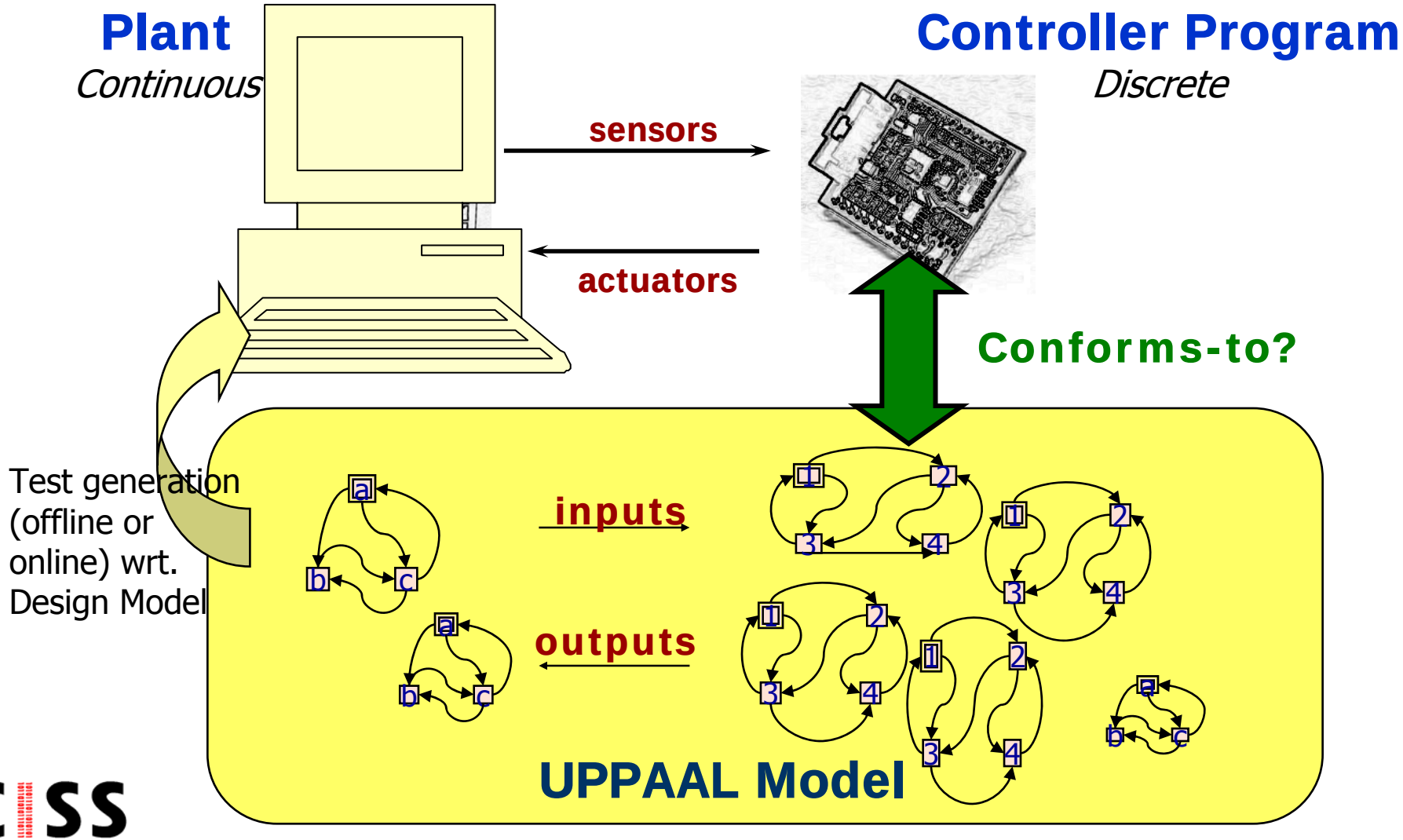
Real-time Model-Based Testing



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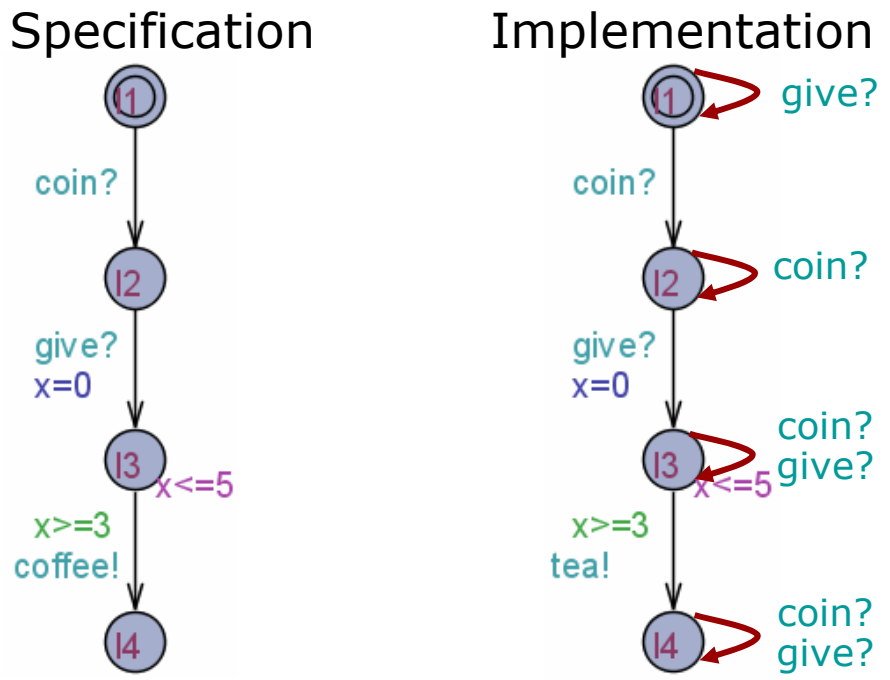
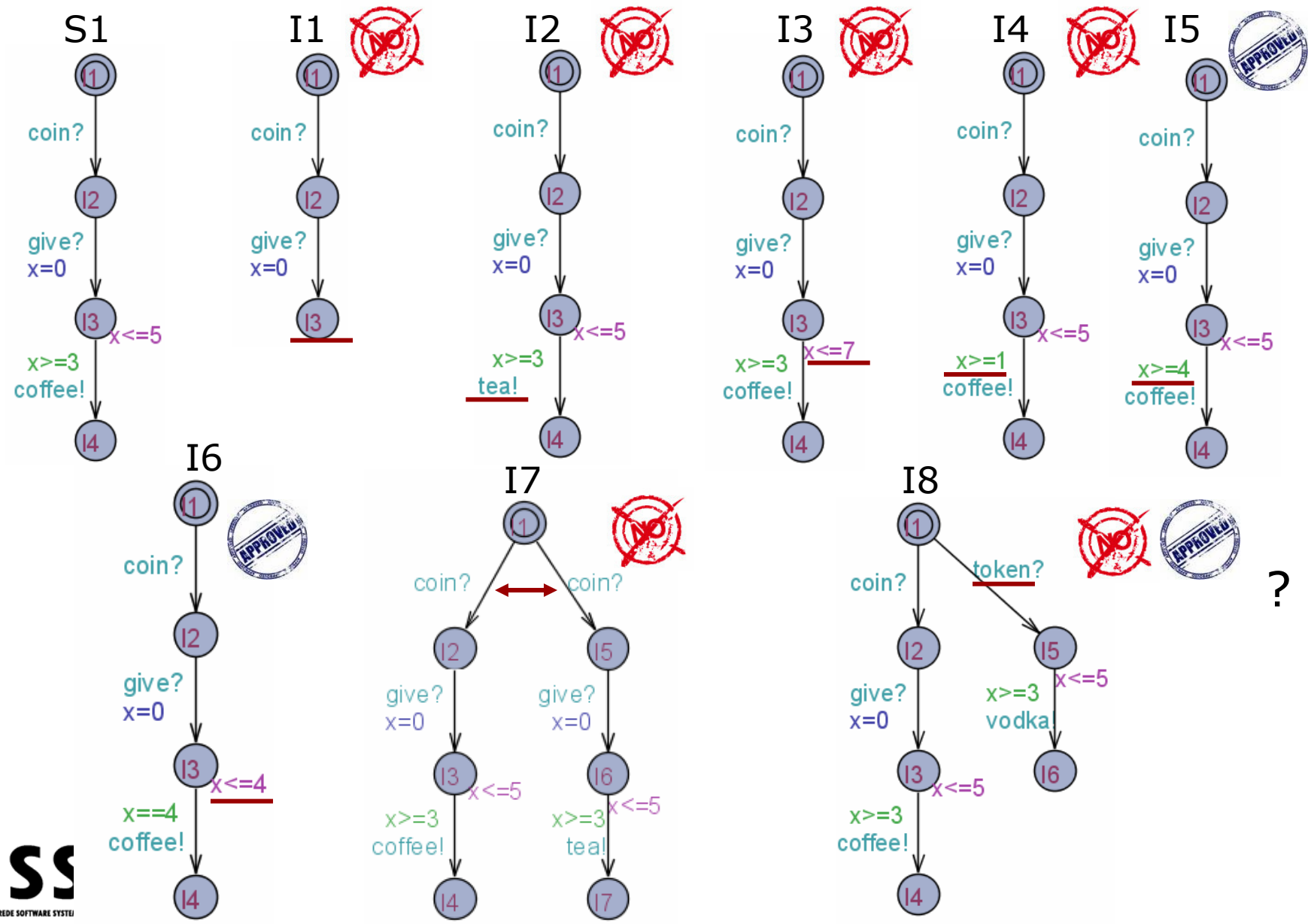
Conformance Relation

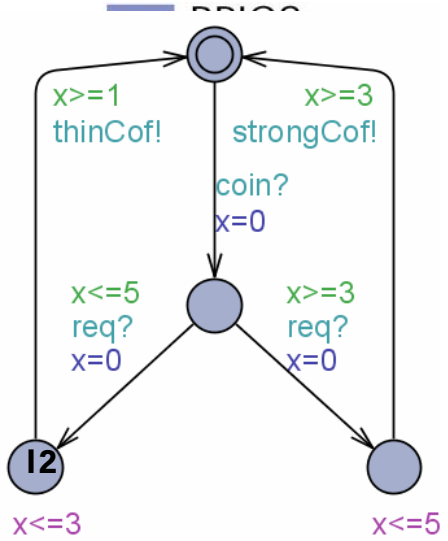


- Timed Automata with Timed-LTS semantics
- **Input** actions (?) are controlled by the environment
- **Output** actions (!) are controlled by the implementation
- Implementations are *input enabled*
- ***Testing hypothesis:*** IUT can be modeled by some (unknown) TA

Does I_n conform-to S_1 ?



Timed Conformance



- Derived from Tretman's IOCO

- Let **I, S** be timed I/O LTS, P a set of states
- **TTr**(P): the set of *timed traces* from P
  - eg.: σ = coin?.**5**.req?.**2**.thinCoffee!.**9**.coin?
- **Out**(P **after** σ) = possible ***outputs*** and ***delays*** after σ
  - eg. out ({l2,x=1}): {thinCoffee, **0...2**}

- **I rt-ioco S =def**
  - **∀σ ∈ TTr(S): Out(I after σ) ⊆ Out(S after σ)**
  - **TTr(I) ⊆ TTr(S)** *if s and I are input enabled*

- **Intuition**
  - **no illegal output is produced and**
  - **required output is produced (at right time)**

See also [Krichen&Tripakis, Khoumsi]

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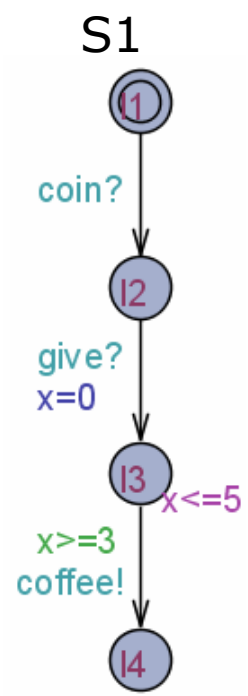
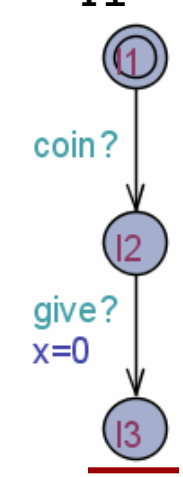
Does I_n conform-to S_1 ?



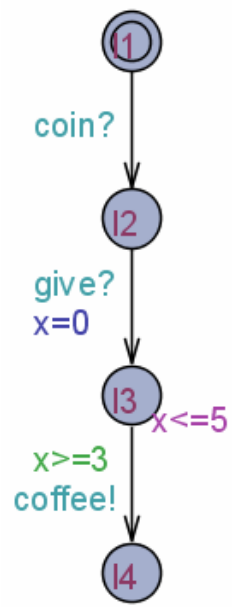


σ=coin.give.10
$\sigma \in$ **TTr**(I1), $\sigma \notin$ **TTr**(S1)

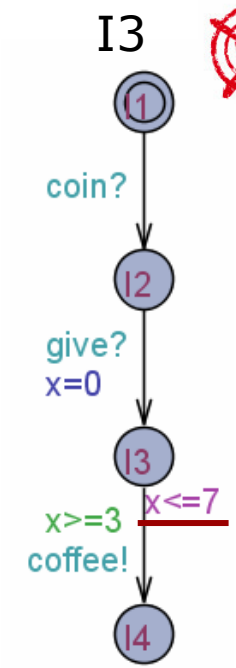
out(I1 **after** coin.give.3)={0... ∞}
$\not\subset$
out(S1 **after** coin.give.3)={coffee,0…2}

Does I_n conform-to S_1 ?

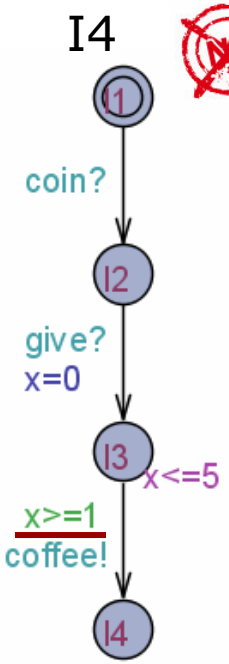
S1



I3



I4



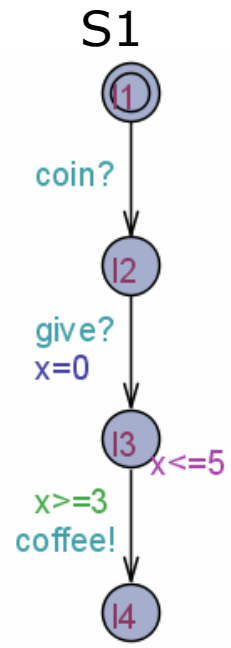
σ=coin.give.7.coffee
σ∈**TTr**(I3), σ ∉TTr(S1)

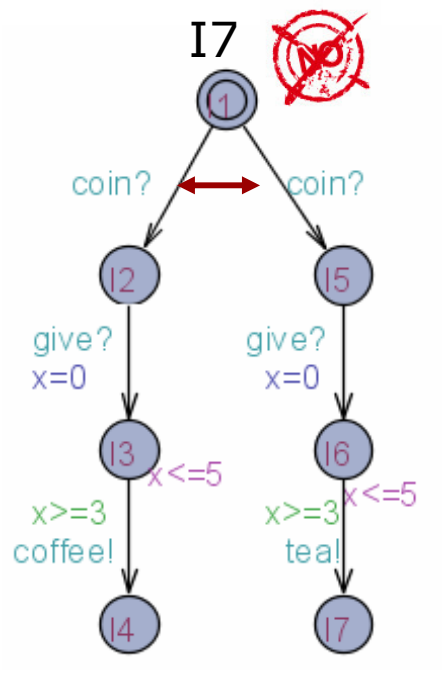
σ=coin.give.1.coffee
σ∈**TTr**(I4), σ ∉TTr(S1)

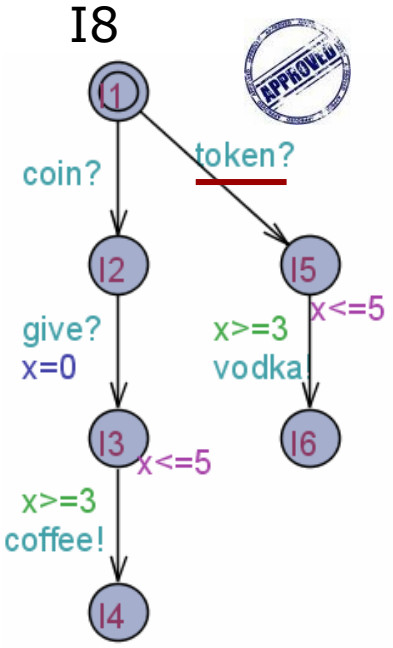
out(I3 after coin.give.7)={coffee,0}
⊄
out(S1 after coin.give.7)={}

out(I4 after coin.give.1)={coffee,0...4}
⊄
out(S1 after coin.give.1)={0...4}

Does I_n conform-to S_1 ?





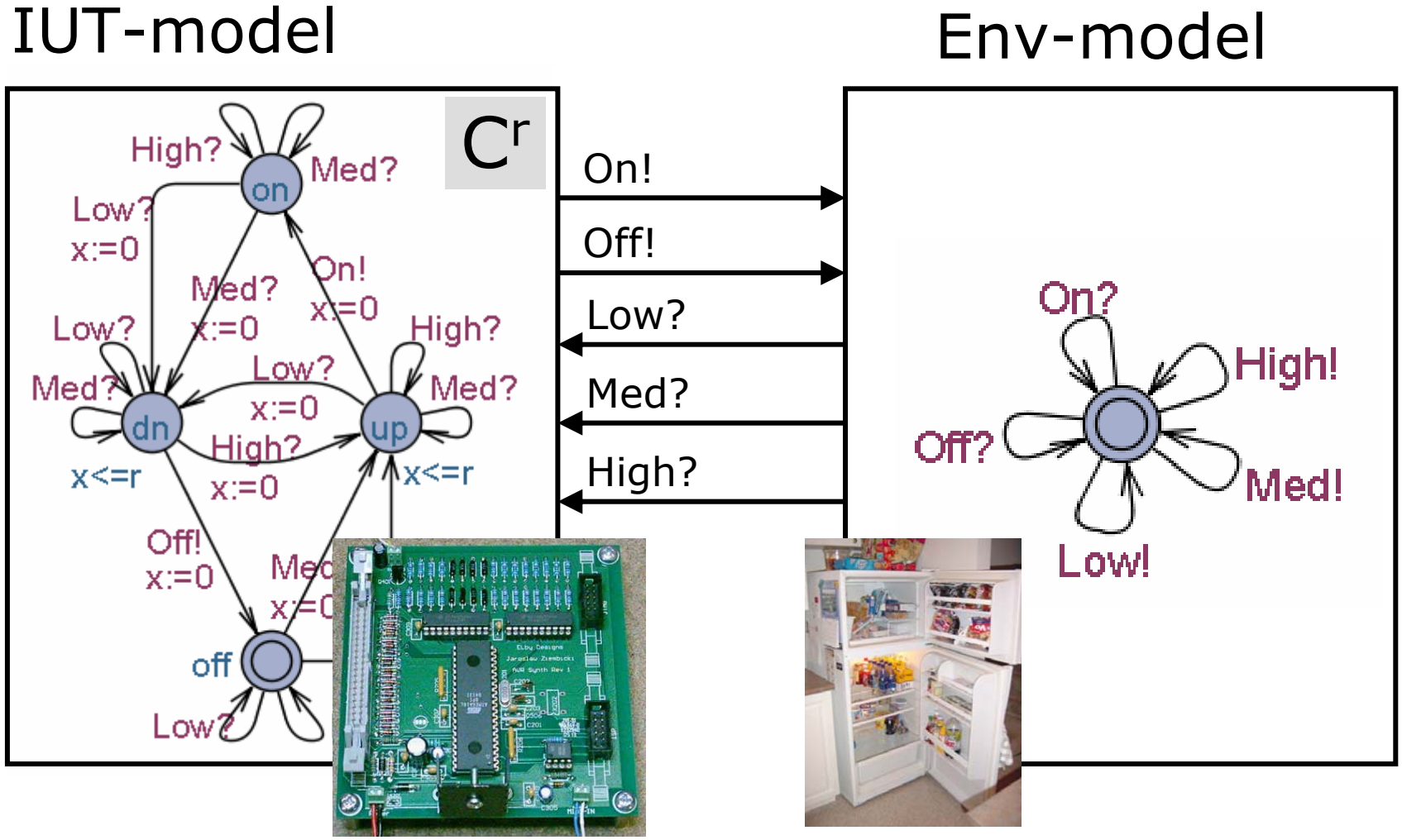


σ=coin.give.5.tea
σ∈**TTr**(I7), σ ∉**TTr**(S1)

σ=token.5.vodka
σ∈**TTr**(I8), σ ∉**TTr**(S1)
But σ was not specified

out(I7 **after** coin.give.5)={tea, coffee,0}
⊄
out(S1 **after** coin.give.5)={coffee,0}

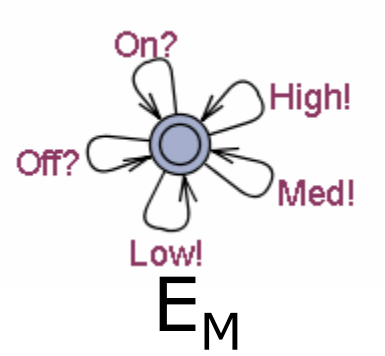
Sample Cooling Controller



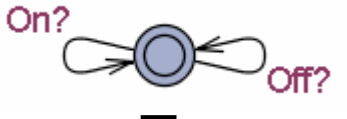
- When T is high (low) switch on (off) cooling within r secs.
- When T is medium cooling may be either on or off (impl freedom)

Environment Modeling

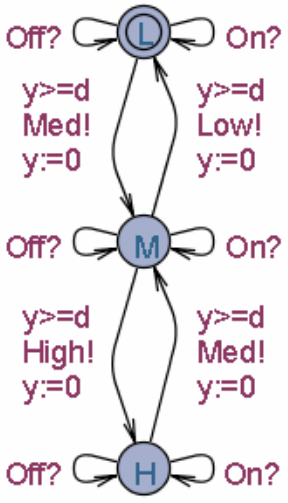
- E_M Any action possible at any time
- E_1 Only realistic temperature variations
- E_2 Temperature never increases when cooling
- E_L No inputs (completely passive)



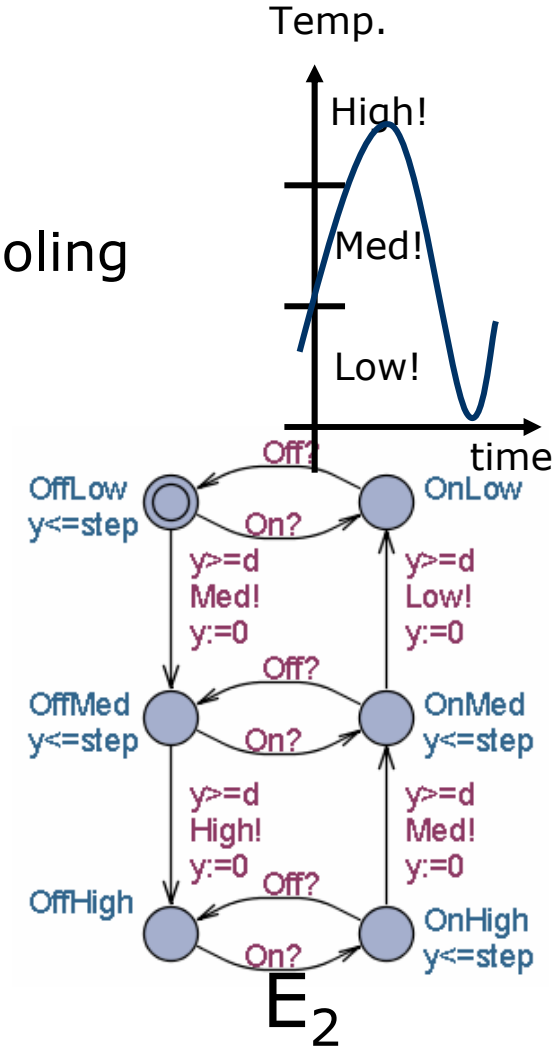
E_M



E_L



E_1

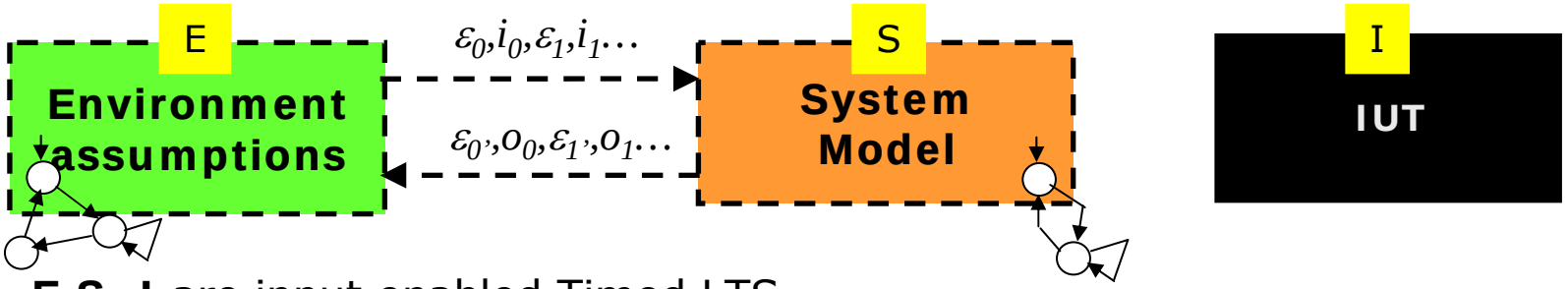


E_2

$$E_L \sqsubseteq E_2 \sqsubseteq E_1 \sqsubseteq E_M$$

Implementation relation

Relativized real-time io-conformance



- **E,S, I** are input enabled Timed LTS
- **Let** *P* **be a set of states**
- **TTr**(*P*): the set of *timed traces* from states in *P*
- *P* **after** σ = the set of states reachable after timed trace σ
- **Out**(*P*) = possible outputs and delays from states in *P*

- I rt-ioco$_E$ S $=_{def}$
  $\forall \sigma \in TTr(E)$: Out((E,I) after σ) $\subseteq$ Out((E,S) after σ)

- I rt-ioco$_E$ s iff $TTr(I) \cap TTr(E) \subseteq TTr(S) \cap TTr(E)$ *// input enabled*

- **Intuition, for all assumed environment behaviors, the IUT**
  - **never produces illegal output, and**
  - **always produces required output in time**

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Re-use Testing Effort

- Given I, E, S
- Assume I rt-ioco$_E$ S

1. Given new (weaker) system specification S'

$$\text{If } S \sqsubseteq S' \text{ then I rt-ioco}_E\ S'$$

2. Given new (stronger) environment specification E'

$$\text{If } E' \sqsubseteq E \text{ then I rt-ioco}_{E'}\ S$$

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Off-Line Test Generation

Controllable Timed Automata

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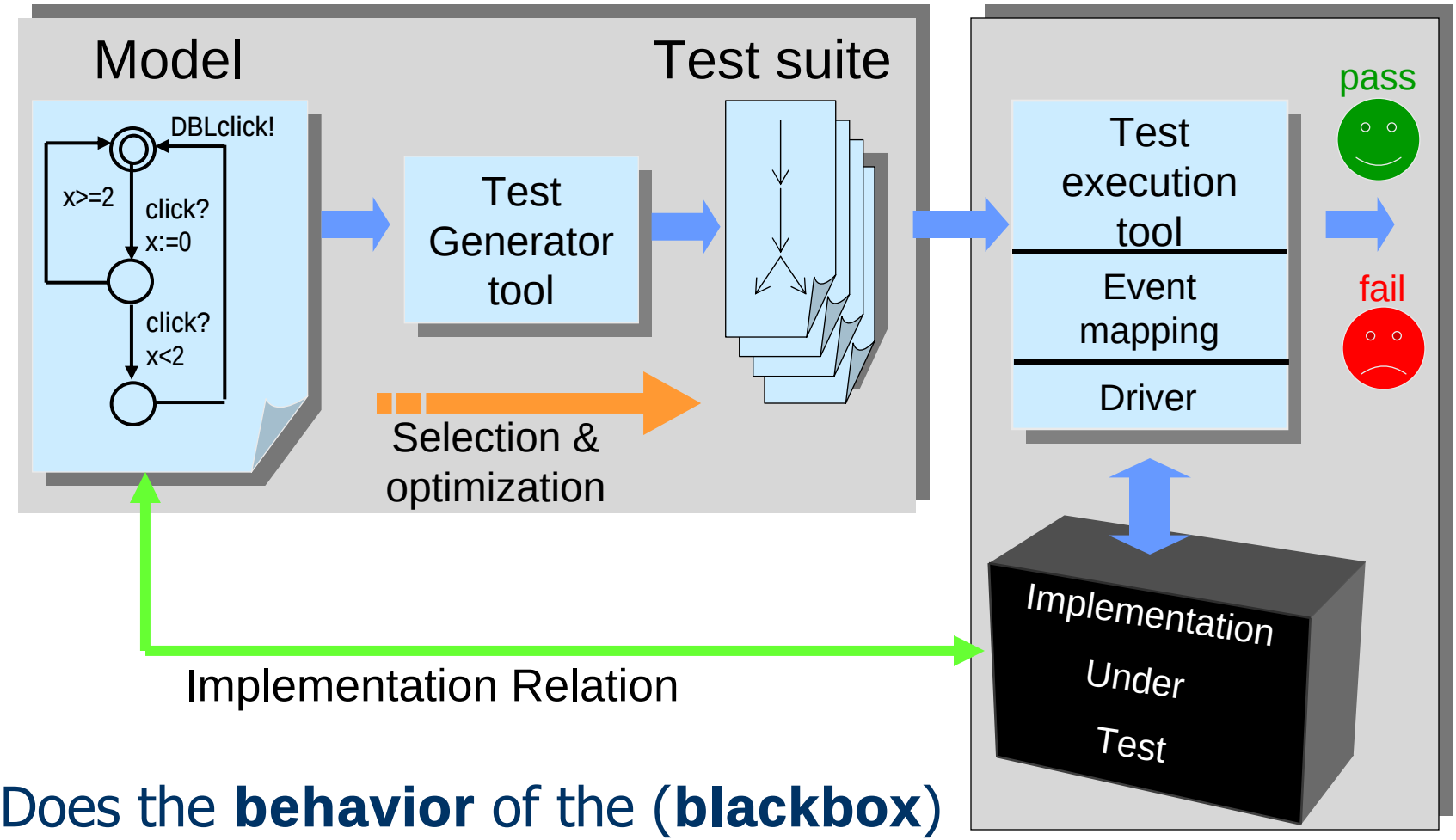
Model Based Conformance Testing



Does the **behavior** of the (**blackbox**) implementation ***comply*** to that of the specification?

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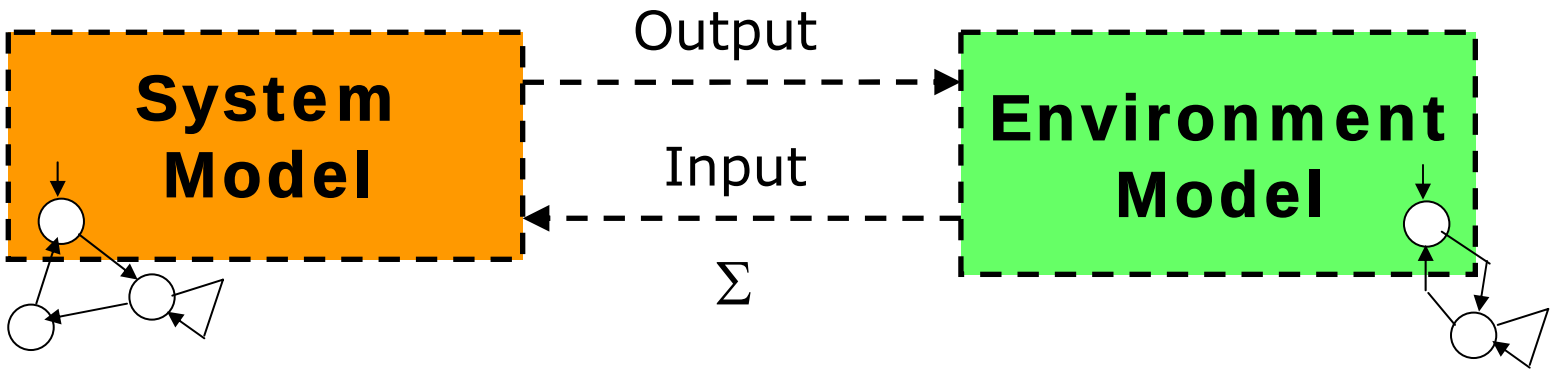
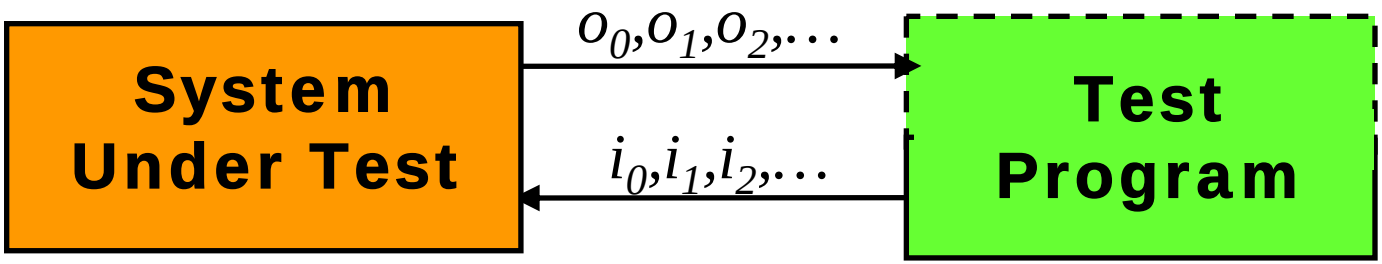
Model-Based Testing



- FSM model of system and environment
- Determinizable/deterministic models
- Test purpose $P \approx$ reachability property ϕ_P
- Test-case generation $\approx$ witness generation
- Test input sequence $\sigma_{\phi p} = i_0, i_1, i_2, \ldots$
- Test suite $T = \{\sigma_1, \ldots, \sigma_n\}$, minimized by excluding all σ_i substring of some other σ_j

Testing Verdict



- Test program $\sigma_{\phi p} = i_0,i_1,i_2,\ldots$
- Test in/output $\delta_{\phi p} = i_0,o_0,i_1,o_1,i_2,i_3,\ldots$
- Test Verdict:
  - OK, if $\delta_{\phi p} = i_0,o_0,i_1,o_0,i_2,i_3,\ldots$ run of system model
  - NOK, otherwise

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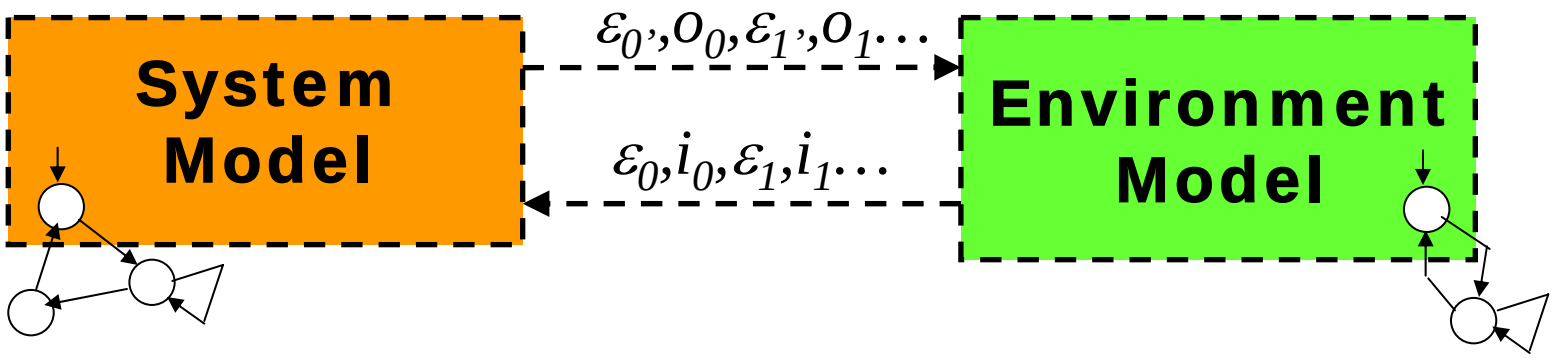
Testing Real-Time Systems



- Test input sequence $\sigma_{\phi p} = \varepsilon_0,i_0,\varepsilon_1,i_1,\varepsilon_2,i_2,\ldots$
- Test in/output $\delta_{\phi p} = \varepsilon_0,i_0,\varepsilon_1,o_0,\varepsilon_1,i_1,o_1,\ldots$
- Test Verdict:
  - OK, if $\delta_{\phi p} = \varepsilon_0,i_0,\varepsilon_1,o_0,\varepsilon_1,i_1,o_1,\ldots$run of system model
  - NOK, otherwise
- Timed Automata?

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This work

- Test case generation from timed automata
  - by reachability analysis
  - implementation in UPPAAL
- Testing Criteria:
  - single test purpose
  - coverage criteria: location, branching, definition/use pairs, etc.
- Optimality:
  - Test Cases: $\sigma_{\phi p} = \varepsilon_0, i_0, \varepsilon_1, i_1, \varepsilon_2, i_2, \ldots$ with minimum cost
    e.g. $min(\varepsilon_0 + \varepsilon_1 + \ldots + \varepsilon_n)$
  - Test Suites: $T = \{\sigma_1, \ldots, \sigma_n\}$ with minimum cost

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Controllable Timed Automata

Input Enabled:
all inputs can always be accepted.

Assumption about model of SUT

Output Urgent:
enabled outputs will occur immediately.

Determinism:
two transitions with same input/output leads to the same state.

Isolated Outputs:
if an output is enabled, no other output is enabled.

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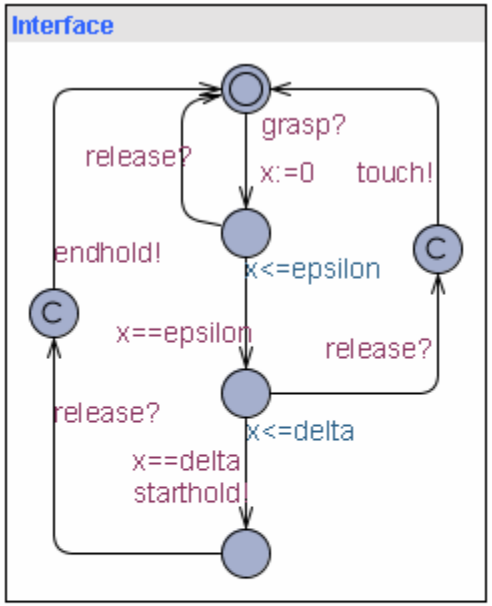
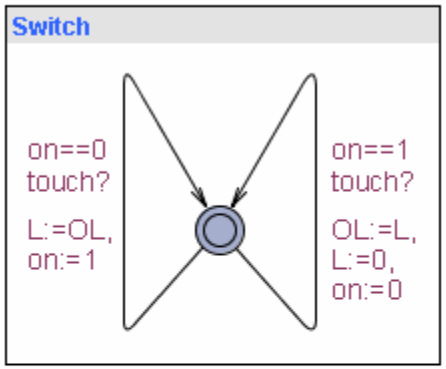
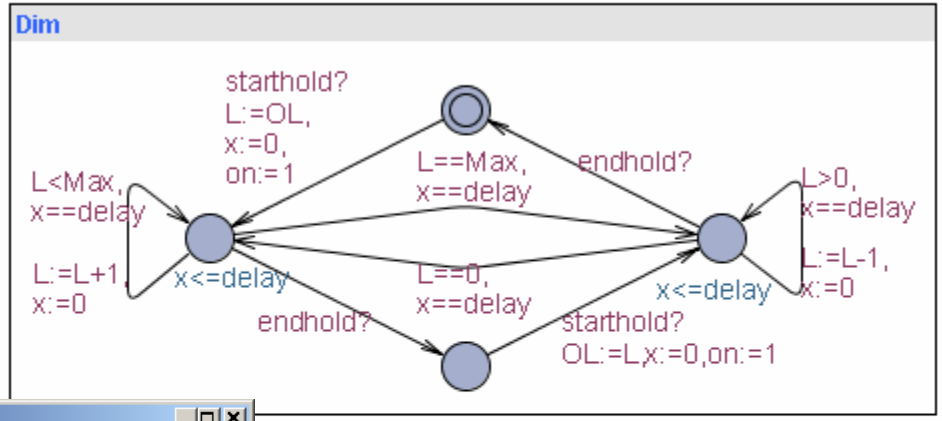
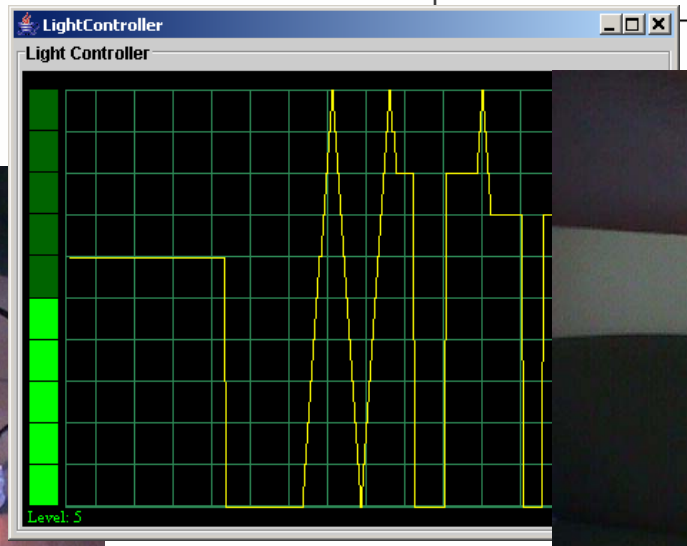
Example

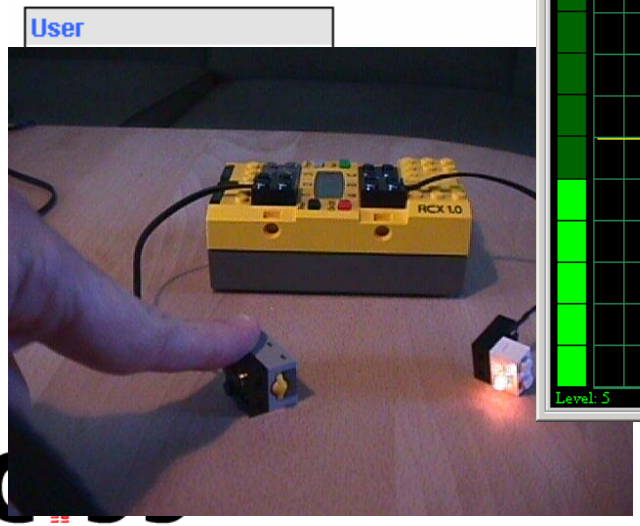
Light Controller











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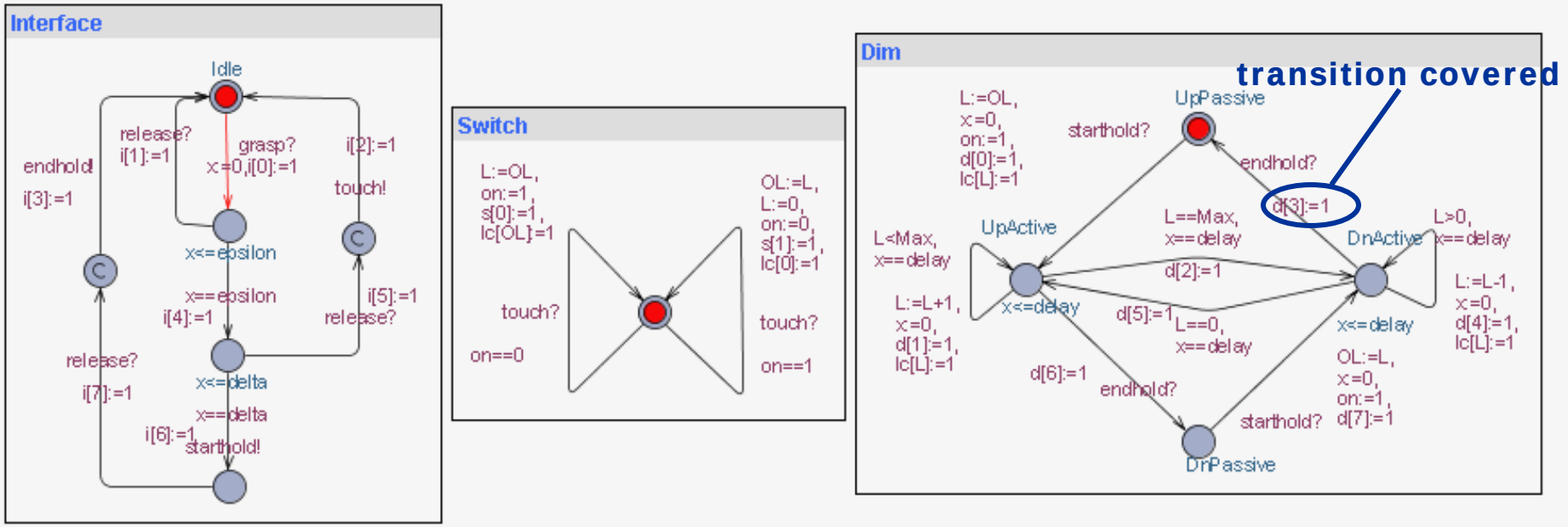
Off-Line Testing = *Optimal Reachability*



- Specific Test Purposes
- Model Coverage
- Optimal test-suites

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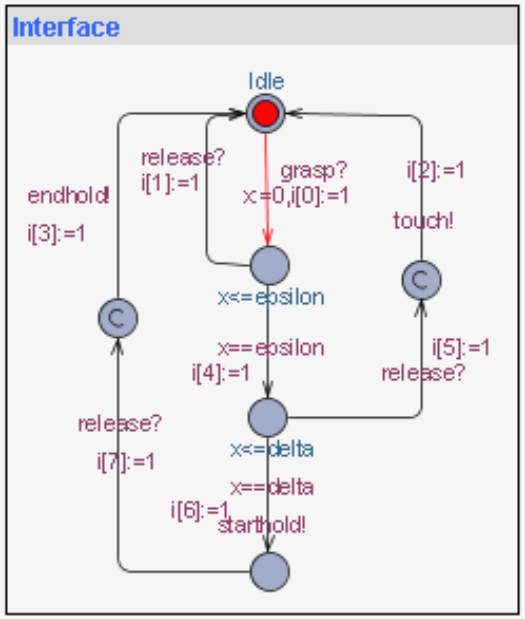
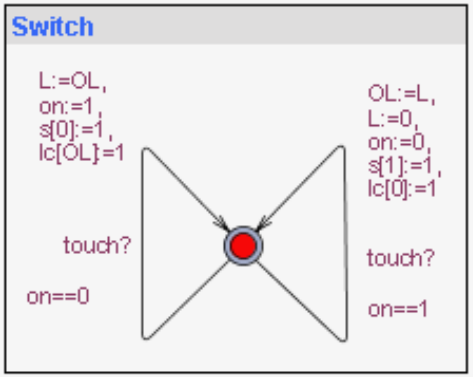
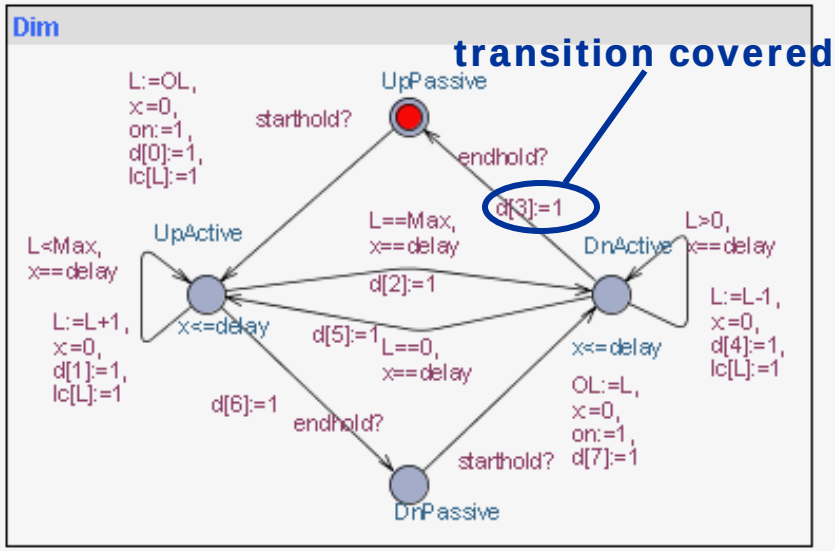
Off-Line Testing = *Optimal Reachability*

Fastest Transition Coverage =12600 ms








```
out(IGrasp);              //touch:switch light on
silence(200);
out(IRelease);
in(OSetLevel,0);

out(IGrasp); //@200        // touch: switch light off
silence(200);
out(IRelease);//touch
in(OSetLevel,0);

//9
out(IGrasp); //@400        //Bring dimmer from ActiveUp
silence(500); //hold       //To Passive DN (level=0)
in(OSetLevel,0);
out(IRelease);
```

Page 1

```
//13
out(IGrasp); //@900        // Bring dimmer  PassiveDn->ActiveDN->
silence(500);//hold        // ActiveUP+increase to level 10
silence(1000); in(OSetLevel,1);
silence(1000); in(OSetLevel,2);
silence(1000); in(OSetLevel,3);
silence(1000); in(OSetLevel,4);
silence(1000); in(OSetLevel,5);
silence(1000); in(OSetLevel,6);
silence(1000); in(OSetLevel,7);
silence(1000); in(OSetLevel,8);
silence(1000); in(OSetLevel,9);
silence(1000); in(OSetLevel,10
silence(1000);  in(OSetLevel,9); //bring dimm State to ActiveDN

out(IRelease);            //check release->grasp is ignored
out(IGrasp); //@12400
out(IRelease);
silence(dfTolerance);
```

Page 2

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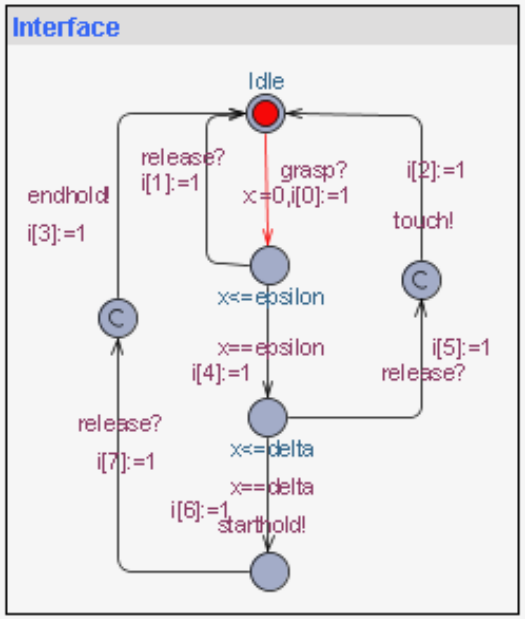
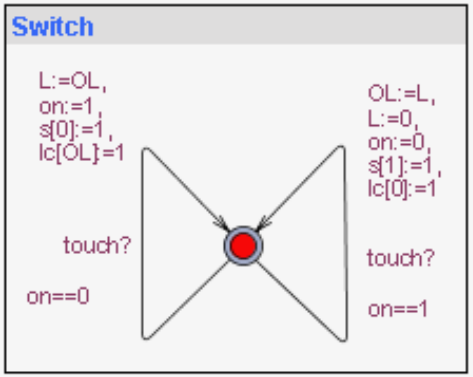
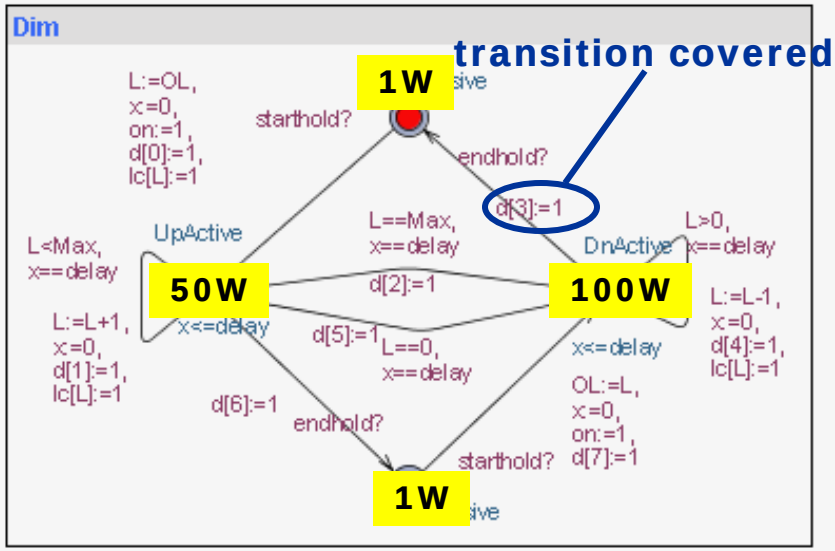
Off-Line Testing = *Optimal Reachability*







- Specific Test Purposes
- Model Coverage
- Optimal test-suites

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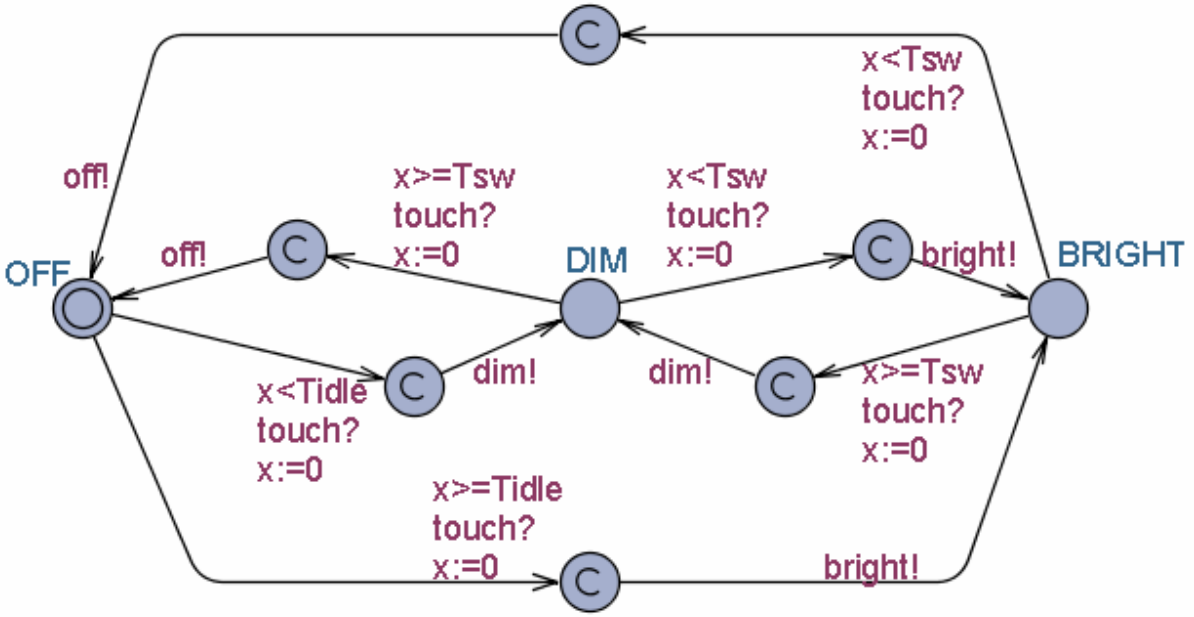
Timed Automata

(E)FSM+clocks+guards+resets




```
T_sw=4
T_idle=20
```

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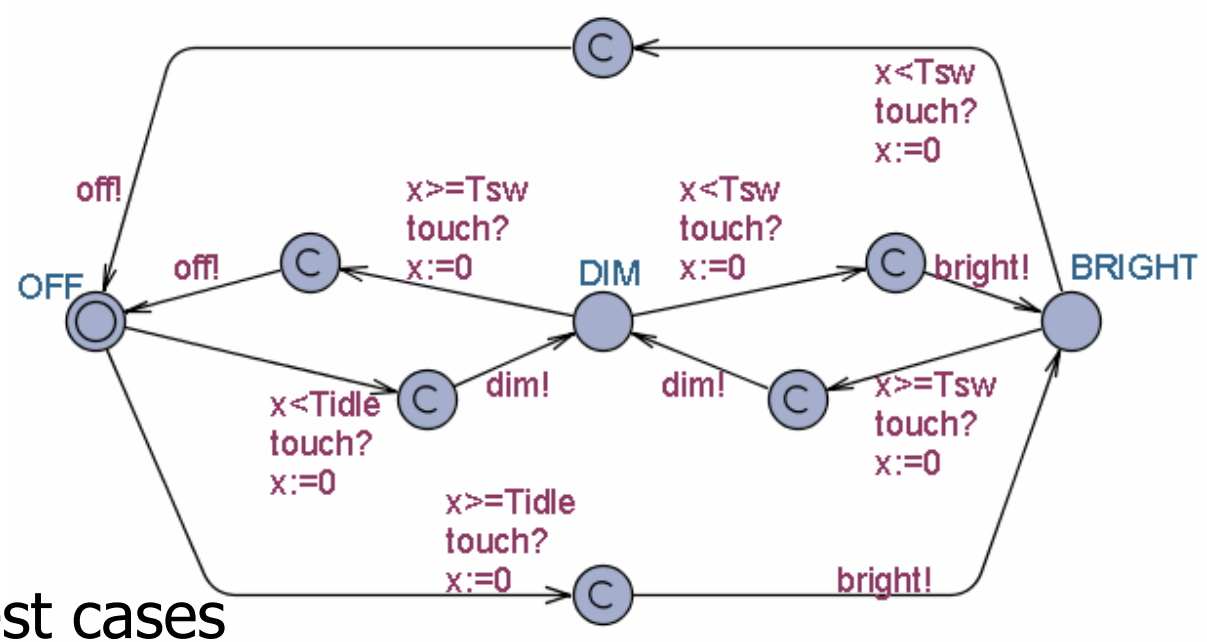
WANT: if touch is issued twice quickly then the light will get brighter; otherwise the light is turned off.

Solution: Add real-valued clock **x**

Timed Tests



T_sw=4
T_idle=20

EXAMPLE test cases

0·touch!·0·dim?·2·touch!·0·bright?·2·touch!·off?·PASS

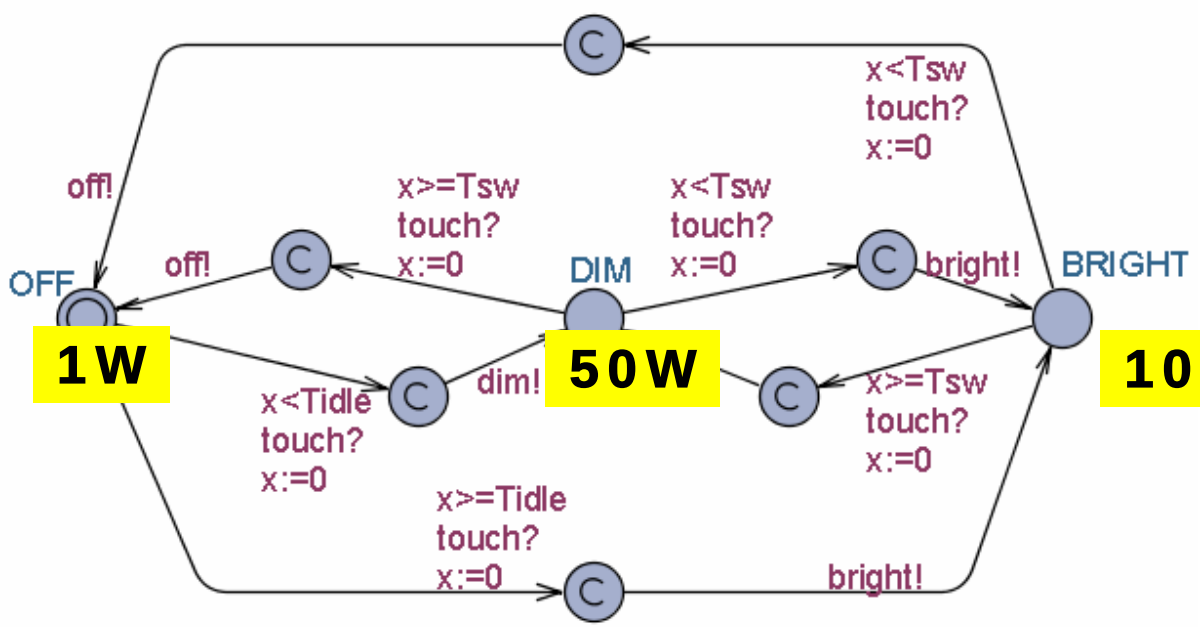
0·touch!·0.dim?·2½·touch!·0·bright?·3·touch!·off?·PASS

0·touch!·0·dim?·5touch!·0·off?·PASS

0·touch!·0·dim?·5·touch!·0·off?·50·touch!·0·bright?·6·touch!·0·dim?·PASS

INFINITELY MANY SEQUENCES!!!!!

Optimal Tests

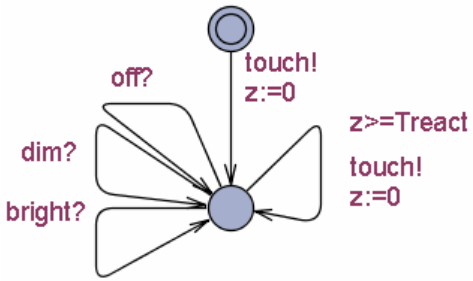



```
T_sw=4
T_idle=20
```

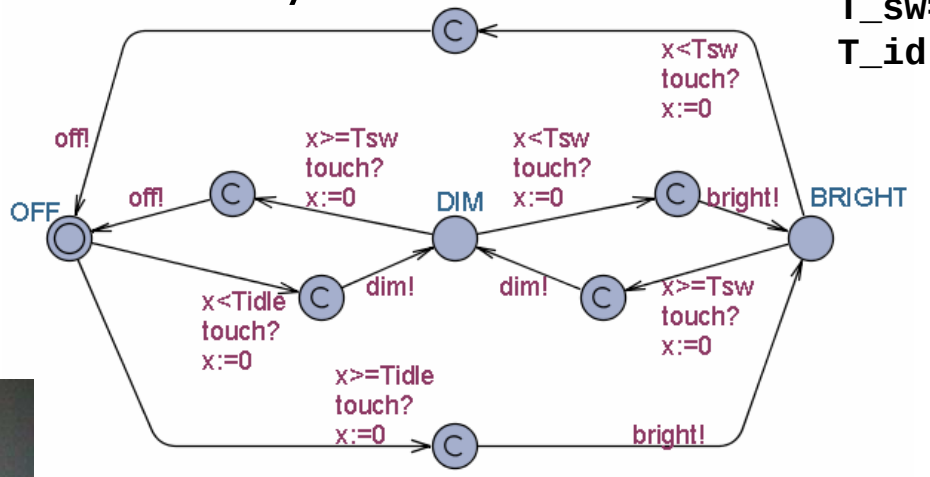
- ***Shortest*** test for bright light??
- ***Fastest*** test for bright light??
- ***Fastest*** edge-covering test suite??
- Least ***power*** consuming test??

Simple Light Controller

Environment model



System model

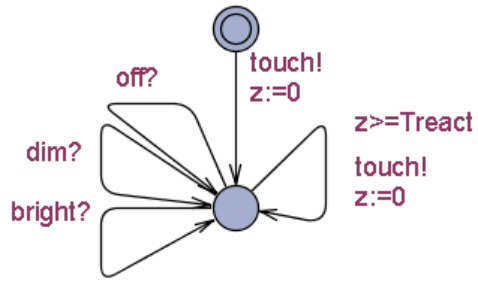



```
T_react=2
T_sw=4
T_idle=20
```

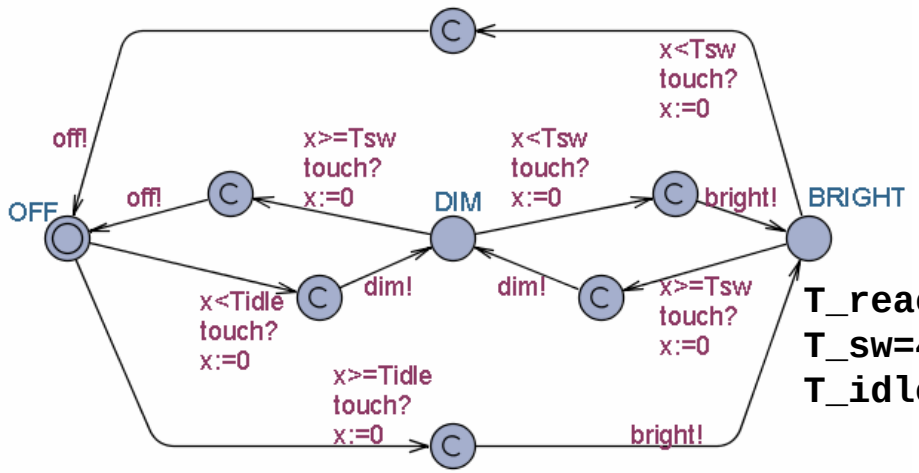
Test Purposes

A specific test objective (or observation) the tester wants to make on SUT

Environment model



System model




```
T_react=2
T_sw=4
T_idle=20
```

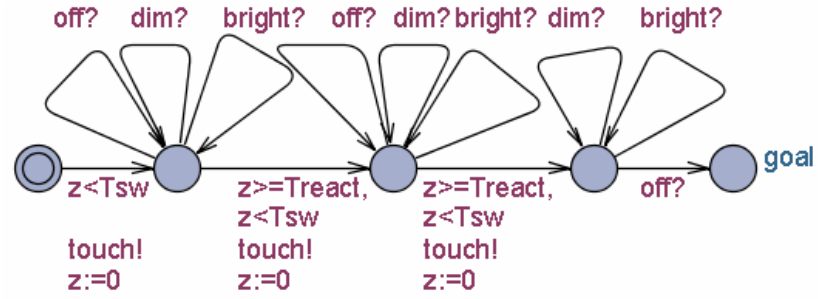
TP1: Check that the light can become bright:

`E<> LightController.bright`

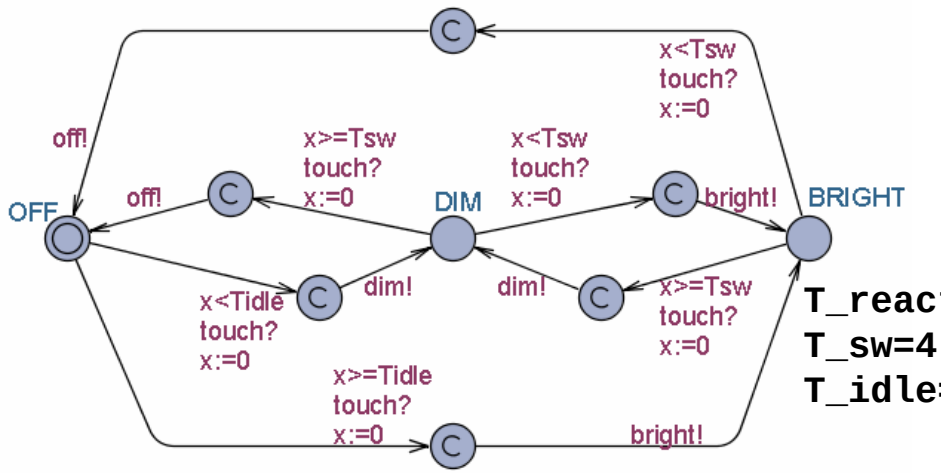
- *Shortest* Test: 20·touch!·0·bright?·PASS
- *Fastest* Test: 0·touch!·0·dim?·2·touch!·0·bright ?·PASS

Test Purposes 2

Environment model*TP2



System model



TP2: Check that the light switches off after three successive touches

Use restricted environment and **`E<> tpEnv.goal`**

- The fastest test sequence is
0·touch!·0·dim?·2·touch!·0·bright?·2·touch!·0·off?·PASS

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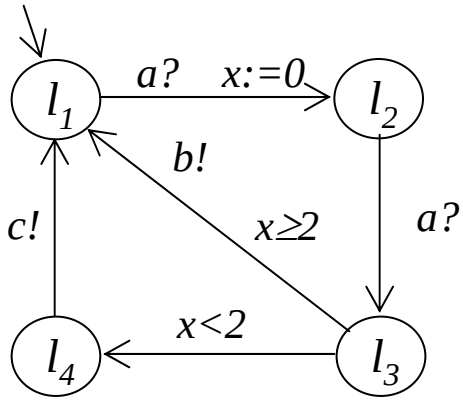
Coverage Based Test Generation

- Multi purpose testing
- Cover measurement
- Examples:
  - Location coverage,
  - Edge coverage,
  - Definition/use pair coverage



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Coverage Based Test Generation

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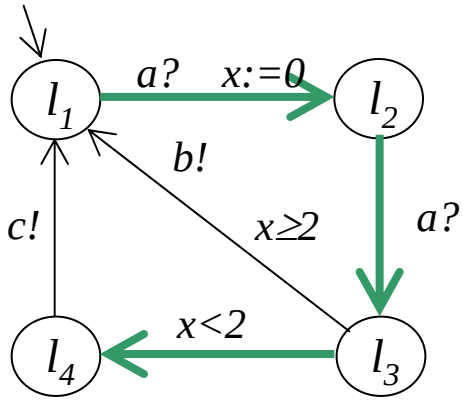

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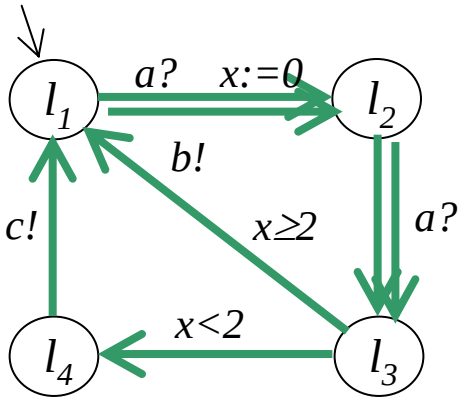

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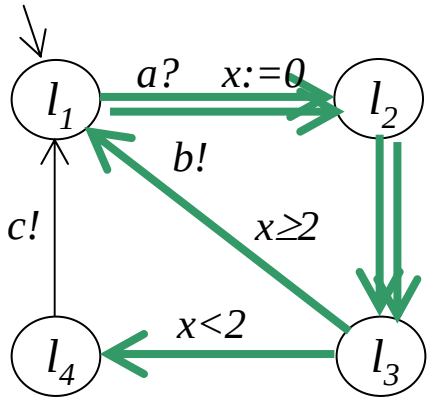

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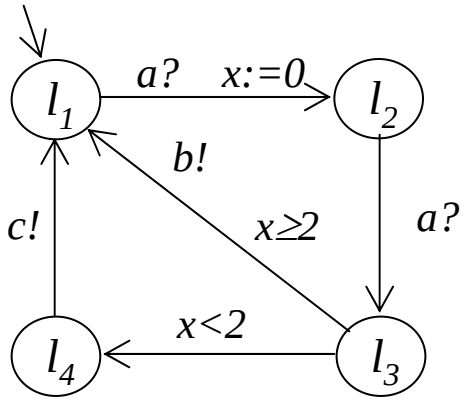
Coverage Based Test Generation

- Multi purpose testing
- Cover measurement
- Examples:
  - Locations coverage,
  - Edge coverage,
  - Definition/use pair coverage
  - All Definition/Use pairs



- Generated by min-cost reachability analysis of annotated graph

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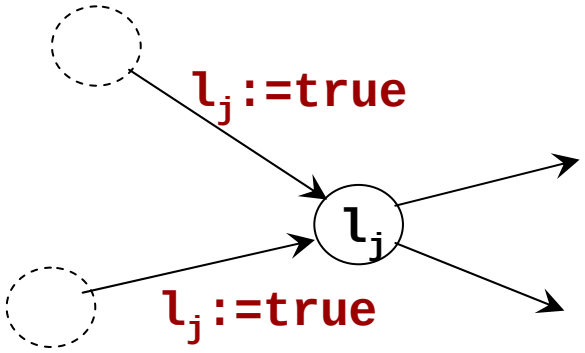
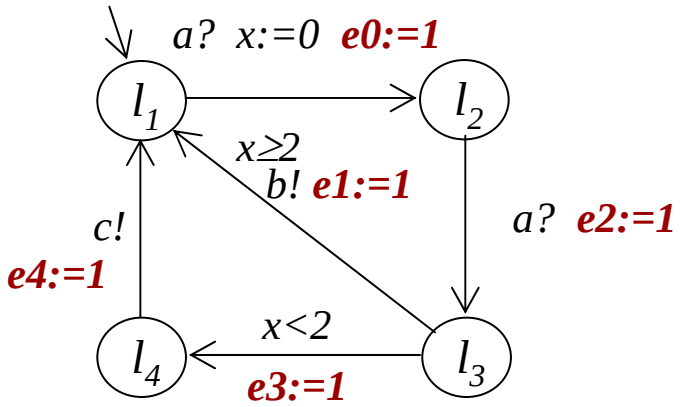
Location Coverage

- Test sequence traversing all locations
- Encoding:
  - Enumerate locations $l_0, \ldots, l_n$
  - Add an auxiliary variable l_i for each location
  - Label each ingoing edge to location i l_i:=true
  - Mark initial visited l_0:=true
- Check: **EF(l_0=true $\wedge$ … $\wedge$ l_n=true)**

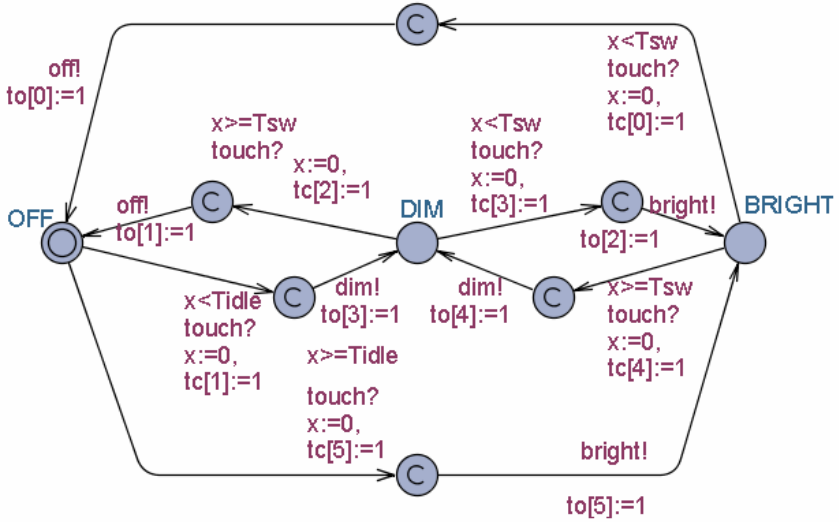


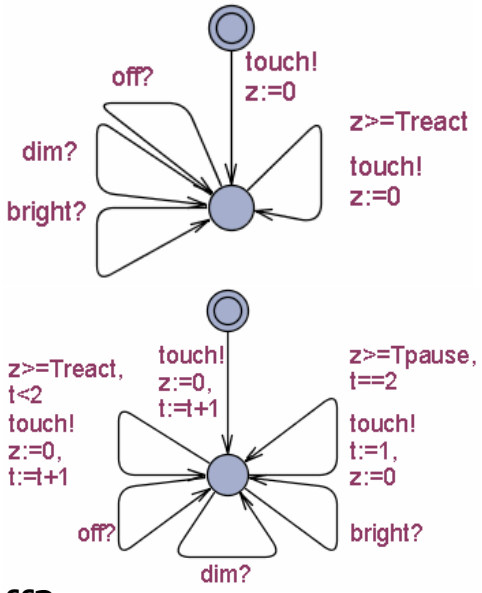
Edge Coverage

- Test sequence traversing all edges
- Encoding:
  - Enumerate edges $e_0, \ldots, e_n$
  - Add auxiliary variable e_i for each edge
  - Label each edge $e_i := \mathbf{true}$
- Check: $\mathbf{EF}(e_0 = \mathbf{true} \wedge \ldots \wedge e_n = \mathbf{true})$



Edge Coverage





EC: *T_react=0*

0·touch!·0·dim?·0·touch!·0·bright?·0·touch!·0·off?·
20·touch!·0·bright?·4·touch!·0·dim?·4·touch!·0·off?·PASS

Time=28

EC': *T_react=2*

0·touch!·0·dim?·4·touch!·0·off?· 20·touch!·0·bright?·
4·touch!·0·dim?·2·touch!·0·bright?·2·touch!·0·off?·PASS

Time=32

EC'': *pausing user T_react=2, T_pause=5*

0·touch!·0·dim?·2·touch!·0·bright?·5·touch!·0·dim?·
4·touch!·0·off?·20·touch!·0·bright?·2·touch!·0·off?·PASS

Time=33

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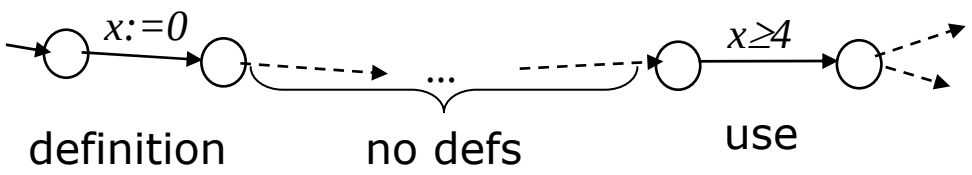
Definition/Use Pair Coverage

- Dataflow coverage technique
- Def/use pair of variable x:



- Encoding:
  - $v_d \in \{ false \} \cup \{ e_0, \ldots, e_n \}$, initially false
  - Boolean array du of size $|E|$ x $|E|$
  - At definition on edge i: $v_d := e_i$
  - At use on edge j: if(v_d) then $du[v_d, e_j] := true$

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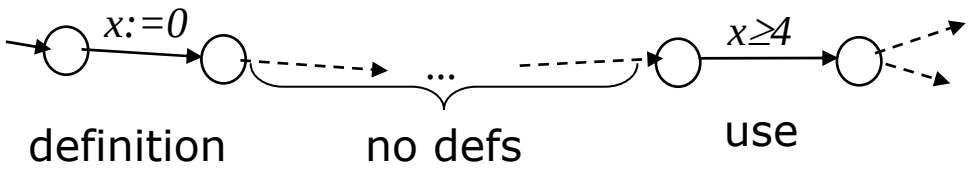
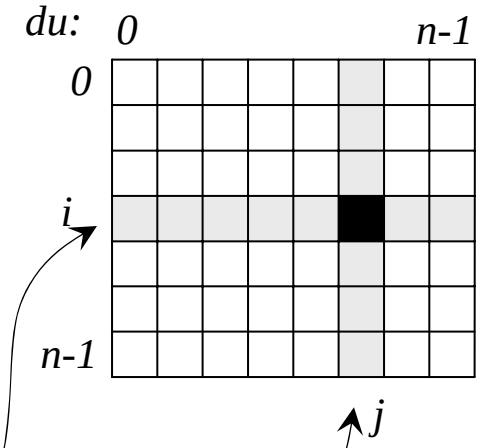
Definition / Use Pair Coverage

- Dataflow coverage technique
- Def/use pair of variable x:

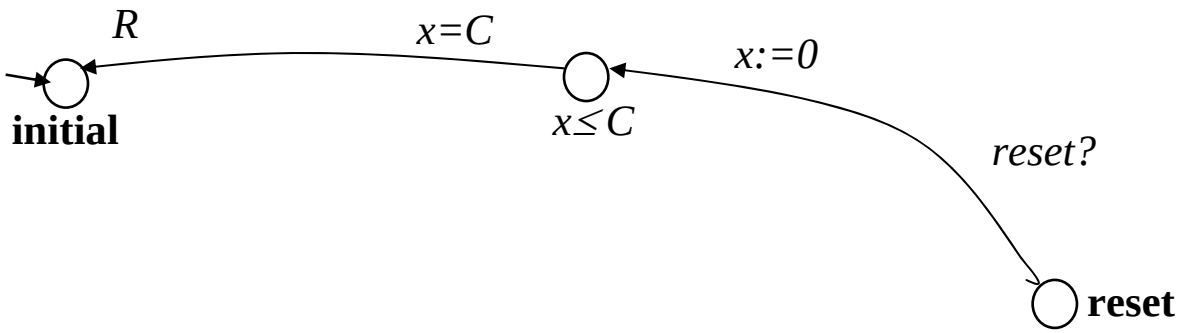




- Encoding:
  - $v_d \in \{ false \} \cup \{ e_0, \ldots, e_n \}$, initially false
  - Boolean array du of size $|E|$ x $|E|$
  - At definition on edge i: $v_d := e_i$
  - At use on edge j: if(v_d) then $du[v_d, e_j] := true$
- Check:
  - EF(all $du[i,j] = true$)

Test Suite Generation

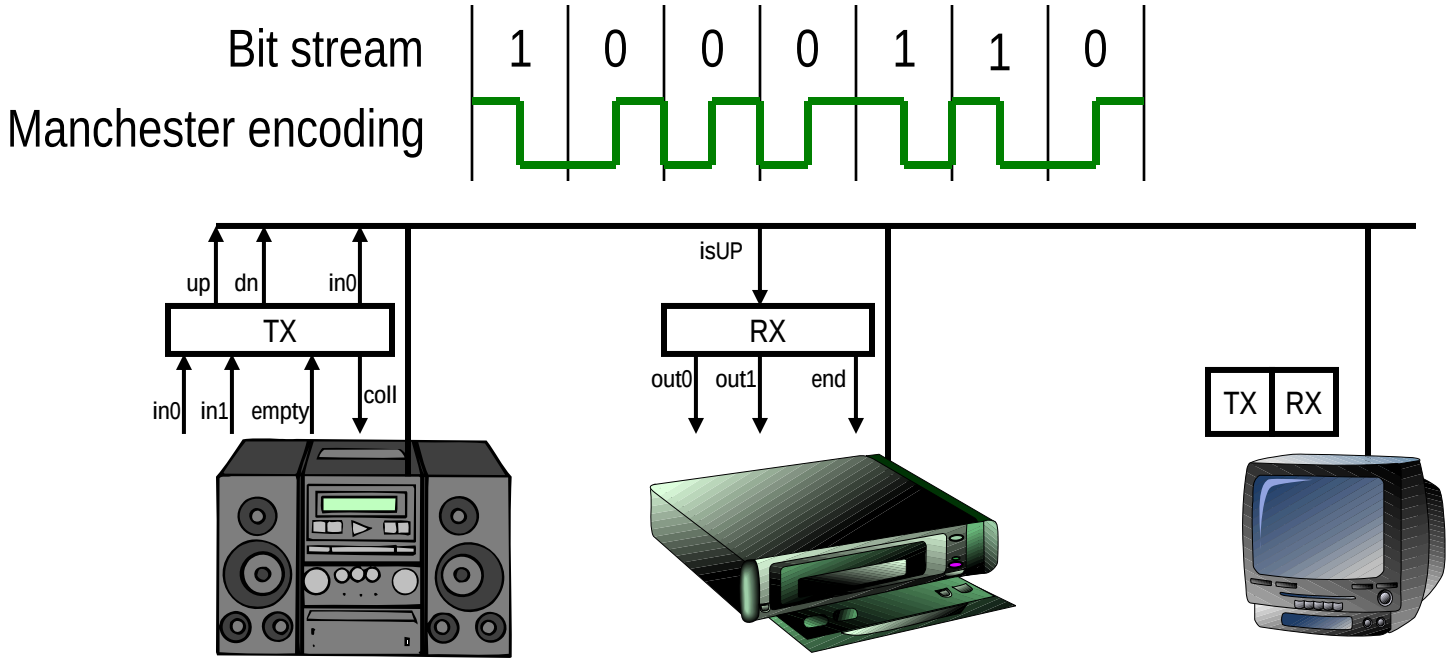
- In general a set of test cases is needed to cover a test criteria
- Add global reset of SUT and environment model and associate a cost (of system reset)



- Same encodings and min-cost reachability
- Test sequence $\sigma = \mathcal{E}_0, i_0, \ldots, \mathcal{E}_1, i_1, \textbf{reset}\ \underbrace{\mathcal{E}_2, i_2, \ldots, \mathcal{E}_0, i_0, \textbf{reset}}_{\sigma_i}, \mathcal{E}_1, i_1, \mathcal{E}_2, i_2, \ldots$
- Test suite $T = \{\sigma_1, \ldots, \sigma_n\}$ with minimum cost

The Philips Audio Protocol

- A bus based protocol for exchanging control messages between audio components
  - Collisions
  - Tolerance on timing events



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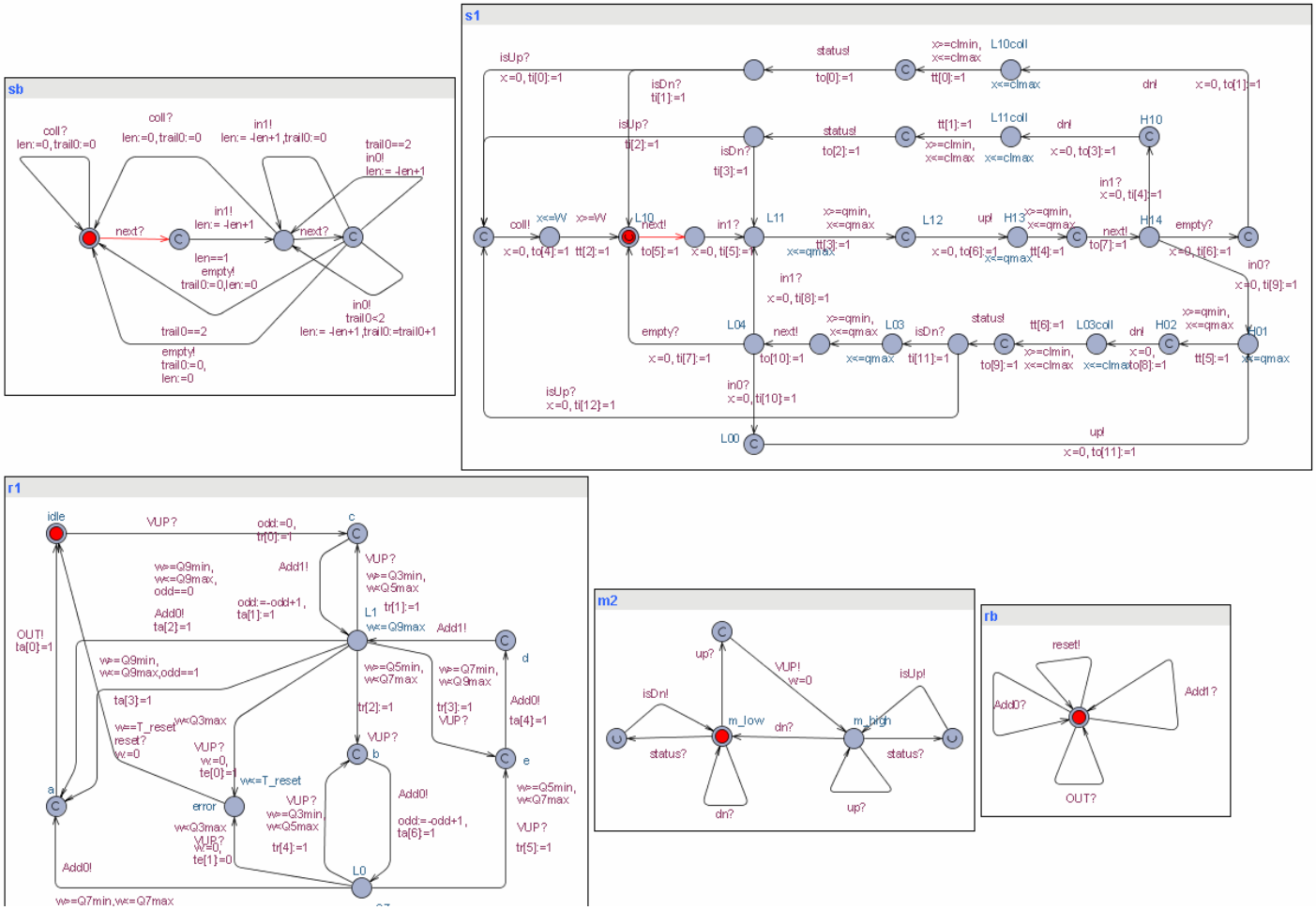
Philips Audio Protocol



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Benchmark Example

- Philips Audio Protocol

Coverage Criterion	Execution time (μs)	Generation time (s)	Memory usage (KB)
Edge_{Sender}	212350	2.2	9416
$\text{Edge}_{Receiver}$	18981	1.2	4984
$\text{Edge}_{Sender,Bus,Receiver}$	114227	129.0	331408

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Off-Line Test Generation

Observable Timed Automata

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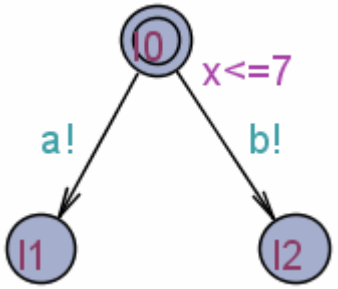
Observable Timed Automata

- **Determinism**:
  two transitions with same input/output leads to the same state
- **Input Enabled**:
  all inputs can always be accepted
- **Time Uncertainty of outputs**:
  timing of outputs uncontrollable by tester
- **Uncontrollable output**:
  IUT controls which enabled output will occur in what order



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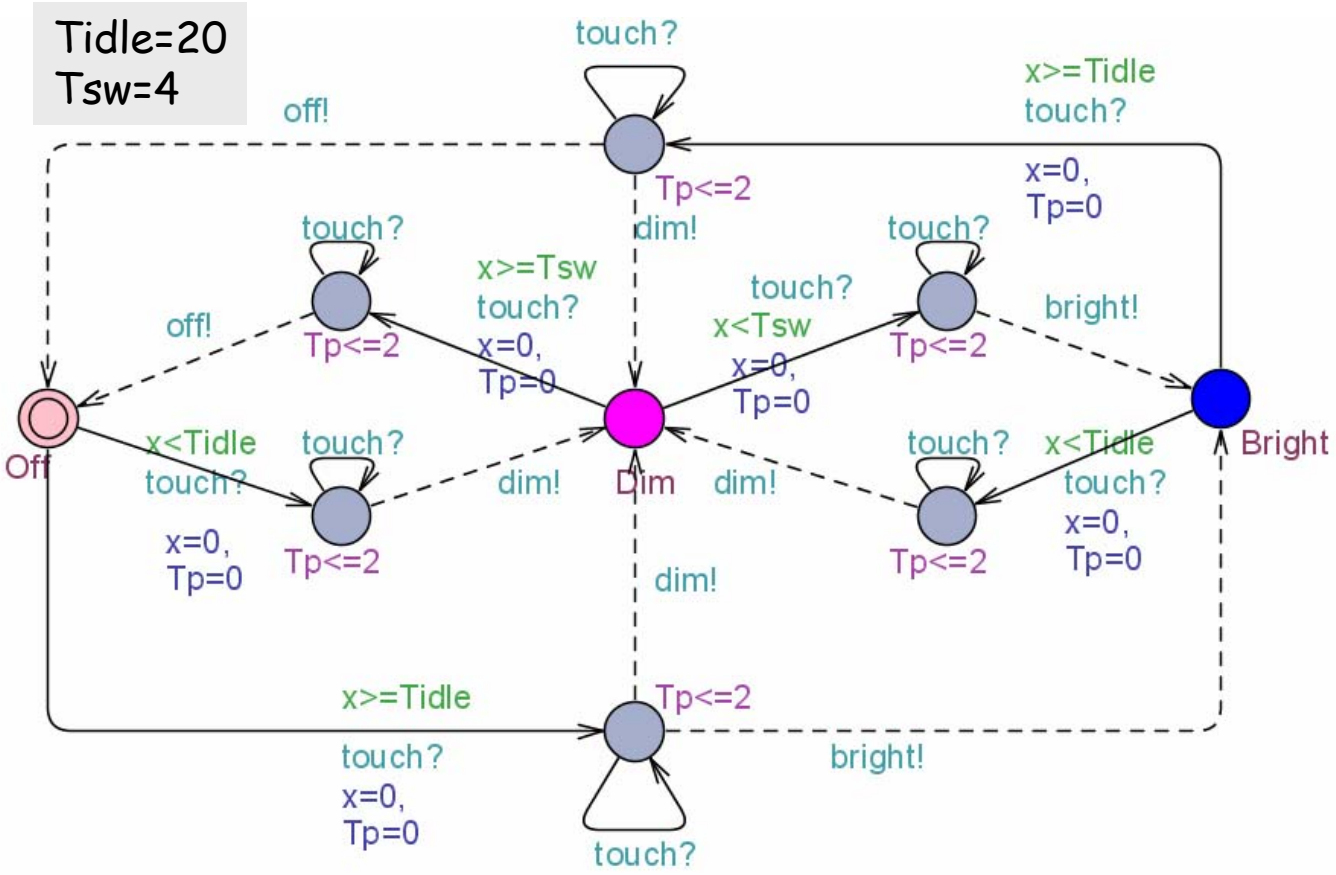
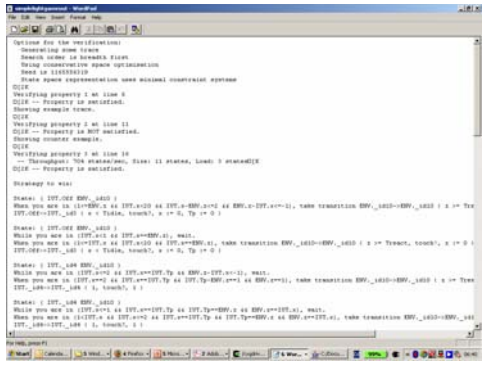
Timed Games and Test Generation

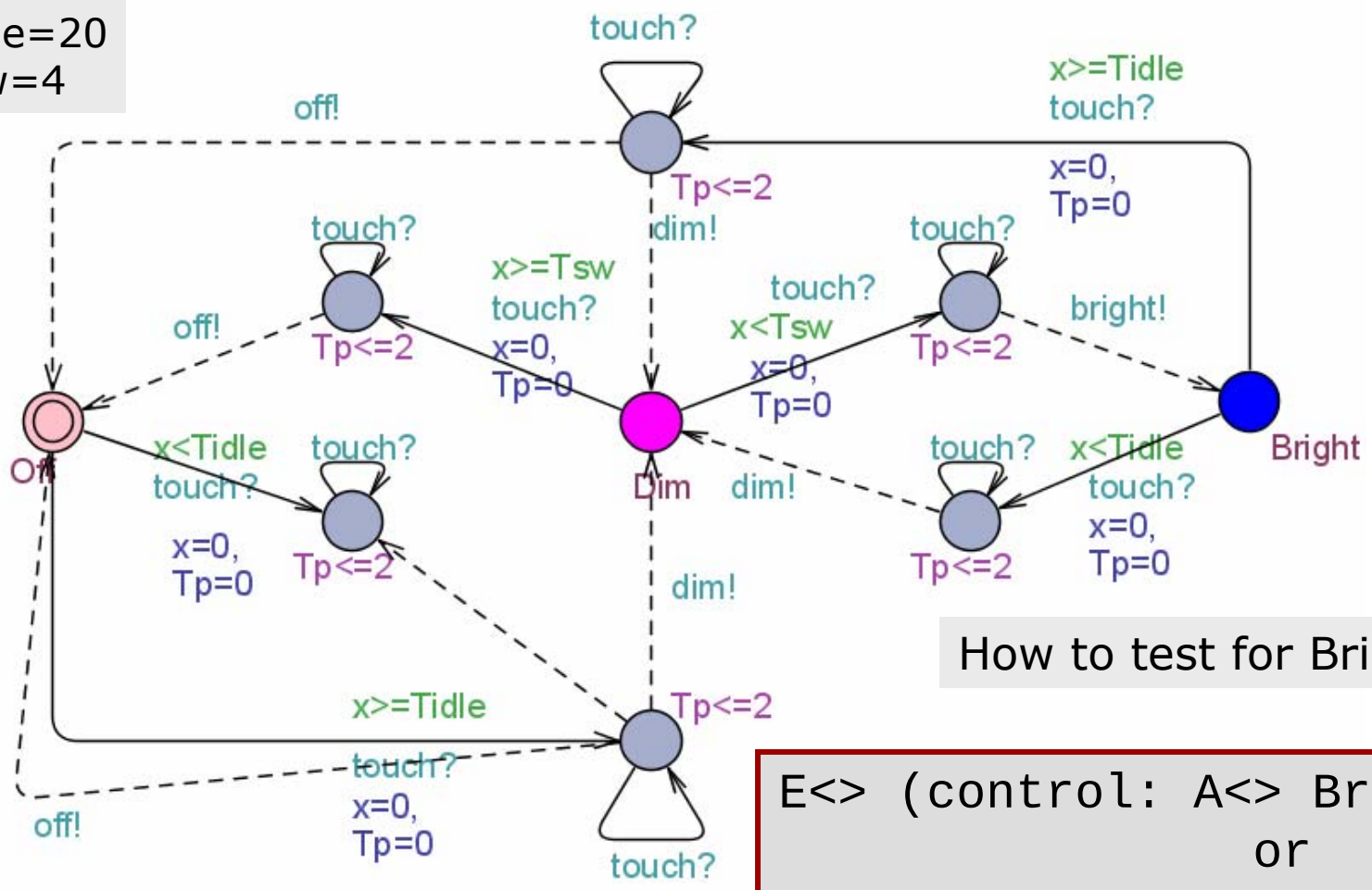




Off-line test-case generation =
Compute winning strategy for reaching **Bright**
Assign verdicts st. lost game means IUT not conforming

A trick light control

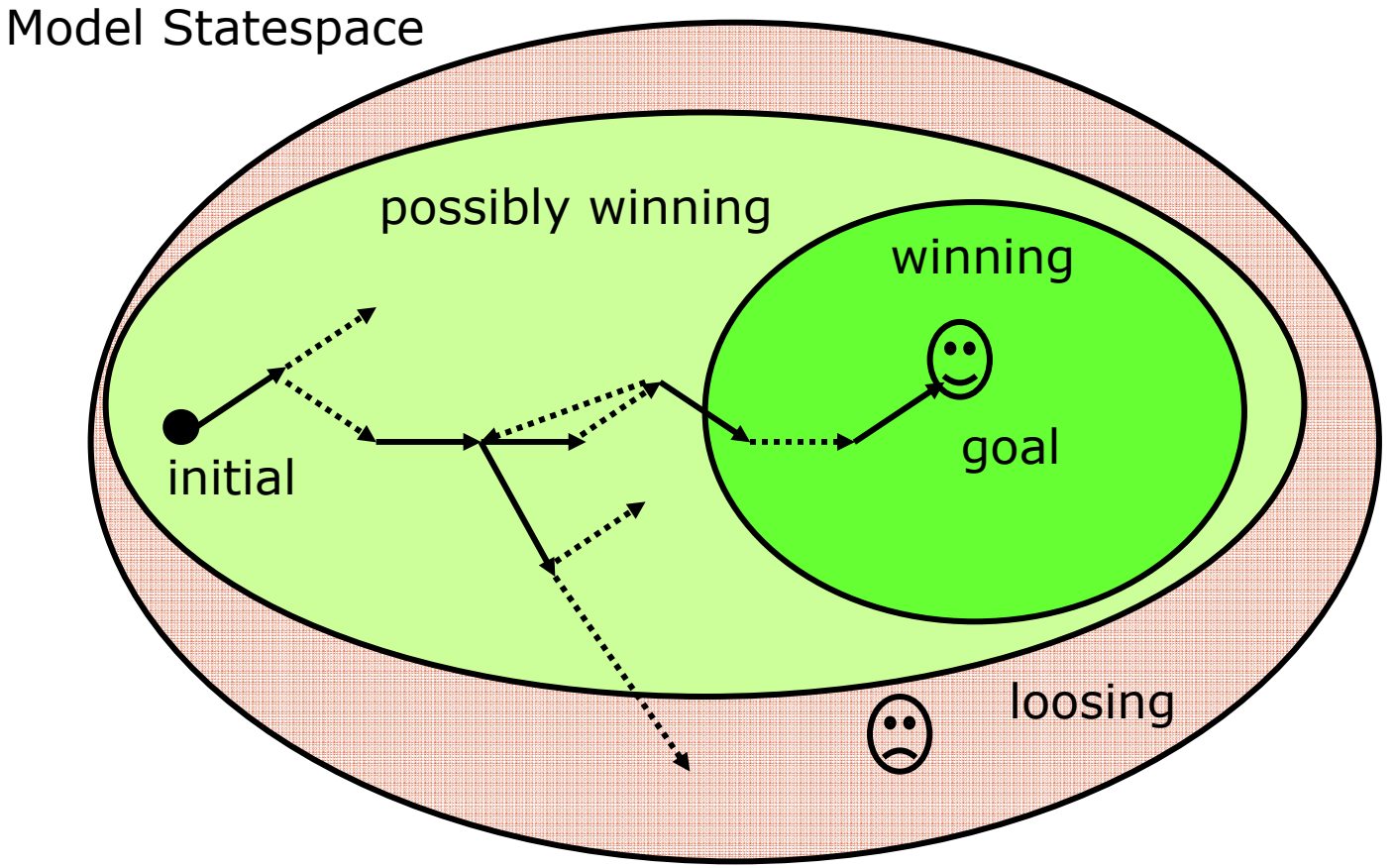
Tidle=20
Tsw=4



How to test for Bright ?

E<> (control: A<> Bright)
or
<<c,u>> ◇(<<c>> ◇ Bright)

Cooperative Strategies



- Play the game (execute test) while time available or game is lost
- Possibly using ranomized online testing

On-Line Testing

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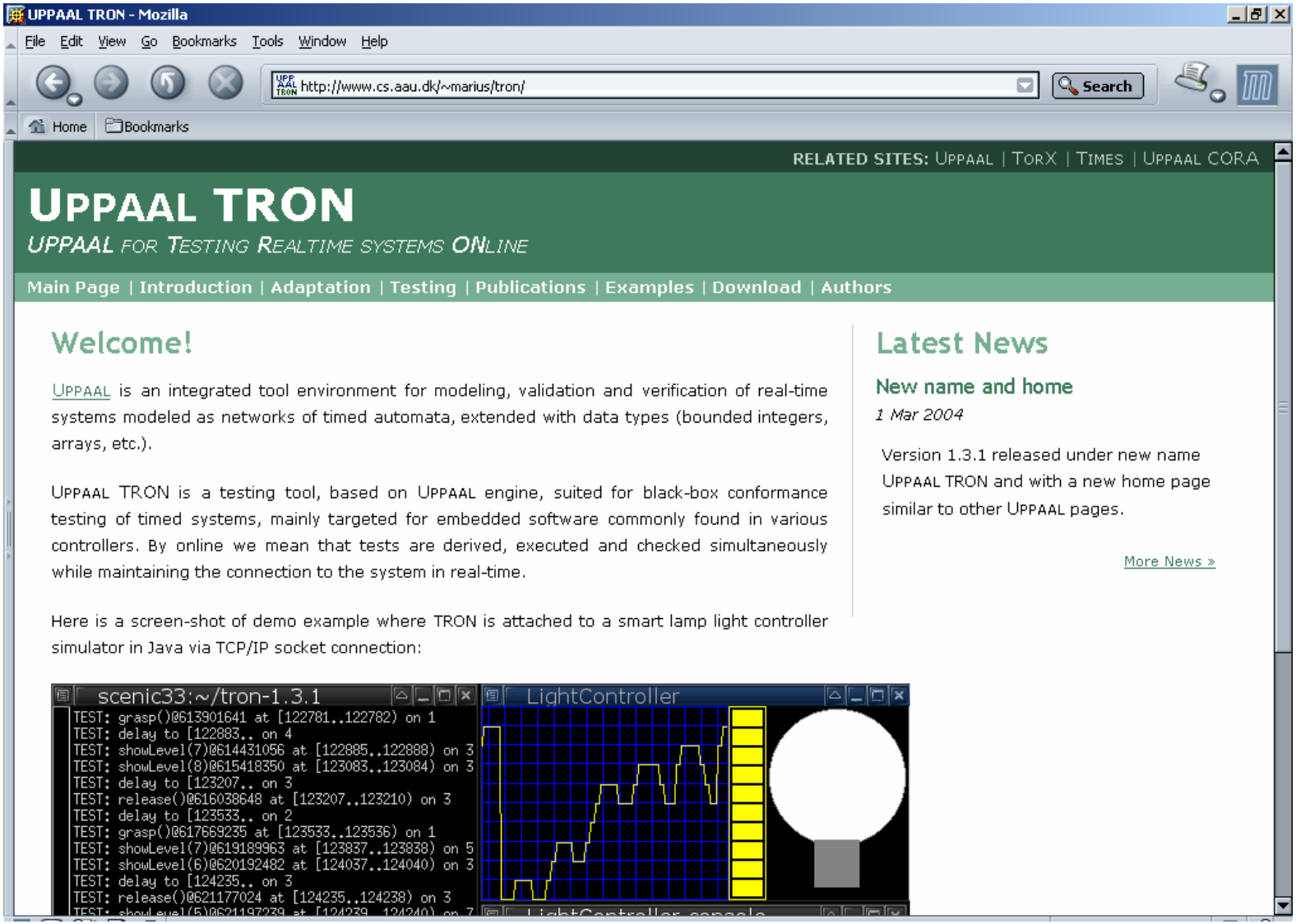

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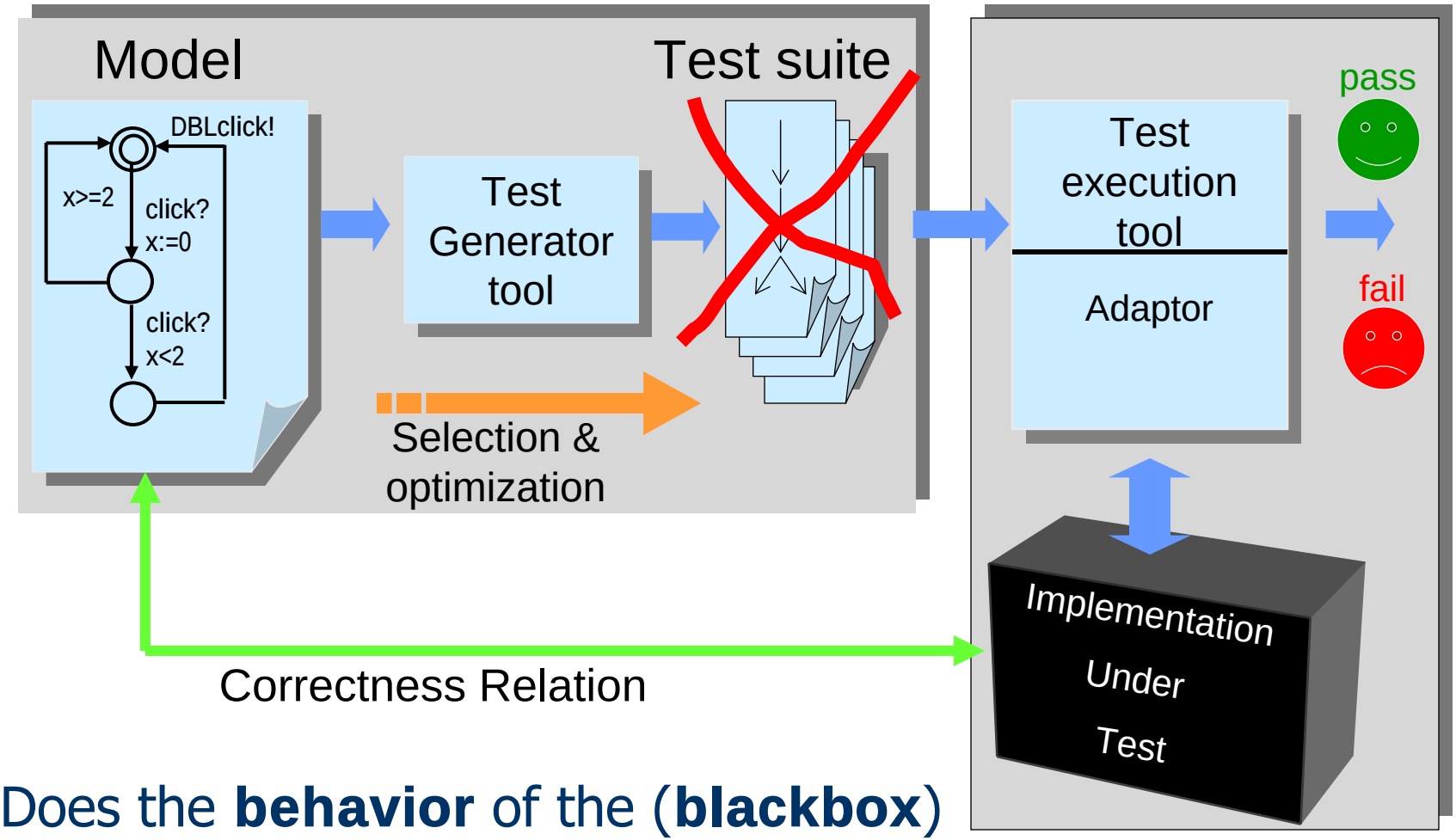
Automated Model Based Conformance Testing



Does the **behavior** of the (**blackbox**) implementation ***comply*** to that of the specification?

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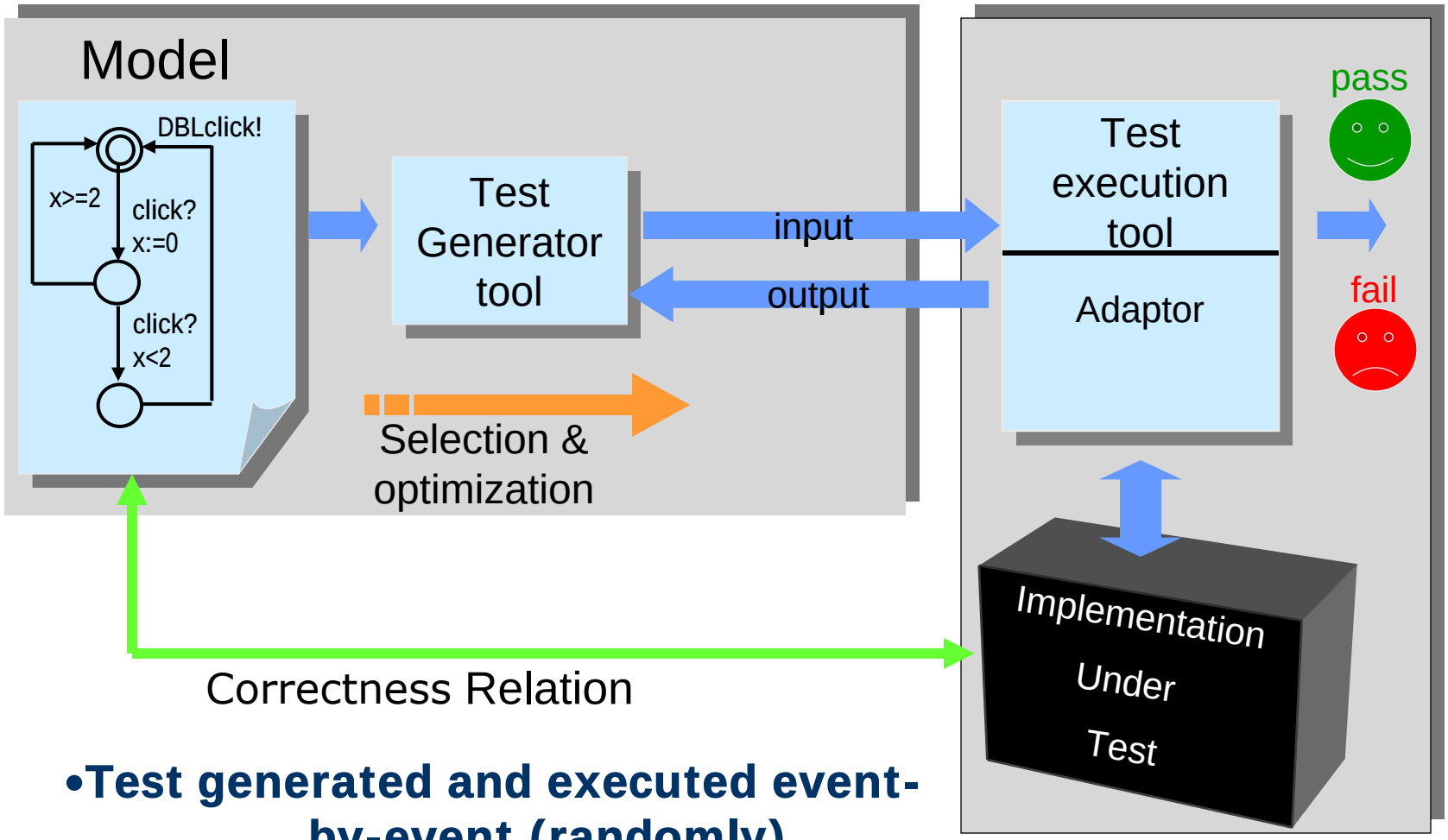
Online Testing



- **Test generated and executed event-by-event (randomly)**
- **A.K.A on-the-fly testing**

An Algorithm

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Algorithm Idea:

State-set tracking

- Dynamically compute all potential states that the model M can reach after the timed trace

  $\varepsilon_0, i_0, \varepsilon_1, o_1, \varepsilon_2, i_2, o_2, \ldots$ [Tripakis] Failure Diagnosis

- $Z = M$ ***after*** $(\varepsilon_0, i_0, \varepsilon_1, o_1, \varepsilon_2, i_2, o_2)$

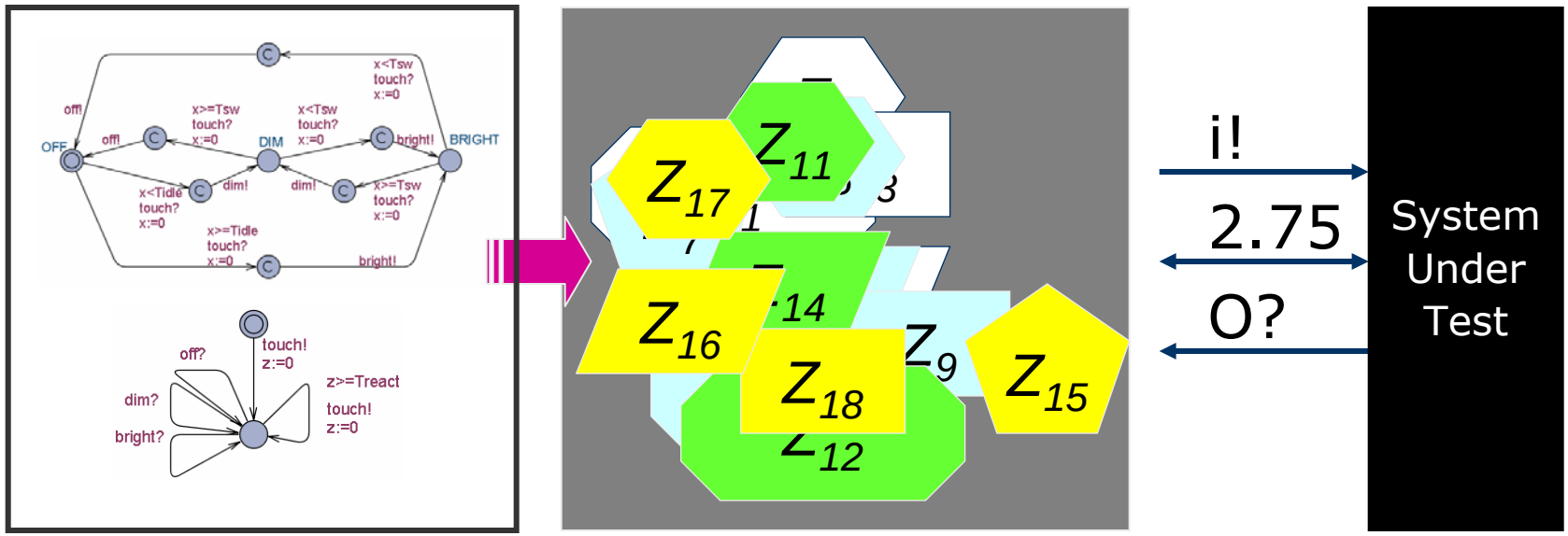
- *If* $Z = \emptyset$ *the IUT has made a computation not in model:* ***FAIL***

- *i is a relevant input in Env iff* $I \in EnvOutput(Z)$

Online State Estimation

Timed Automata Specification

State-set explorer:
maintain and analyse a *set* of *symbolic* states in real time!

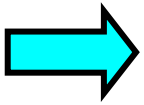


(Abstract) Online Algorithm

Algorithm *TestGenExe (S, E, IUT, T)* **returns** {**pass**, **fail**)
Z := {(s0, e0)}.

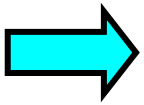
while Z ≠ ∅ **and** ♯iterations ≤ T **do either** randomly:

1. // offer an input

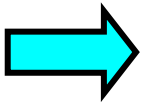


if *EnvOutput(Z)* ≠ ∅
randomly choose *i*∈ *EnvOutput(Z)*
send i to IUT
Z := Z *After* i

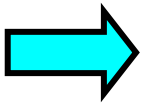
2. // wait d for an output



randomly choose d∈ *Delays(Z)*
wait (for d time units or output o at d′ ≤ d)



if o occurred **then**
Z := Z *After* d′
Z := Z *After* o // may become ∅ (⇒fail)



else
Z := Z *After* d // no output within d delay

3. *restart*:

Z := {(s0, e0)}, **reset** IUT //reset and restart

if Z = ∅ **then return fail else return pass**

(Abstract) Online Algorithm

Algorithm *TestGenExe (S, E, IUT, T)* **returns** {**pass**, **fail**)
Z := {(s0, e0)}.

while Z ≠ ∅ □ ♯iterations ≤ T **do either** randomly:

1. // offer an input

   if *EnvOutput(Z)* ≠ ∅
   randomly choose *i* *EnvOutput(Z)*
   send i to IUT
   Z := Z

2. // wait d fo
   randomly c
   wait (for d
   if o occurre
   Z := Z *A*
   Z := Z *After* o // may become ∅ (⇒fail)
   else
   Z := Z *After* d // no output within d delay

3. *restart*:
   Z := {(s0, e0)}, **reset** IUT //reset and restart

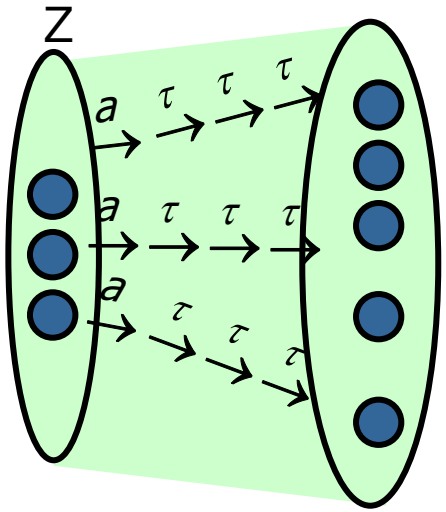
if Z = ∅ **then return fail else return pass**

- Sound
- Complete (as T → ∞)

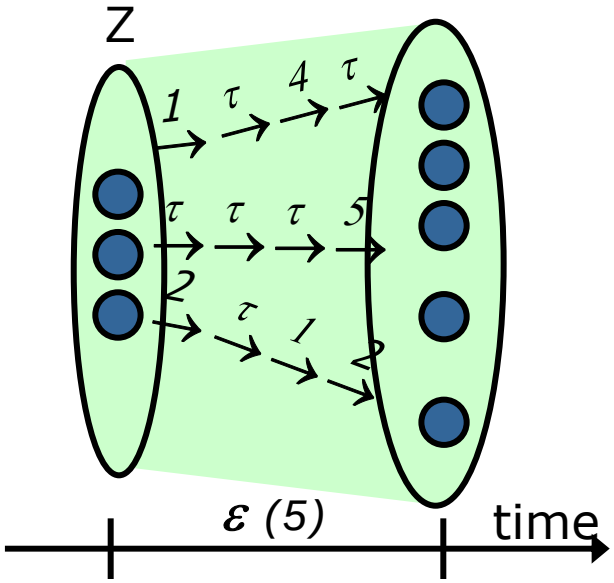
(Under some technical assumptions)

State-set Operations

Z* after *a: *possible states after* ***action a*** *(and* τ^**)*

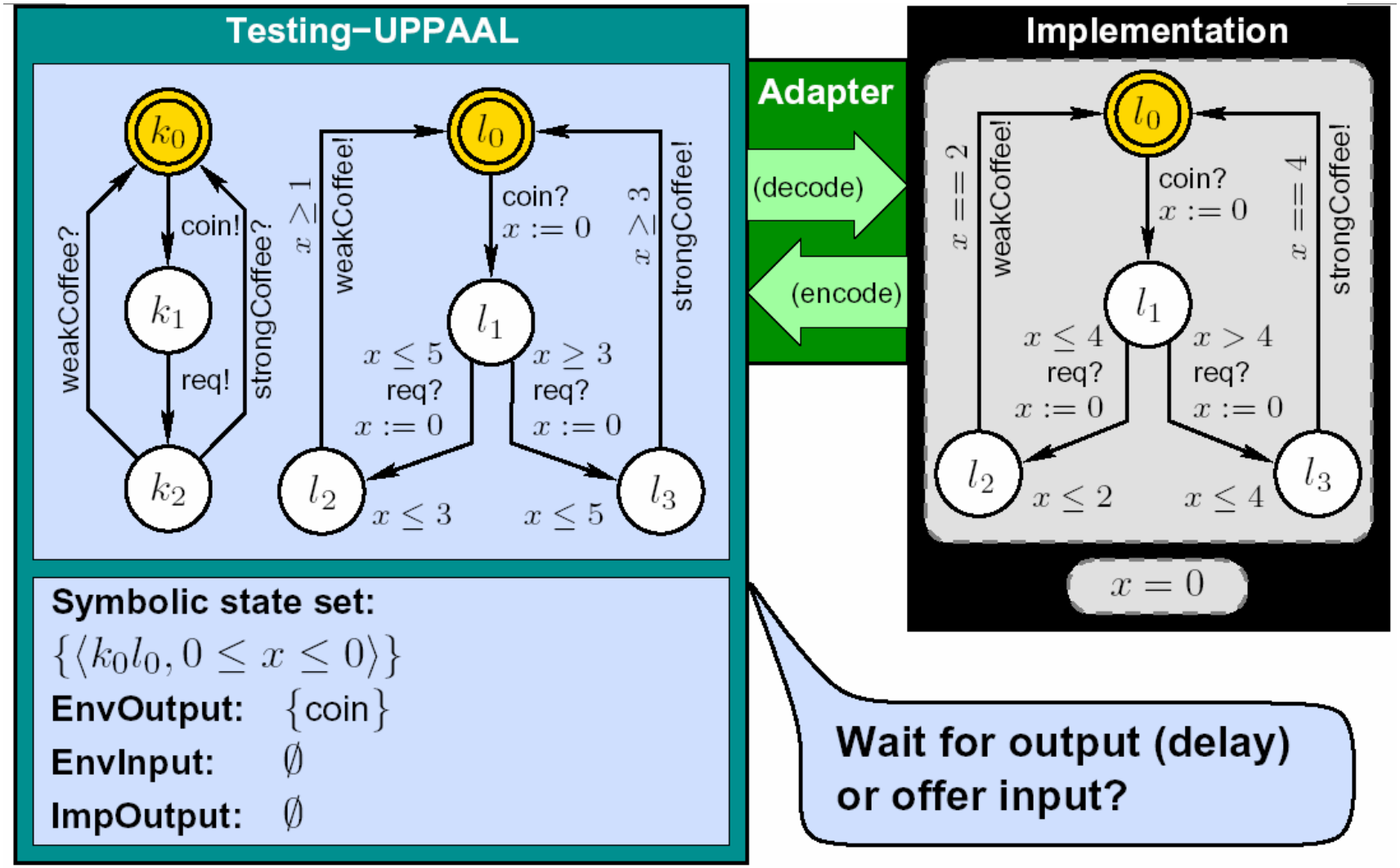


Z* after** ε :*possible states after* τ^* *and* ε_i *, totaling a* ***delay *of* ε

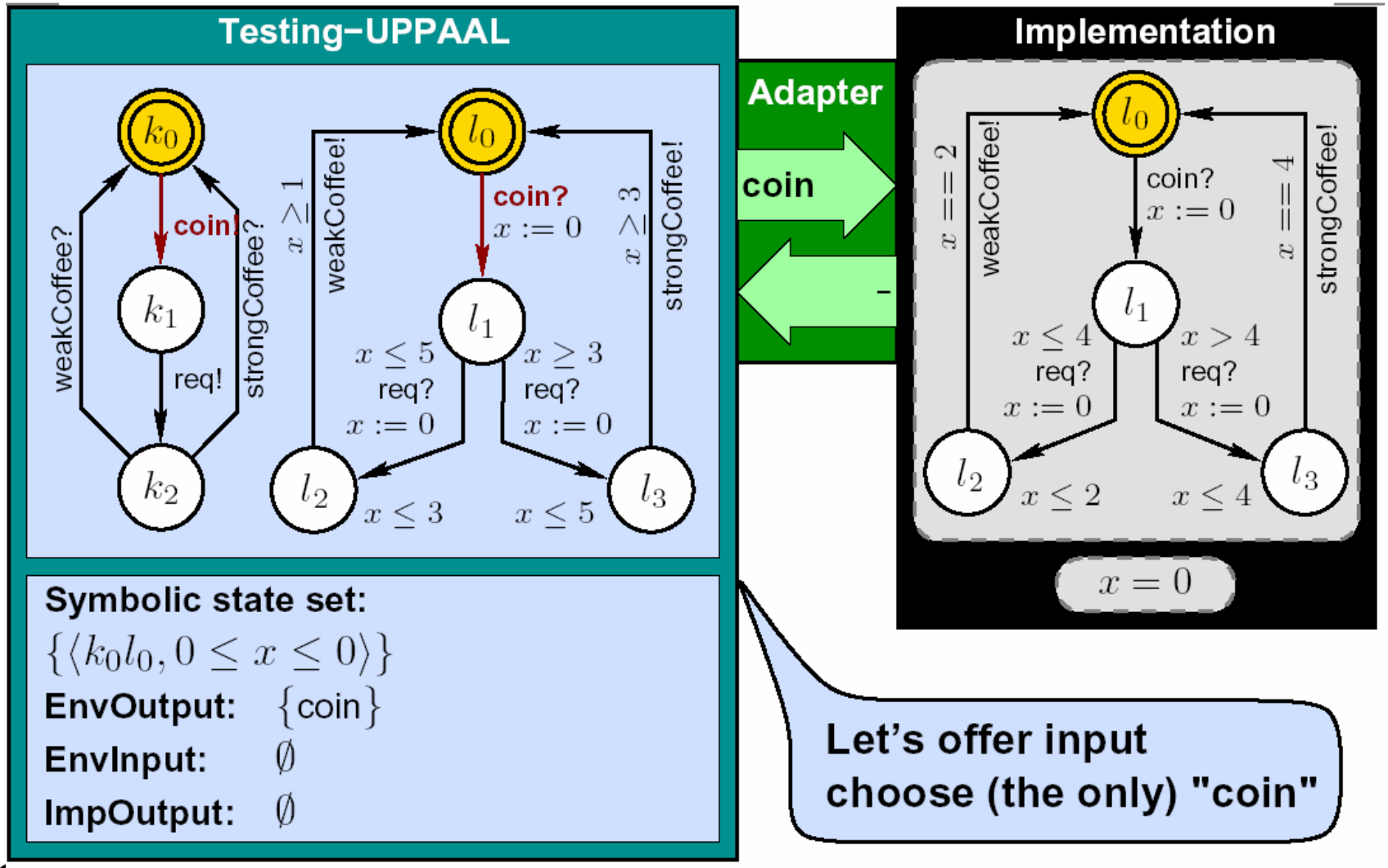


- Can be computed efficiently using the symbolic data structures and algorithms in Uppaal

Online Testing Example



Online Testing



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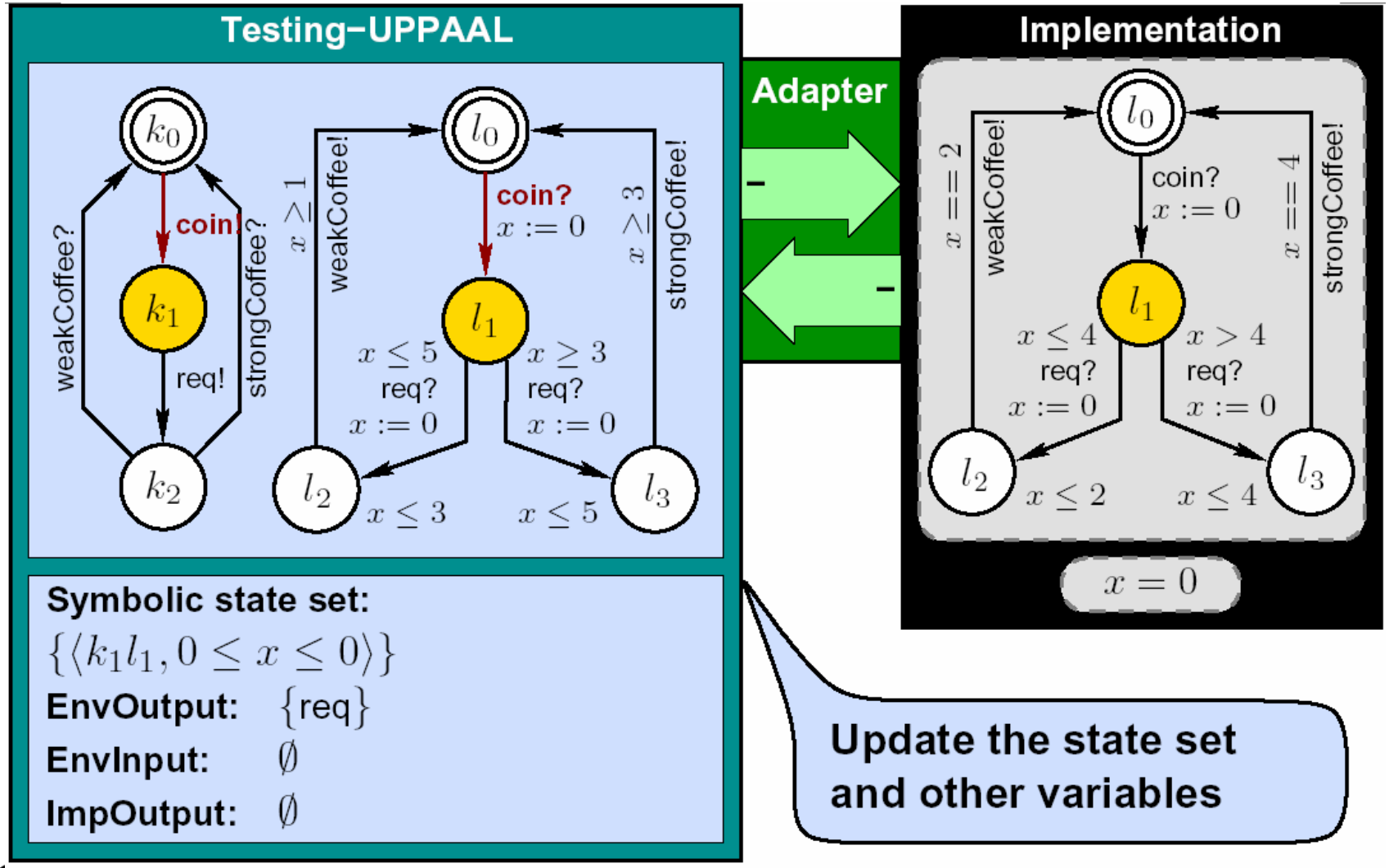

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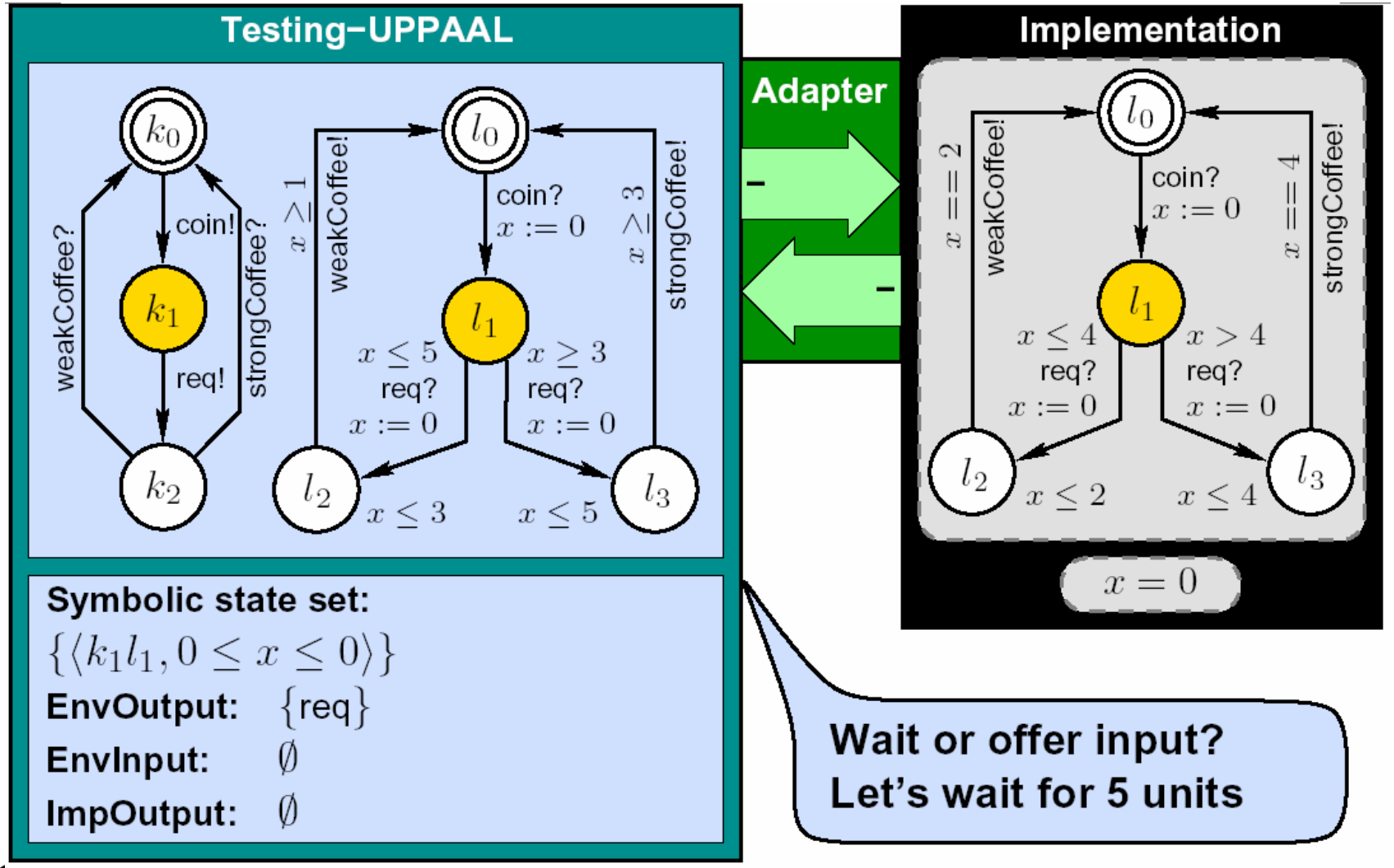

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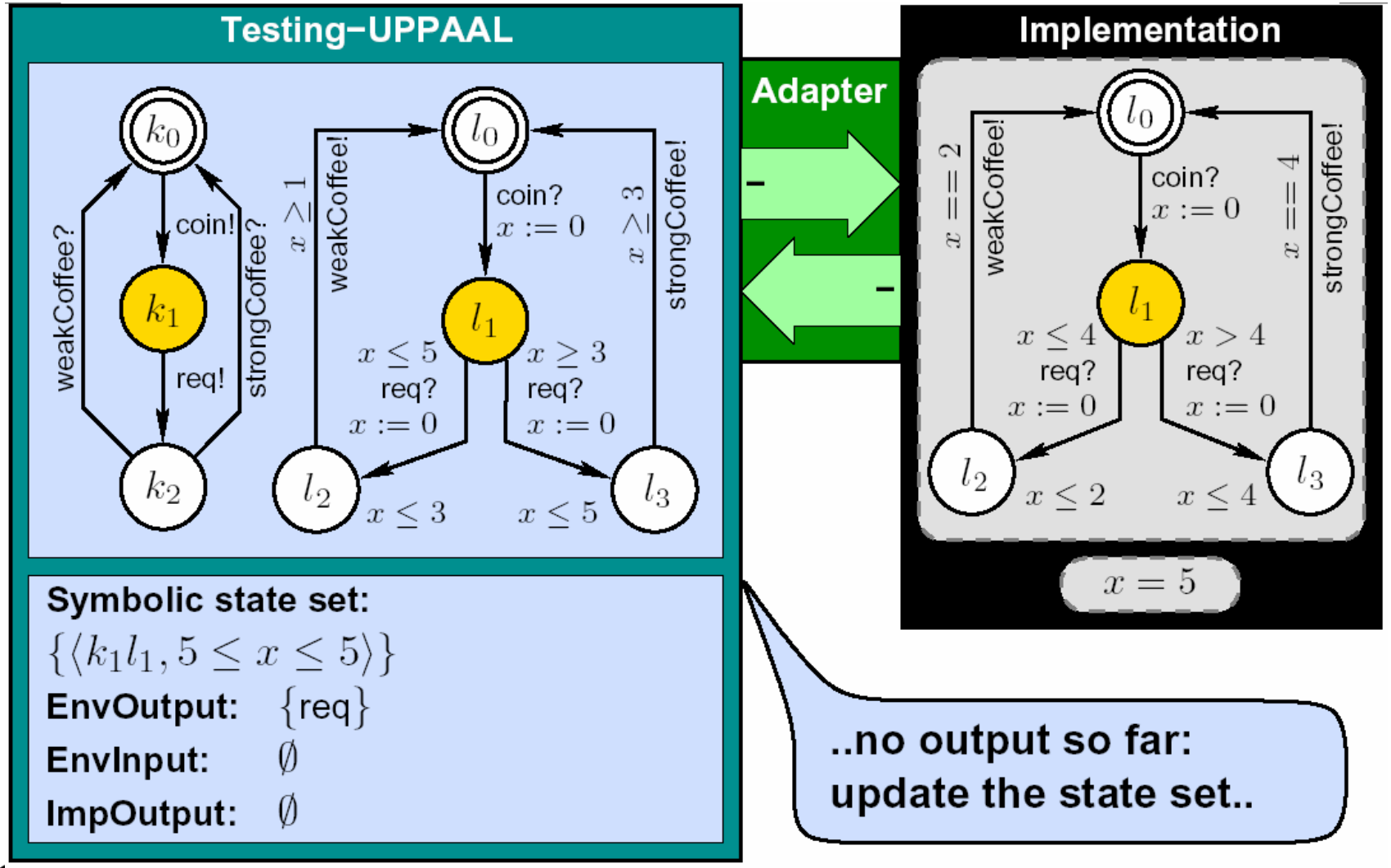

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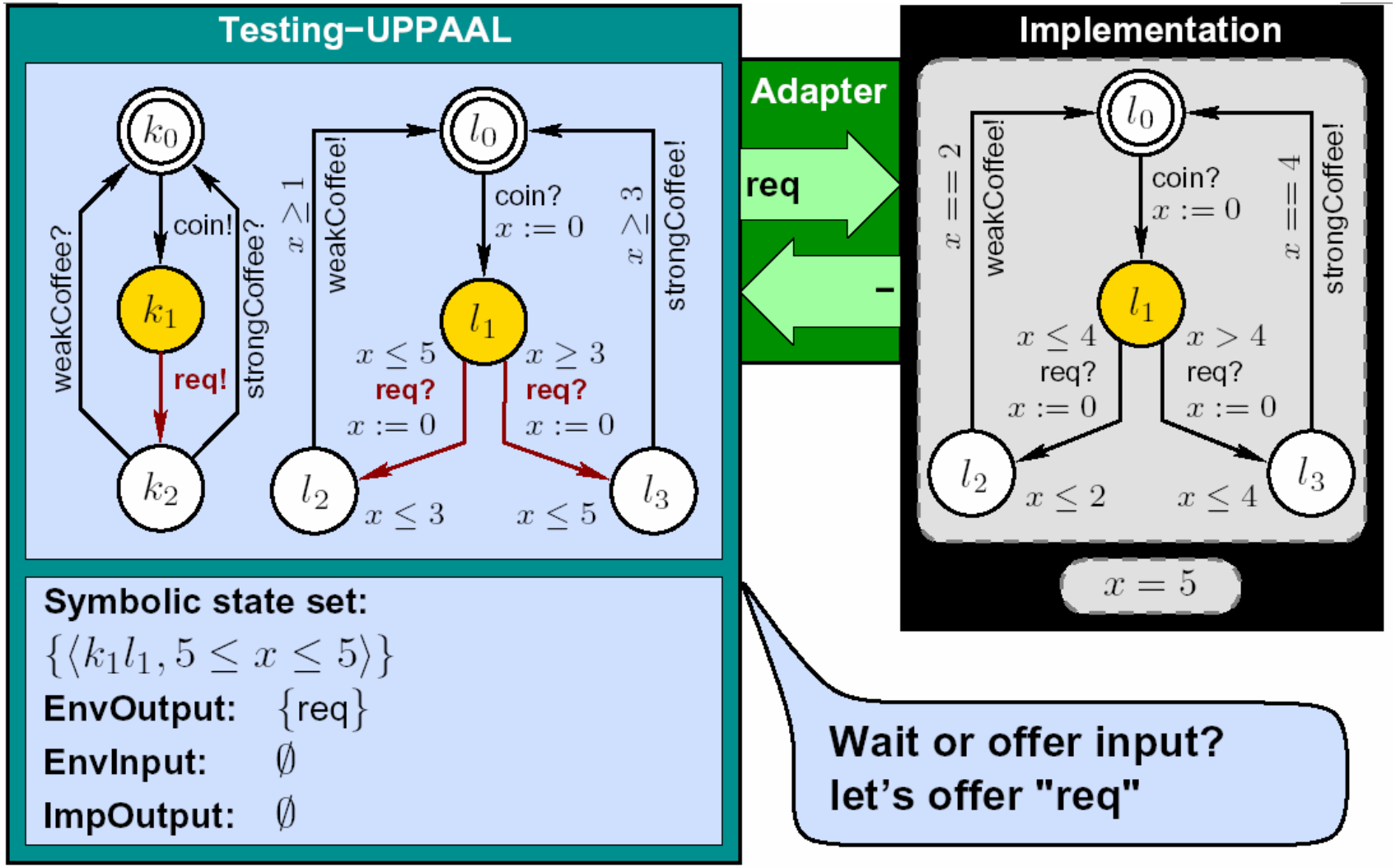
Online Testing



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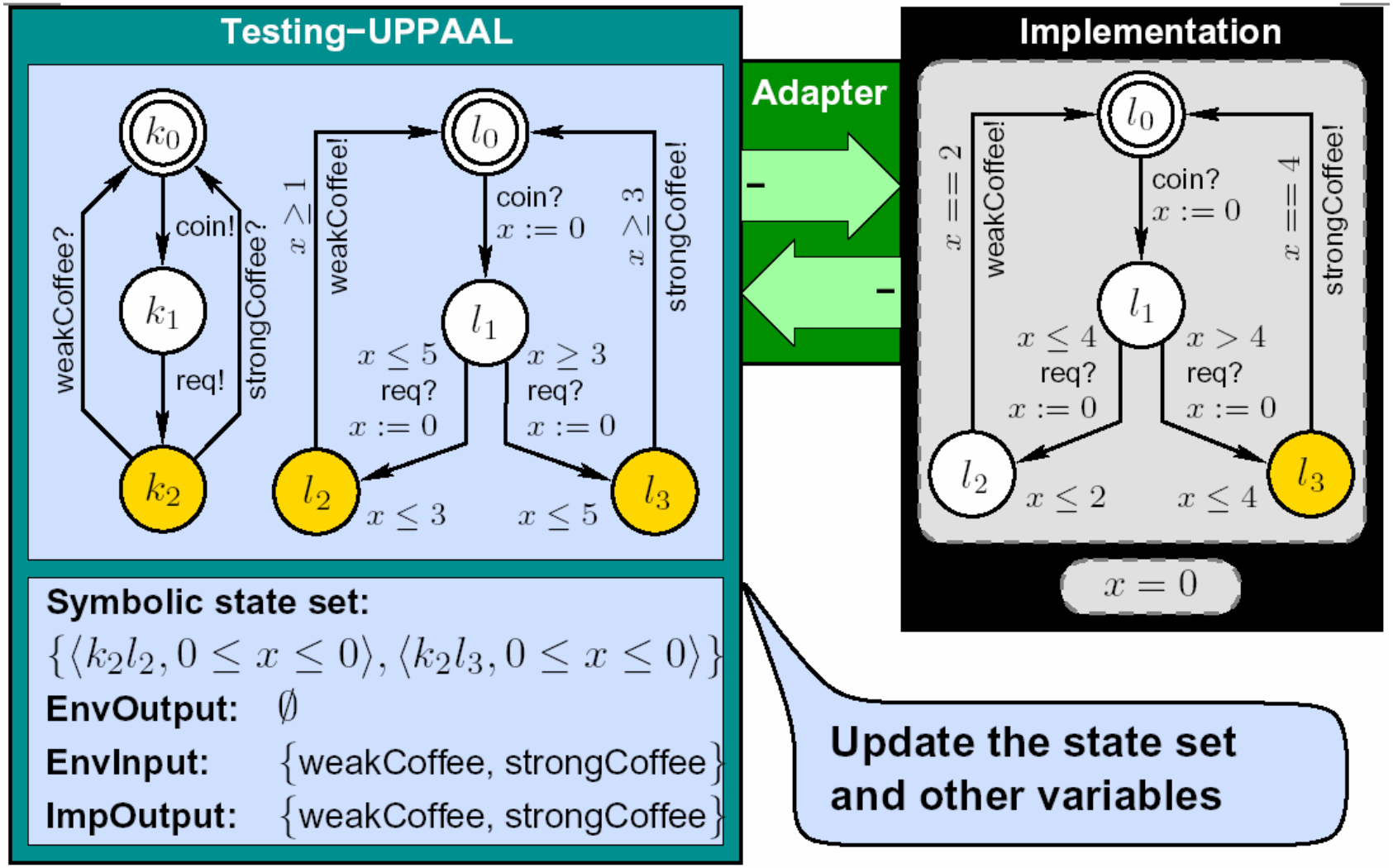
Online Testing



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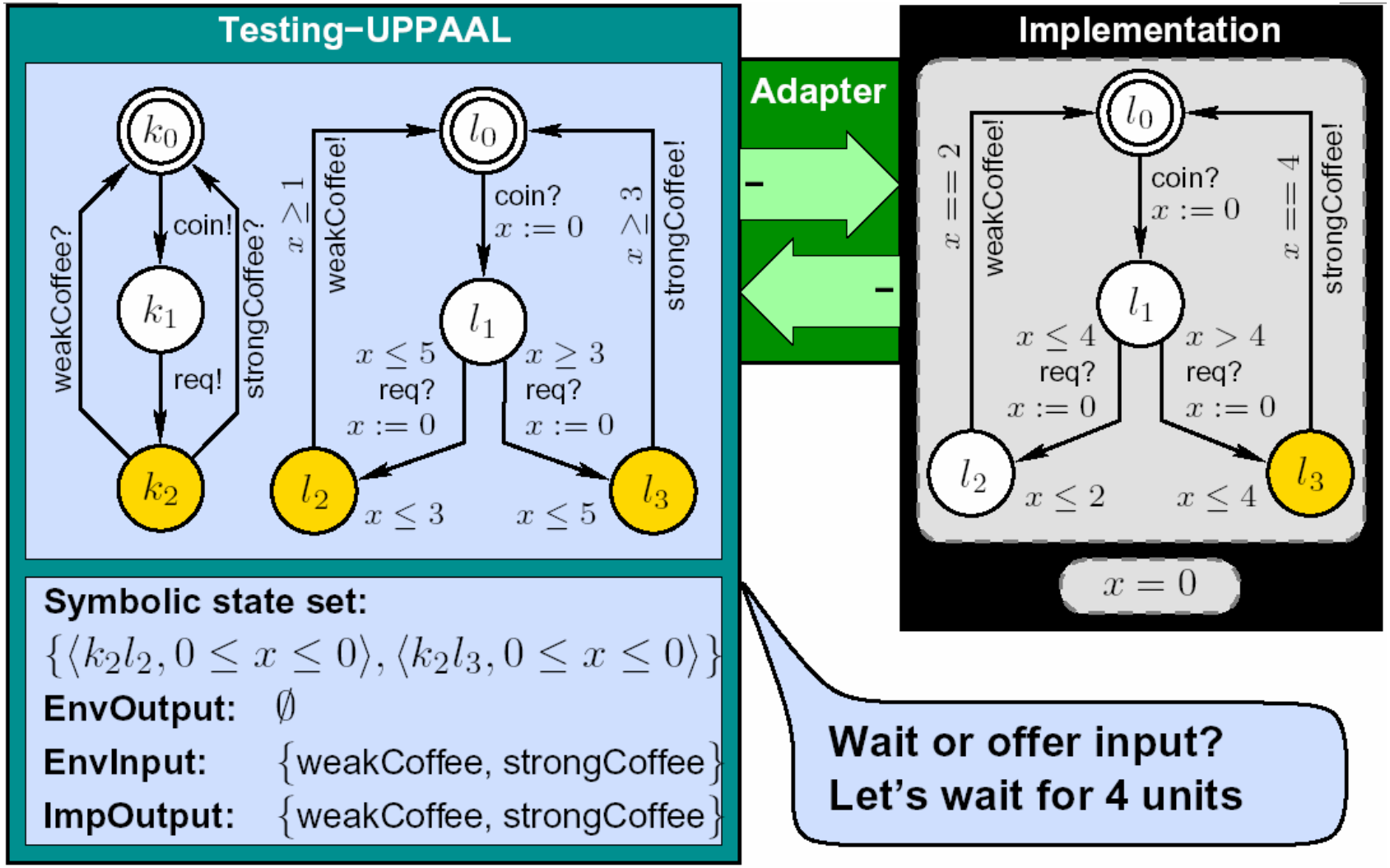
Online Testing



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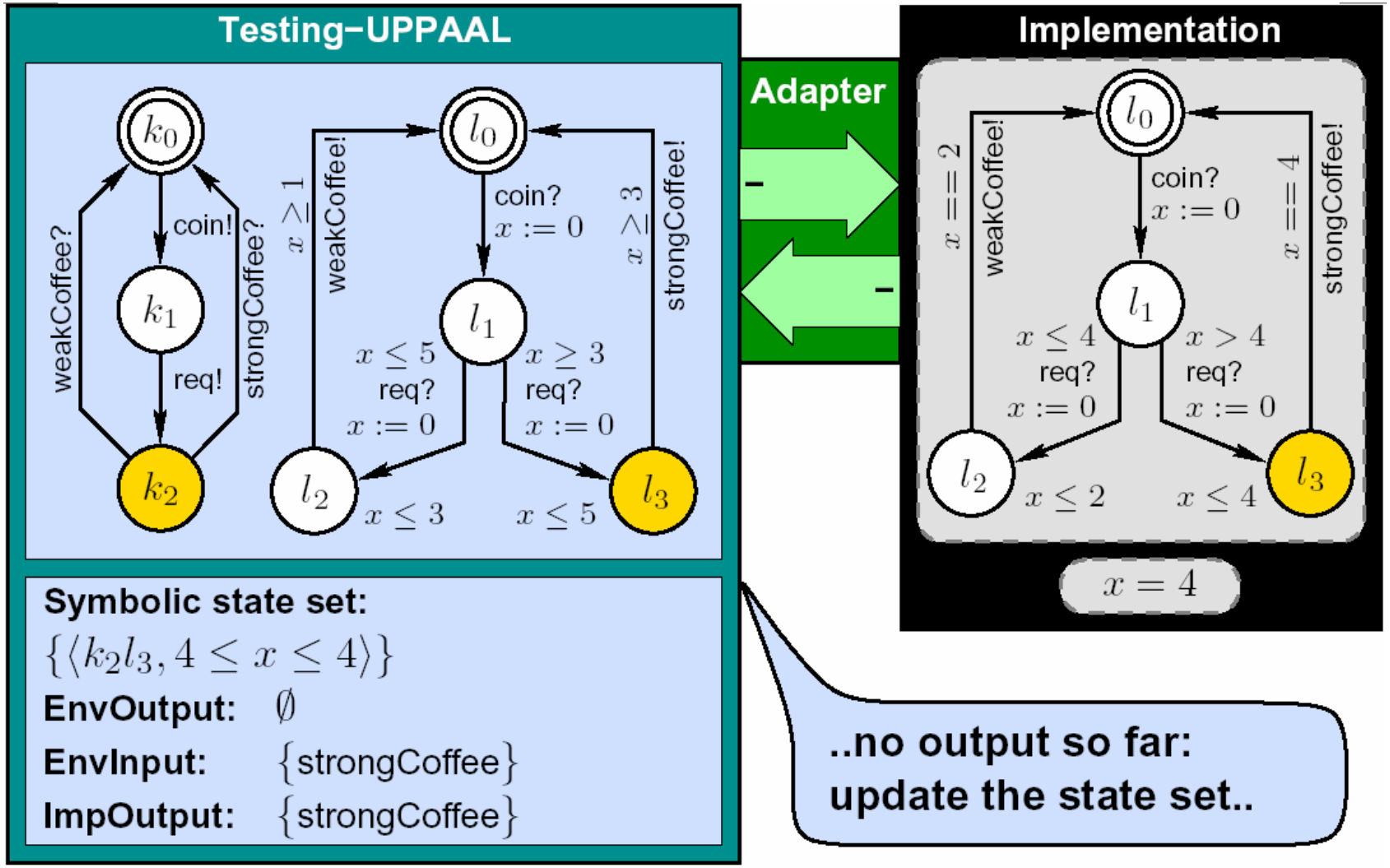
Online Testing



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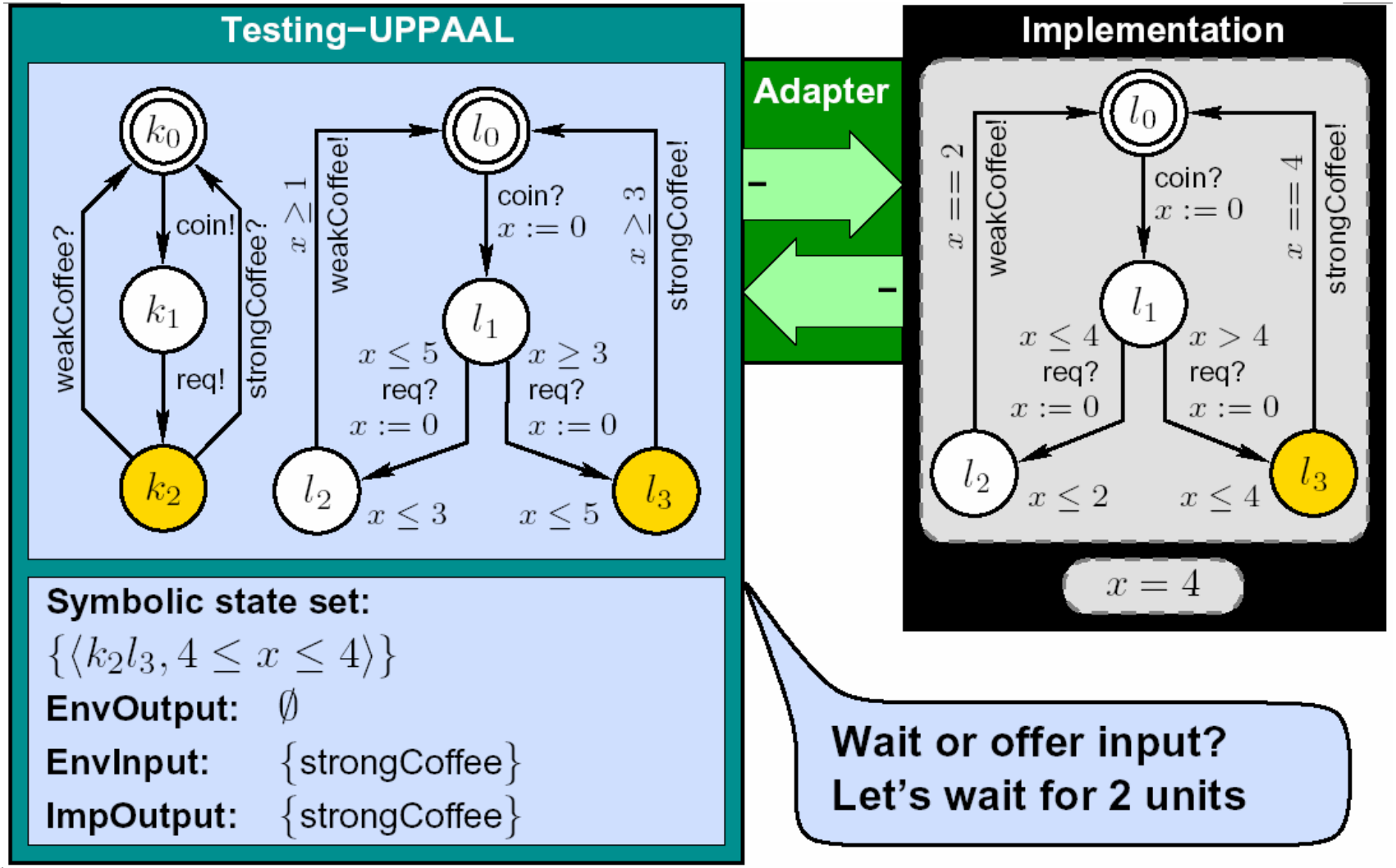

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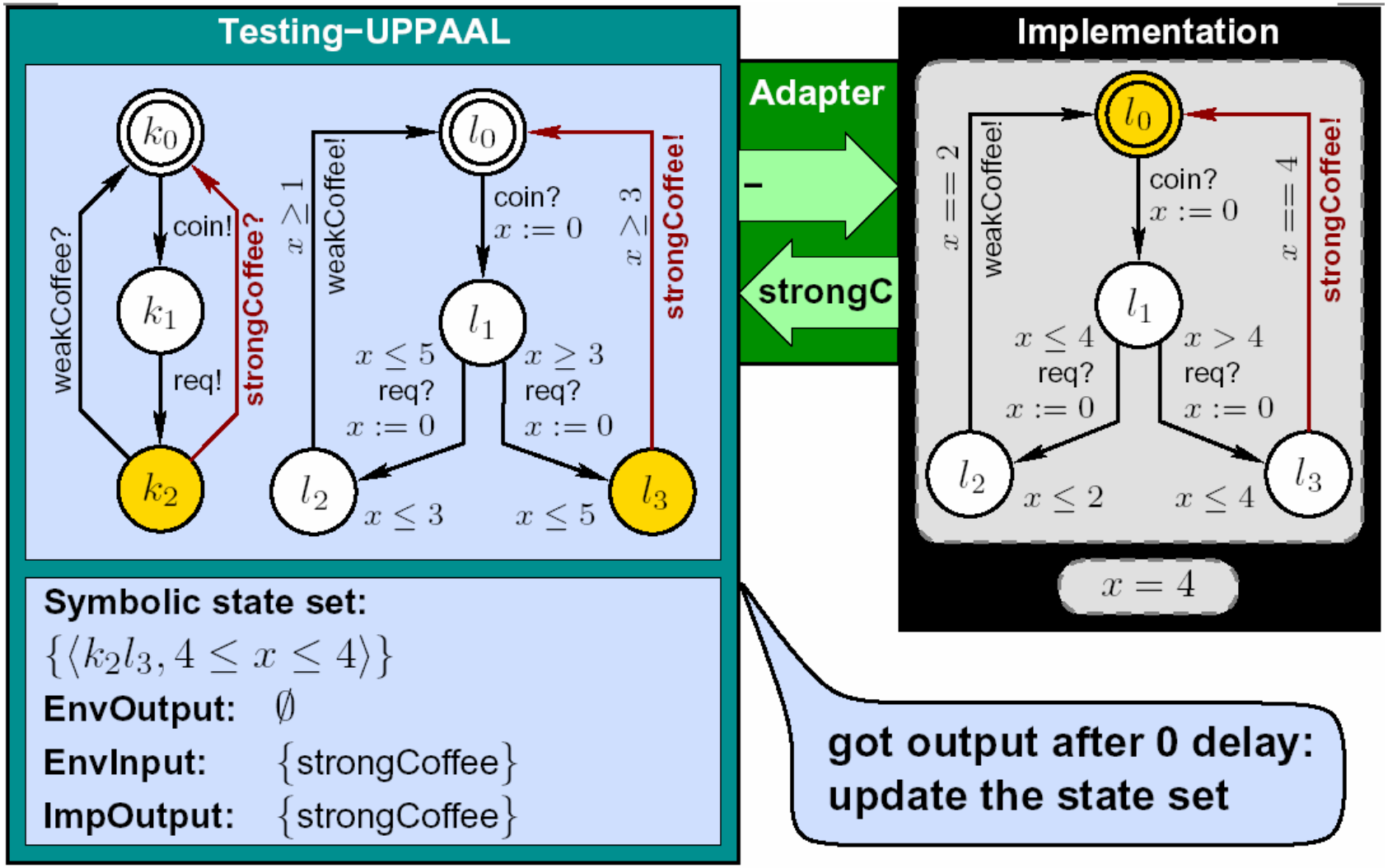
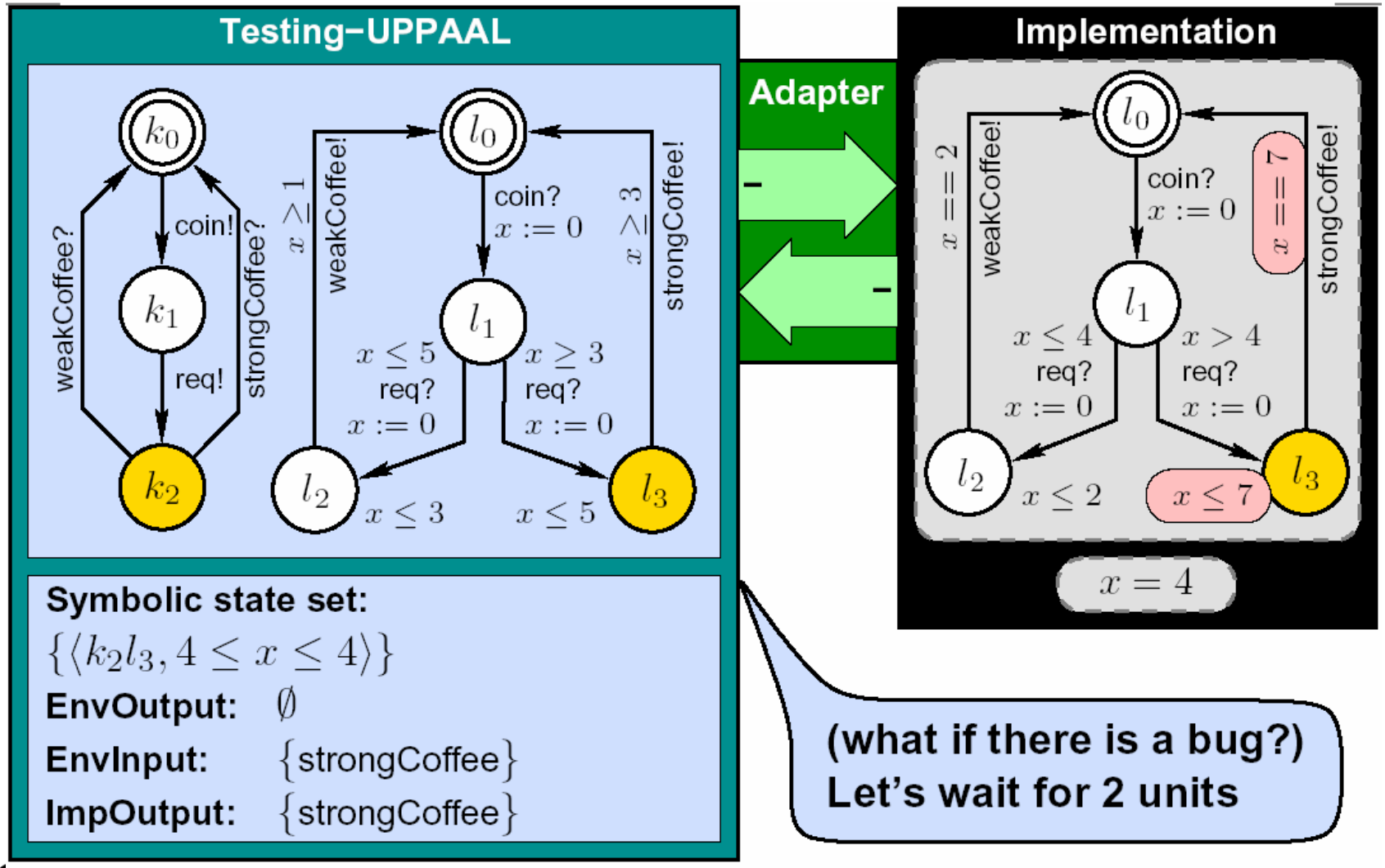
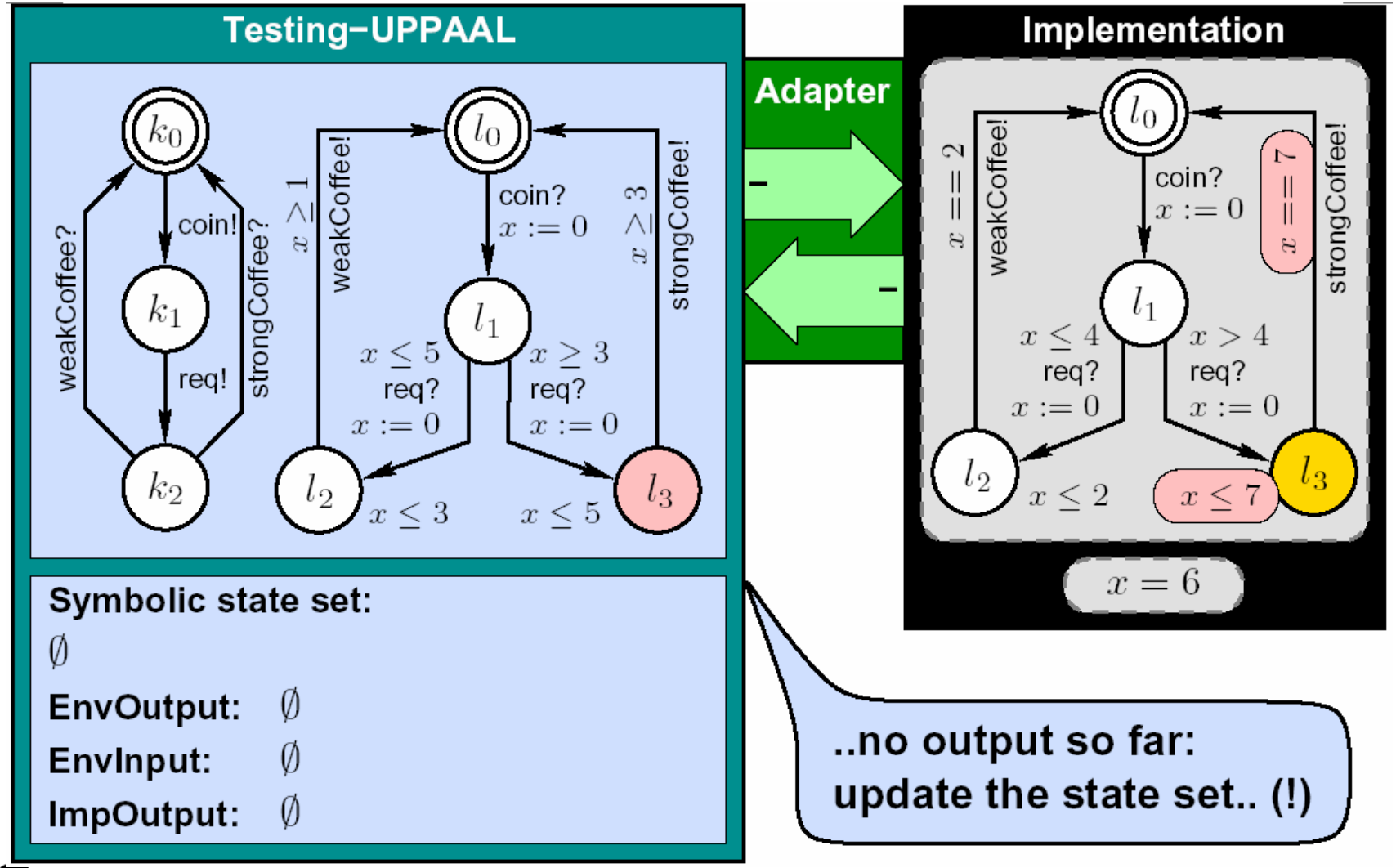


Online Testing



Online Testing



Industrial Application:

Danfoss Electronic Cooling Controller

Sensor Input
- air temperature sensor
- defrost temperature sensor
- (door open sensor)

Keypad Input
- 2 buttons (~40 user settable parameters)

Output Relays
- compressor relay
- defrost relay
- alarm relay
- (fan relay)

Display Output
- alarm / error indication
- mode indication
- current calculated temperature

- Optional real-time clock or LON network module

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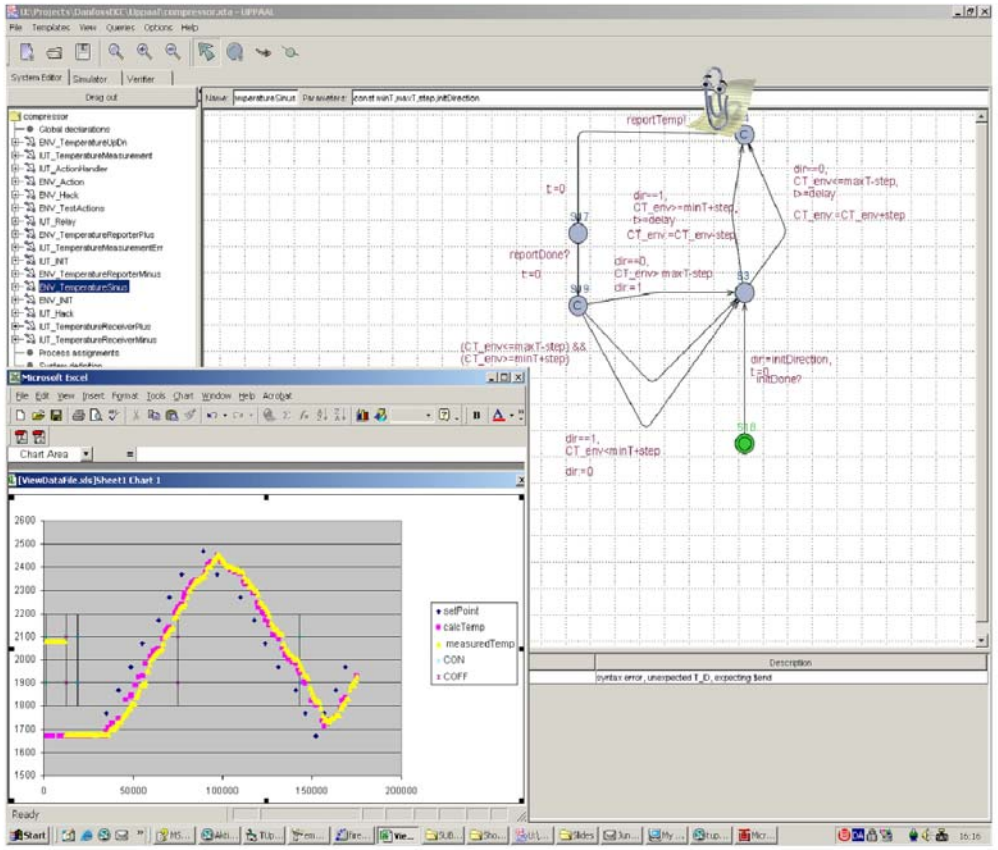
Industrial Application:

Danfoss Electronic Cooling Controller

Sensor Input

- air temperature sensor



- Optional real-time clock or LON network module

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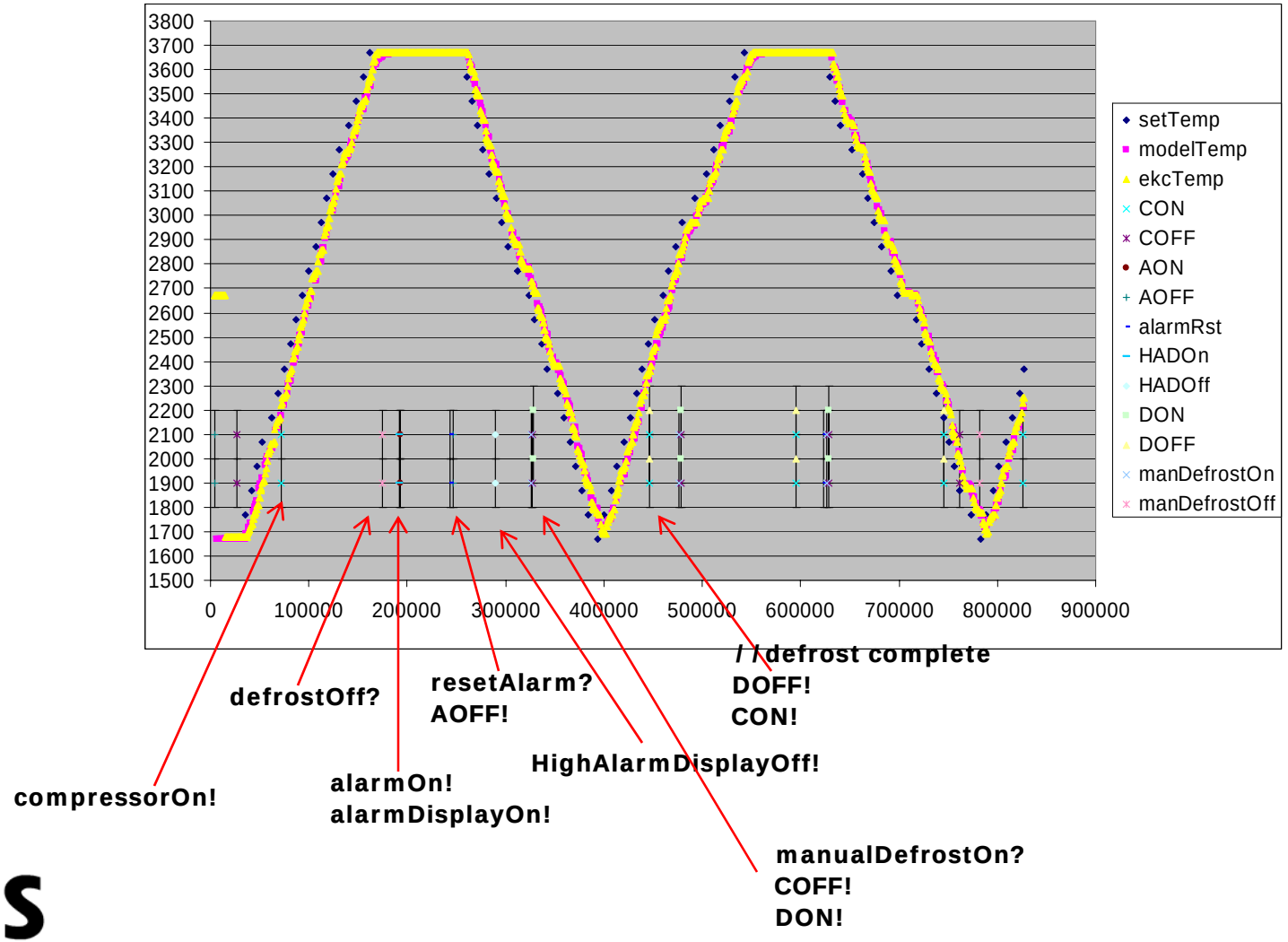
Example Test Run

(log visualization)



Model-based Testing of Real Time Systems

Conclusions

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Conclusions

- Testing real-time systems is theoretically and practically challenging
- Promising techniques and tools
- Explicit environment modeling
  - Realism and guiding
  - Separation of concerns
  - Modularity
  - Creative tool uses
  - Theoretical properties
- Real-time online testing from timed automata is feasible, but
  - Many open research issues

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Research Problems

- Testing Theory
- Timed games with partial observability
- Hybrid extensions
- Other Quantitative Properties
- Probabilistic Extensions, Performance testing
- Efficient data structures and algorithms for state set computation
- Diagnosis & Debugging
- Guiding and Coverage Measurement
- Real-Time execution of TRON
- Adaptor Abstraction, IUT clock synchronization
- Further Industrial Cases

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Related Work

- Formal Testing Frameworks
  - [Brinksma, Tretmans]
- Real-Time Implementation Relations
  - [Khoumsi'03, Briones'04, Krichen'04]
- Symbolic Reachability analysis of Timed Automata
  - [Dill'89, Larsen'97,…]
- Online state-set computation
  - [Tripakis'02]
- Online Testing
  - [Tretmans'99, Peleska'02, Krichen'04]

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