Model Based Testing of Embedded Systems

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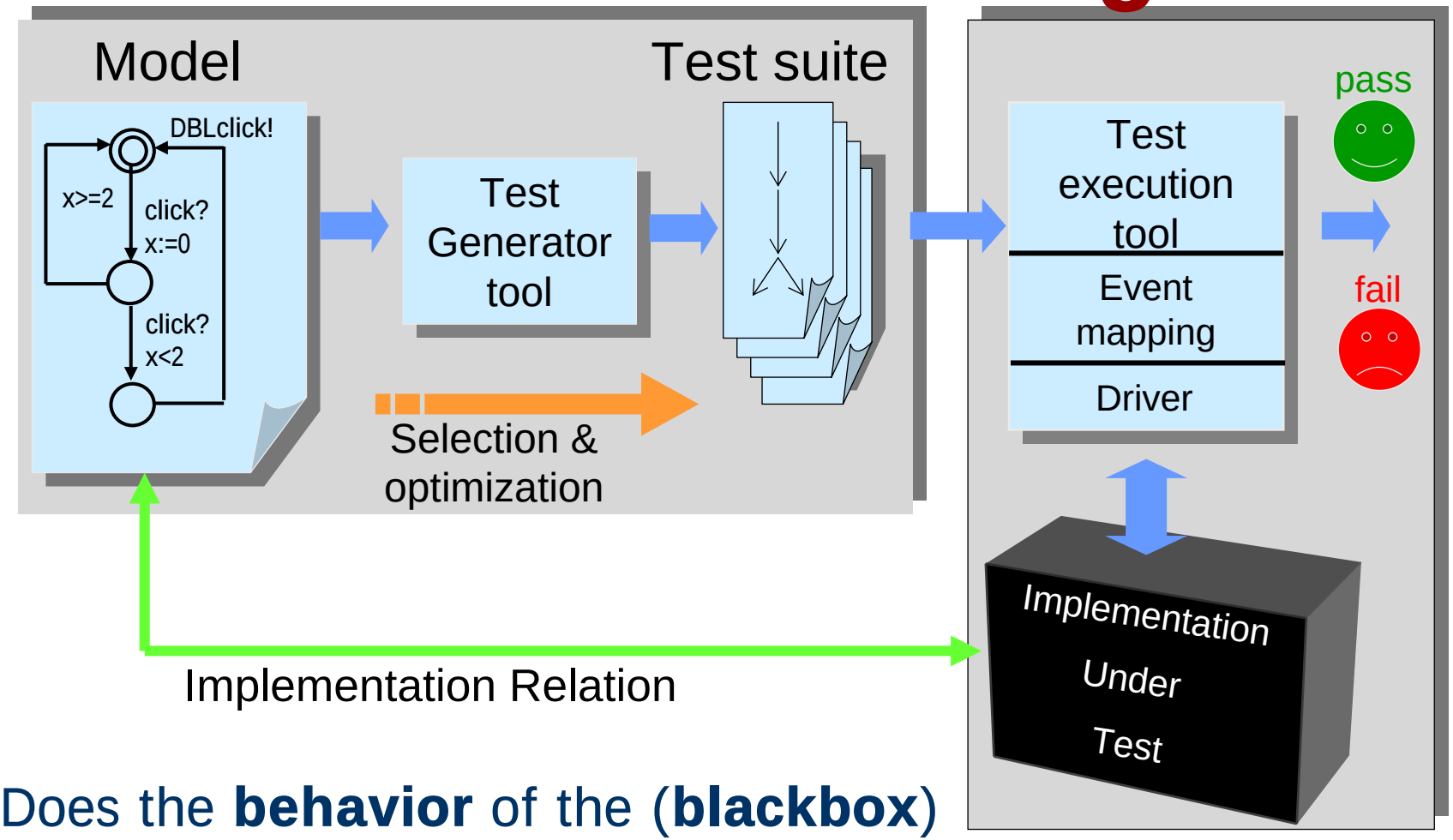
Basic Research
in Computer Science

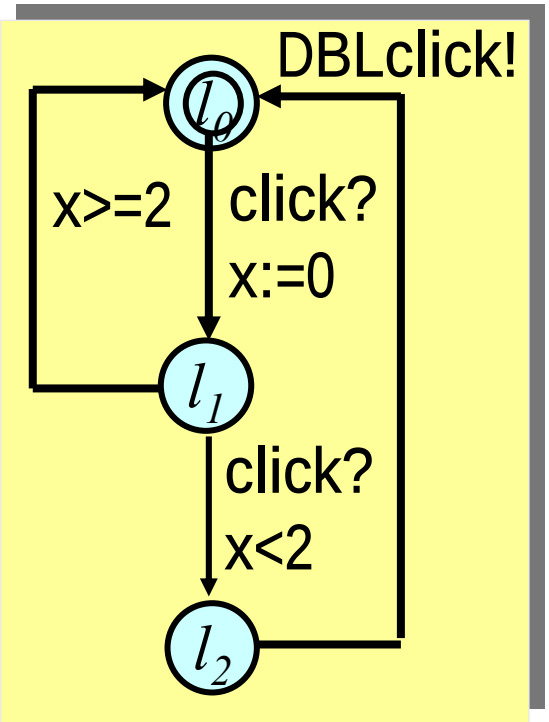
Automated Model Based Conformance Testing



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

Specification Based Testing

A Specification



Test cases

Click!
Wait 1.5
click!
DBLClick?

(pass)

Click!
Wait 5
click!
DBLClick?

(fail)

Click!
Wait 0.1
click!
DBLClick?

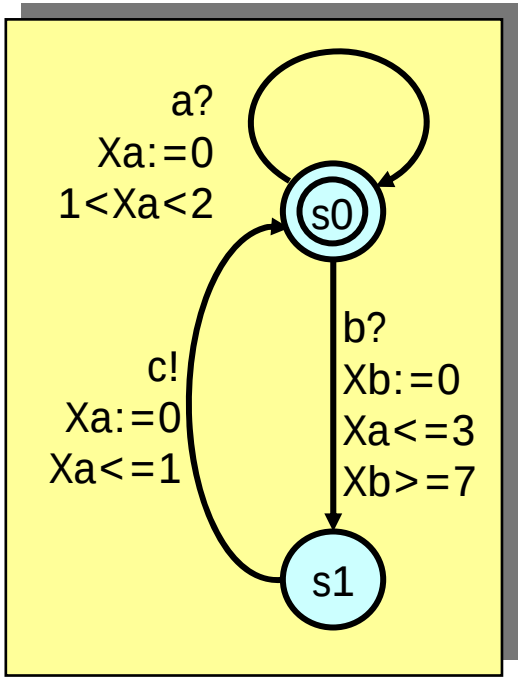
(pass)

Timed Automaton = FSM + Clocks (dense) + Guards + Resets

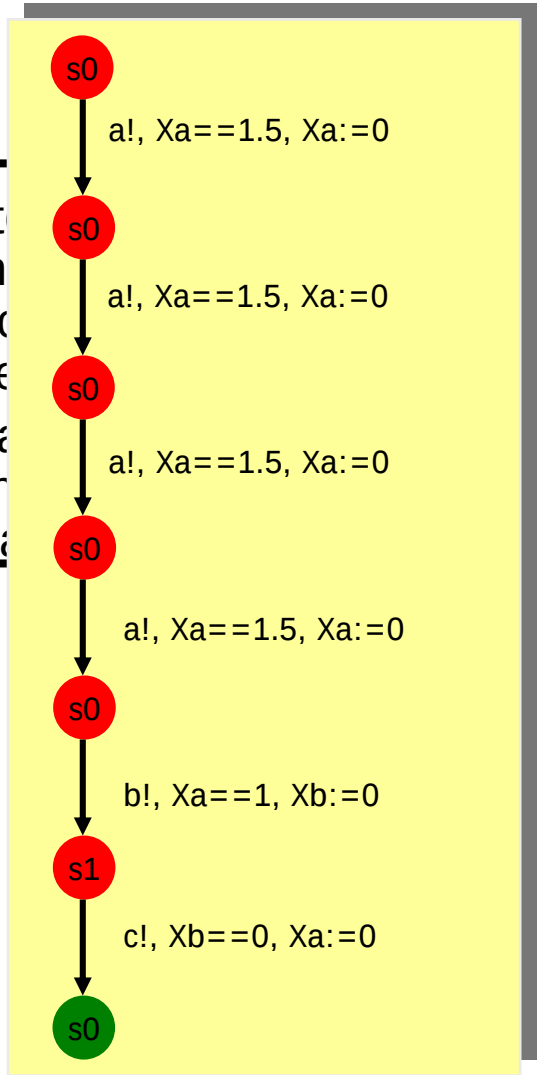
- $x_1 \sim c$, $x_1 - x_2 \sim c$, where $\sim \in \{<,\leq,\geq,>\}$
- $x:=c$
- Semantic state: $(l,\bar{u})$ $\quad (l_1, x = 1.17)$

Exercises

Simple TA-specification



Generated test case



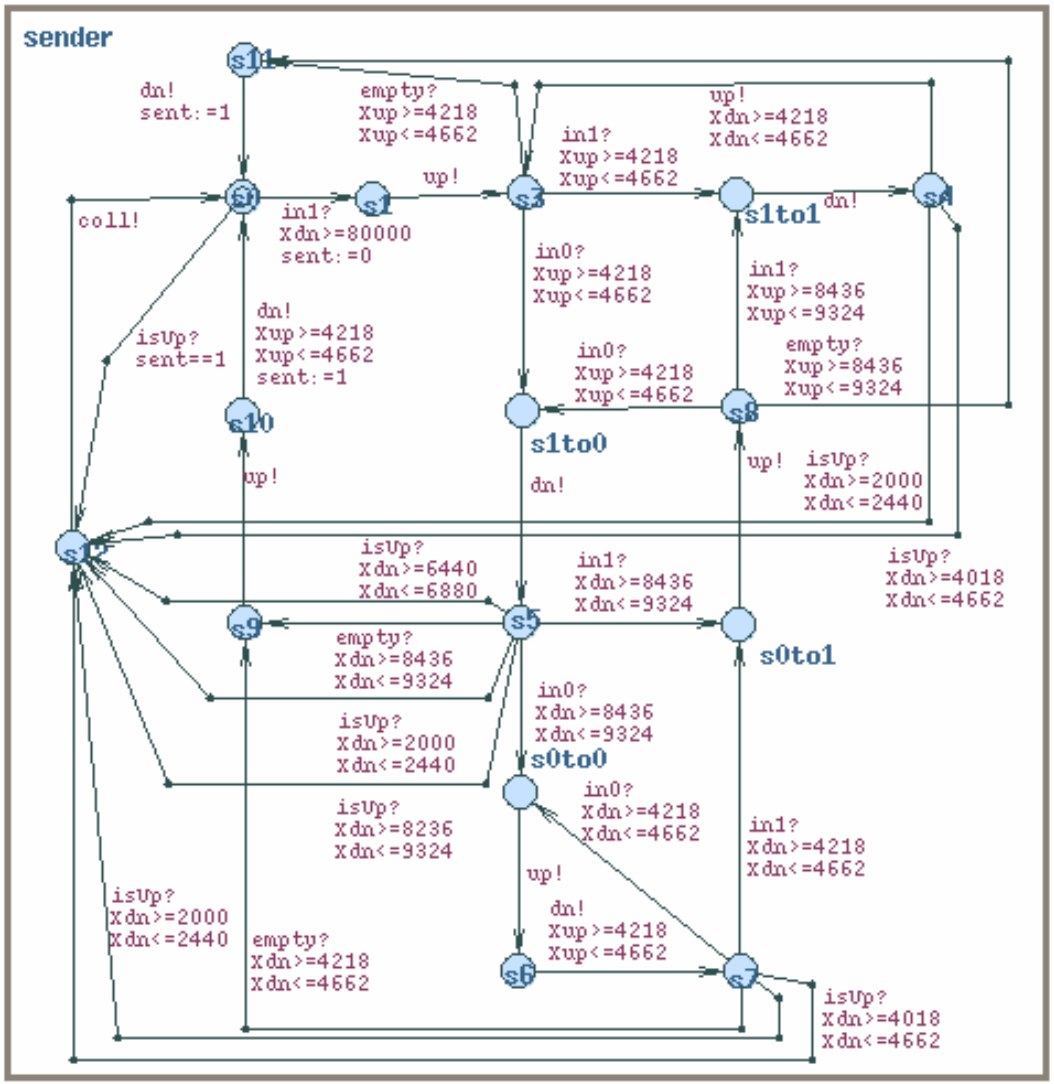
1) comput
trace th
that a "c
produce

2) How ma
you thin
necessa

12 test cases are generated!

How do we cope with real-life specs?

Philips Sender with collision detection




```
config
  system sender;
  int sent;
  observable in1, in0, up, dn, empty, isUp, coll;
```

Correctness Criteria

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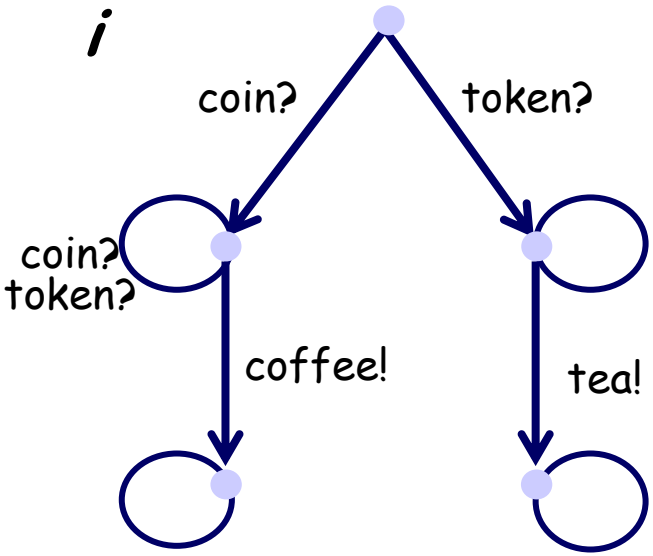
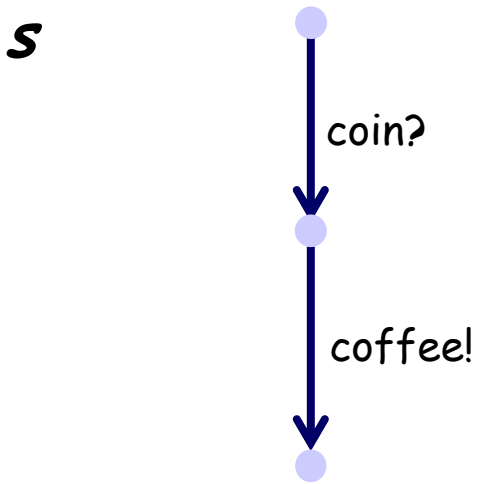
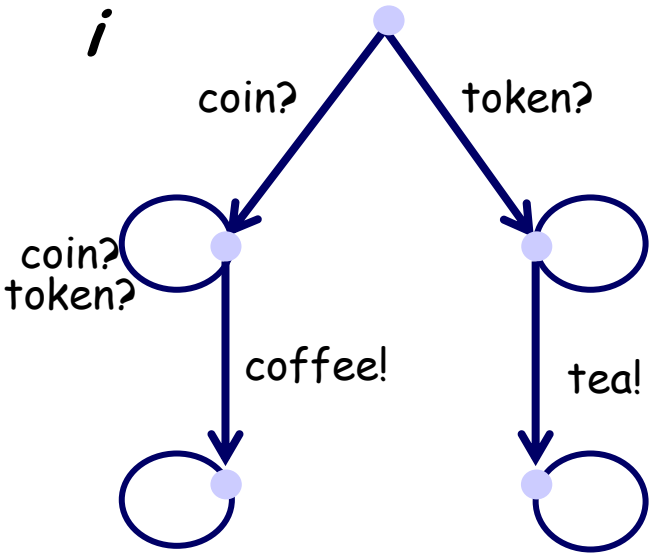
I conforms-to S ??



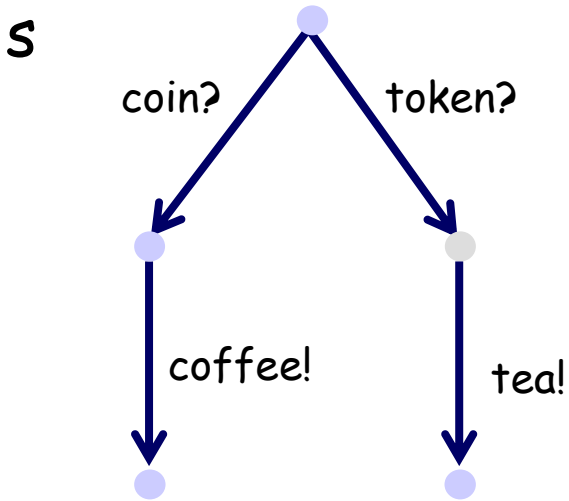
ioco



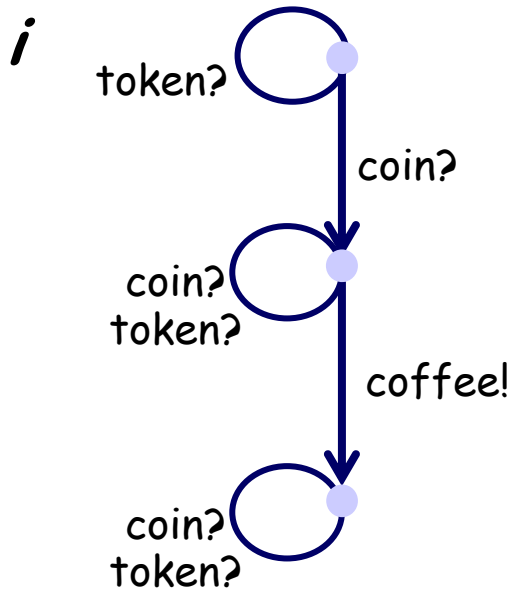
I conforms-to S ??



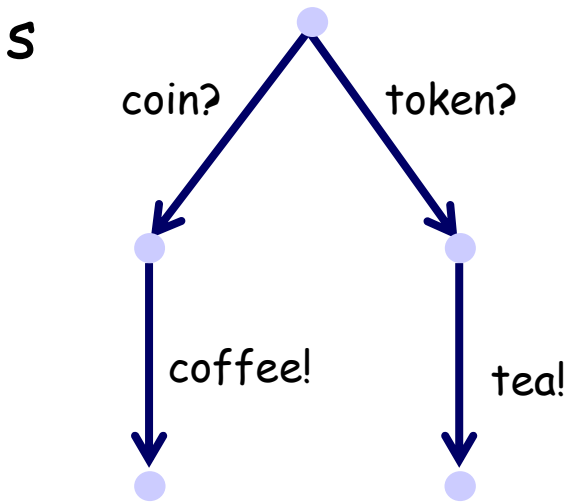
ioco



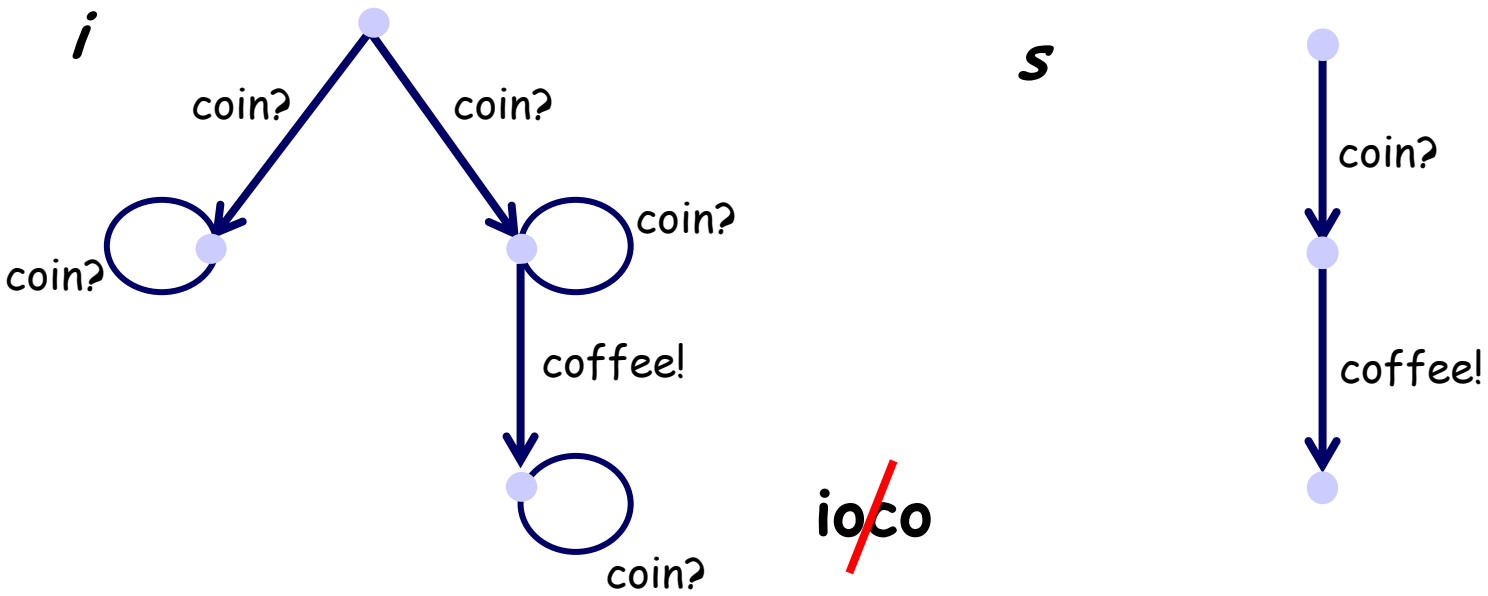
I conforms-to S ??



~~ioco~~



I conforms-to S ??



Implementation Relation ioco

$$\mathbf{i\ ioco\ s} \;=_{def}\; \forall \sigma \in \mathit{Straces}(\mathbf{s}) : \mathit{out}(\mathbf{i\ after}\ \sigma) \subseteq \mathit{out}(\mathbf{s\ after}\ \sigma)$$

$$p\ \mathbf{after}\ \sigma \;=\; \{\, p' \mid p \overset{\sigma}{\Longrightarrow} p' \,\}$$

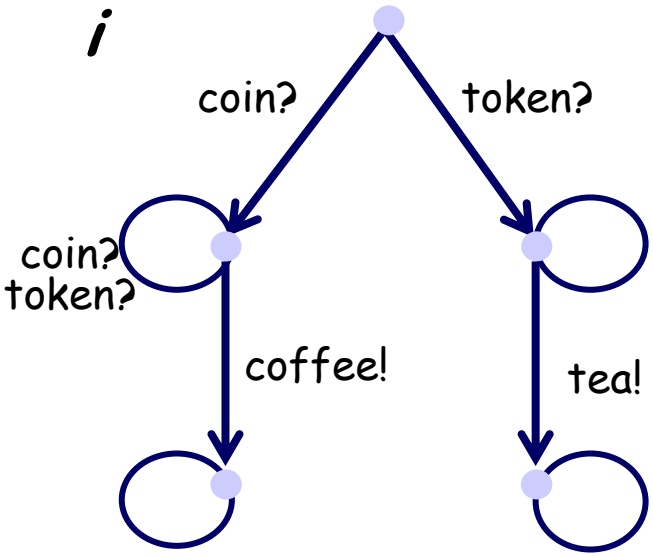
$$p \xrightarrow{\delta} p \;=\; p \xrightarrow{L_U} p \;=\; \forall\ x! \in L_U \cup \{\tau\} : p \not\xrightarrow{x!}$$

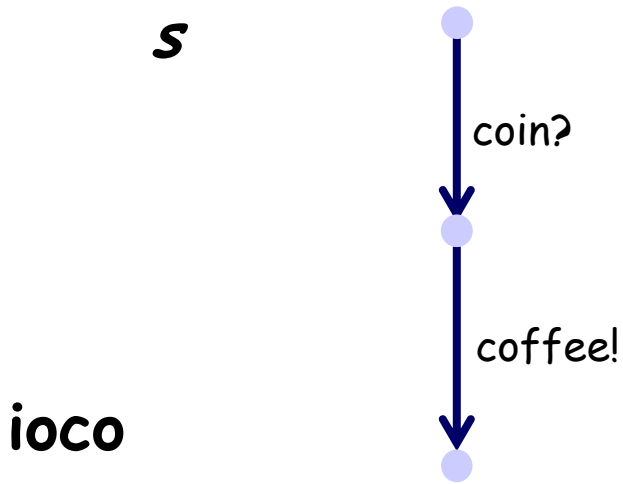
$$\mathit{out}(P) \;=\; \{\, x! \in L_U \mid p \xrightarrow{!x} ,\ p \in P \,\} \cup \{\, \delta \mid p \xrightarrow{\delta} p,\ p \in P \,\}$$

$$\mathit{Straces}(s) \;=\; \{\, \sigma \in (L \cup \{\delta\})^* \mid s \overset{\sigma}{\Longrightarrow} \,\}$$

Implementation Relation ioco

$$i \textbf{ ioco } s \;=_{def}\; \forall \sigma \in \mathit{Straces}(s) : \; \mathit{out}(i \textbf{ after } \sigma) \subseteq \mathit{out}(s \textbf{ after } \sigma)$$





ioco

$\mathit{out}(i \textbf{ after } \text{coin?}) = \{ \text{coffee!} \}$

$\mathit{out}(i \textbf{ after } \text{token?}) = \{ \text{tea!} \}$

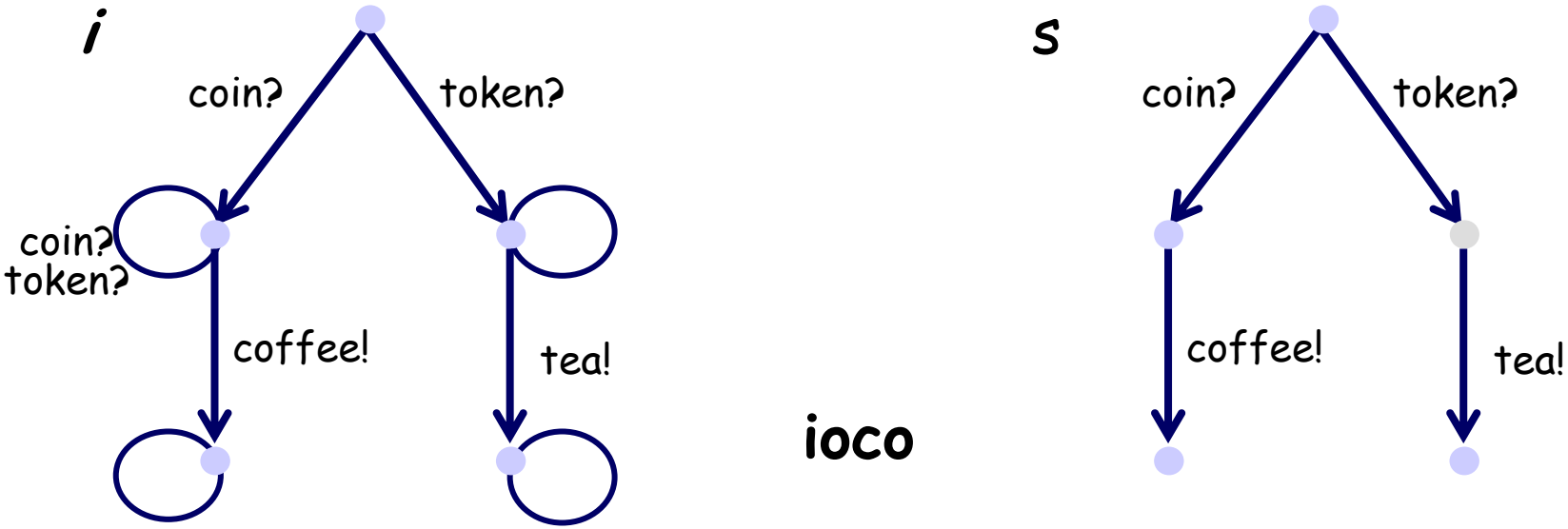
$\mathit{out}(s \textbf{ after } \text{coin?}) = \{ \text{coffee!} \}$

$\mathit{out}(s \textbf{ after } \text{token?}) = \varnothing$

But $\text{token?} \notin \mathit{Straces}(s)$

Implementation Relation ioco

$$i \textbf{ ioco } s \;=_{def}\; \forall \sigma \in \mathit{Straces}(s) : \; \mathit{out}(i \textbf{ after } \sigma) \subseteq \mathit{out}(s \textbf{ after } \sigma)$$



out (*i* **after** coin?) = { coffee! }

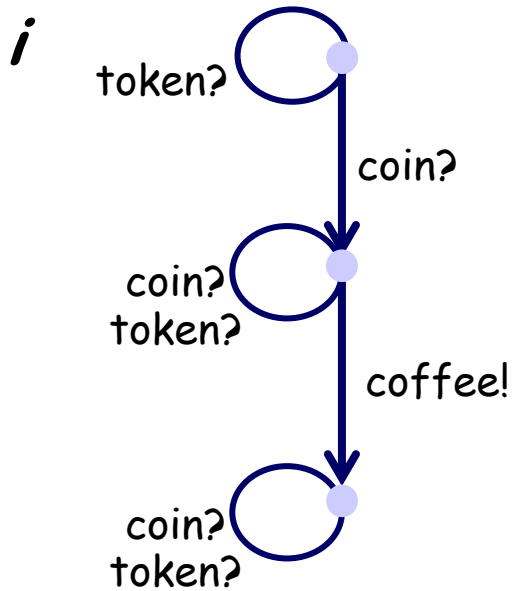
out (*i* **after** token?) = { tea! }

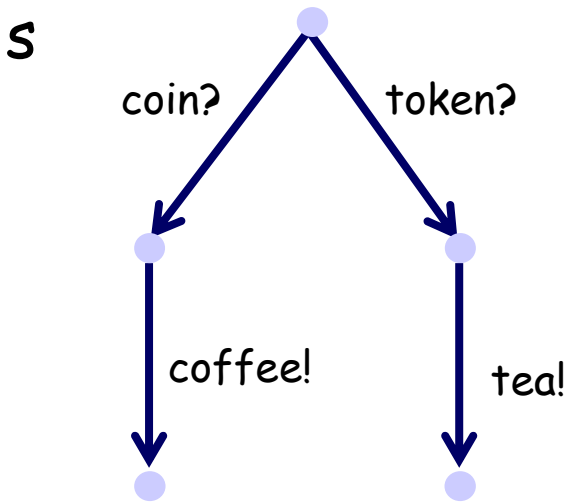
out (*s* **after** coin?) = { coffee! }

out (*s* **after** token?) = { tea! }

Implementation Relation ioco

$$i \textbf{ ioco } s \;=_{def}\; \forall \sigma \in \mathit{Straces}(s) : \; \mathit{out}(i \textbf{ after } \sigma) \subseteq \mathit{out}(s \textbf{ after } \sigma)$$



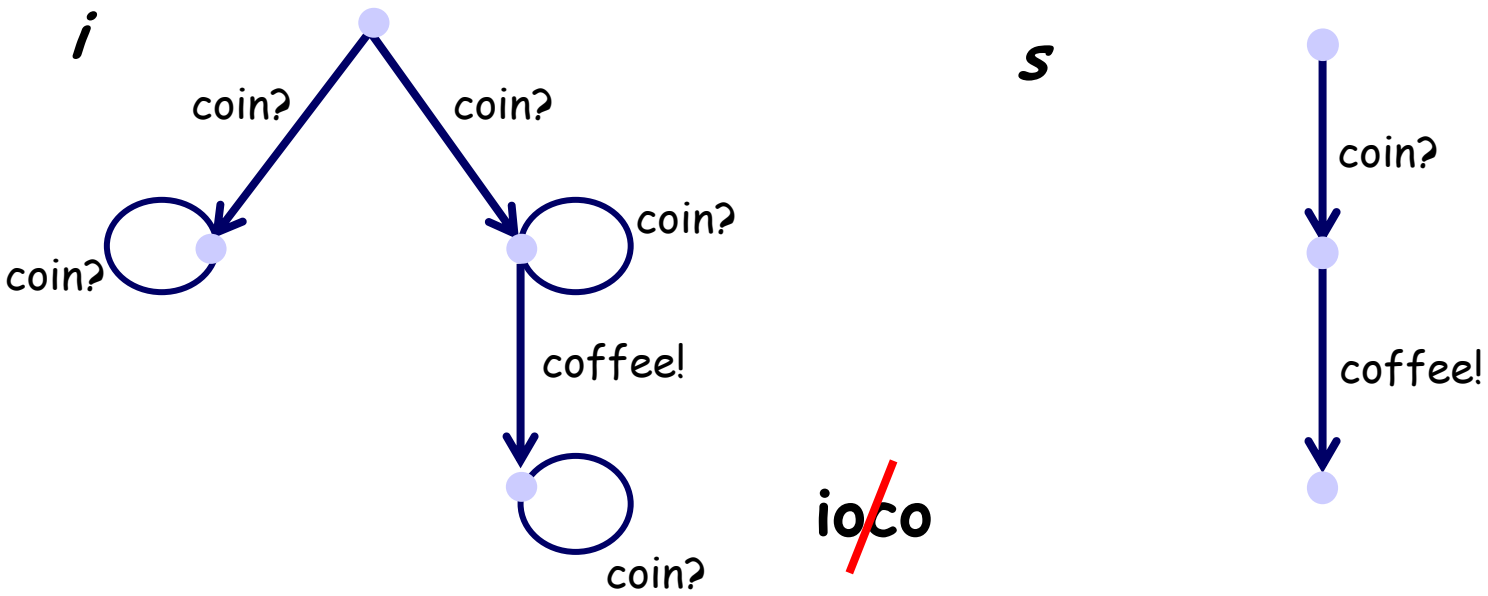


$\mathit{out}(i \textbf{ after } \text{token?}) = \{ \delta \}$

$\mathit{out}(s \textbf{ after } \text{token?}) = \{ \text{tea!} \}$

Implementation Relation ioco

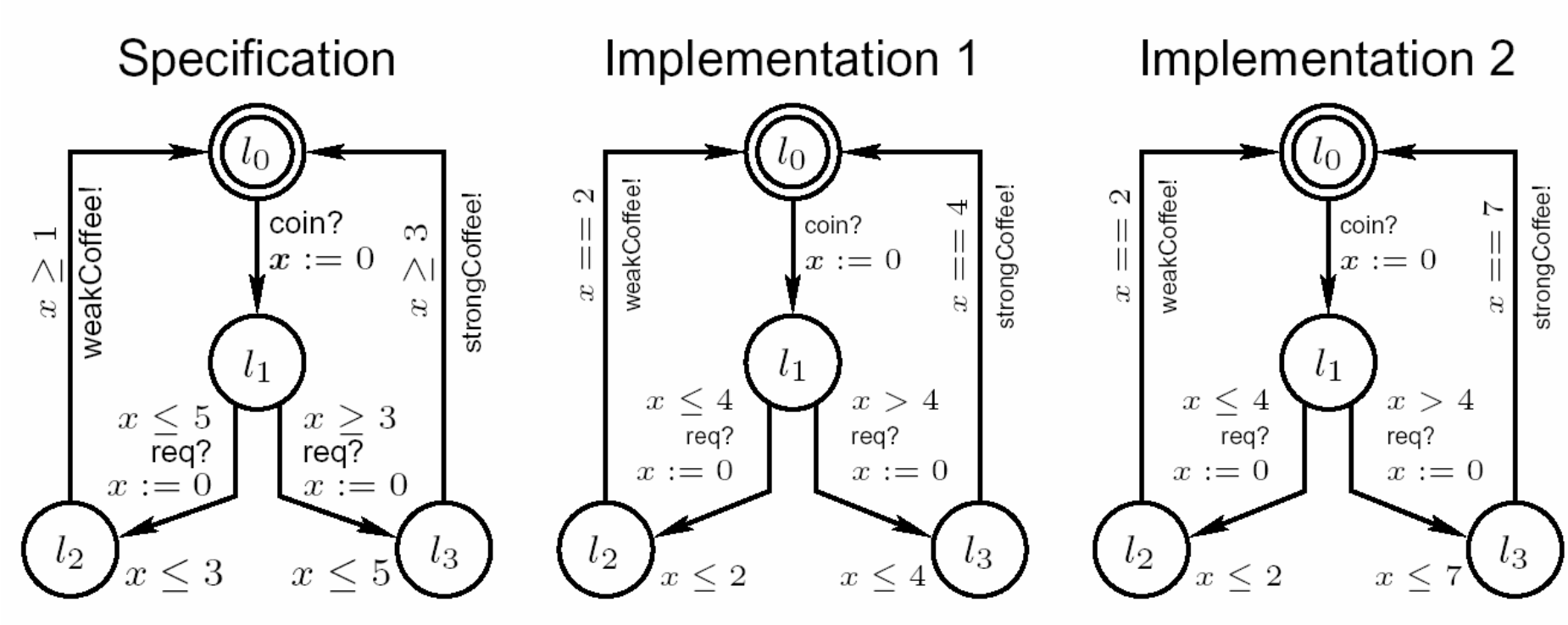
$$i \textbf{ ioco } s \;=_{def}\; \forall \sigma \in \mathit{Straces}(s) : \; \mathit{out}(i \textbf{ after } \sigma) \subseteq \mathit{out}(s \textbf{ after } \sigma)$$



$\mathit{out}(i \textbf{ after } \text{coin?}) \;=\; \{\, \delta, \text{coffee!} \,\}$

$\mathit{out}(s \textbf{ after } \text{coin?}) \;=\; \{\, \text{coffee!} \,\}$

Timed Conformance??



Example Traces

- c?.2.r?.2.weakC
- c?.5.r?.4.strongC

- c?.2.r?.2.weakC
- c?.5.r?.7

I1 **rt-ioco** S

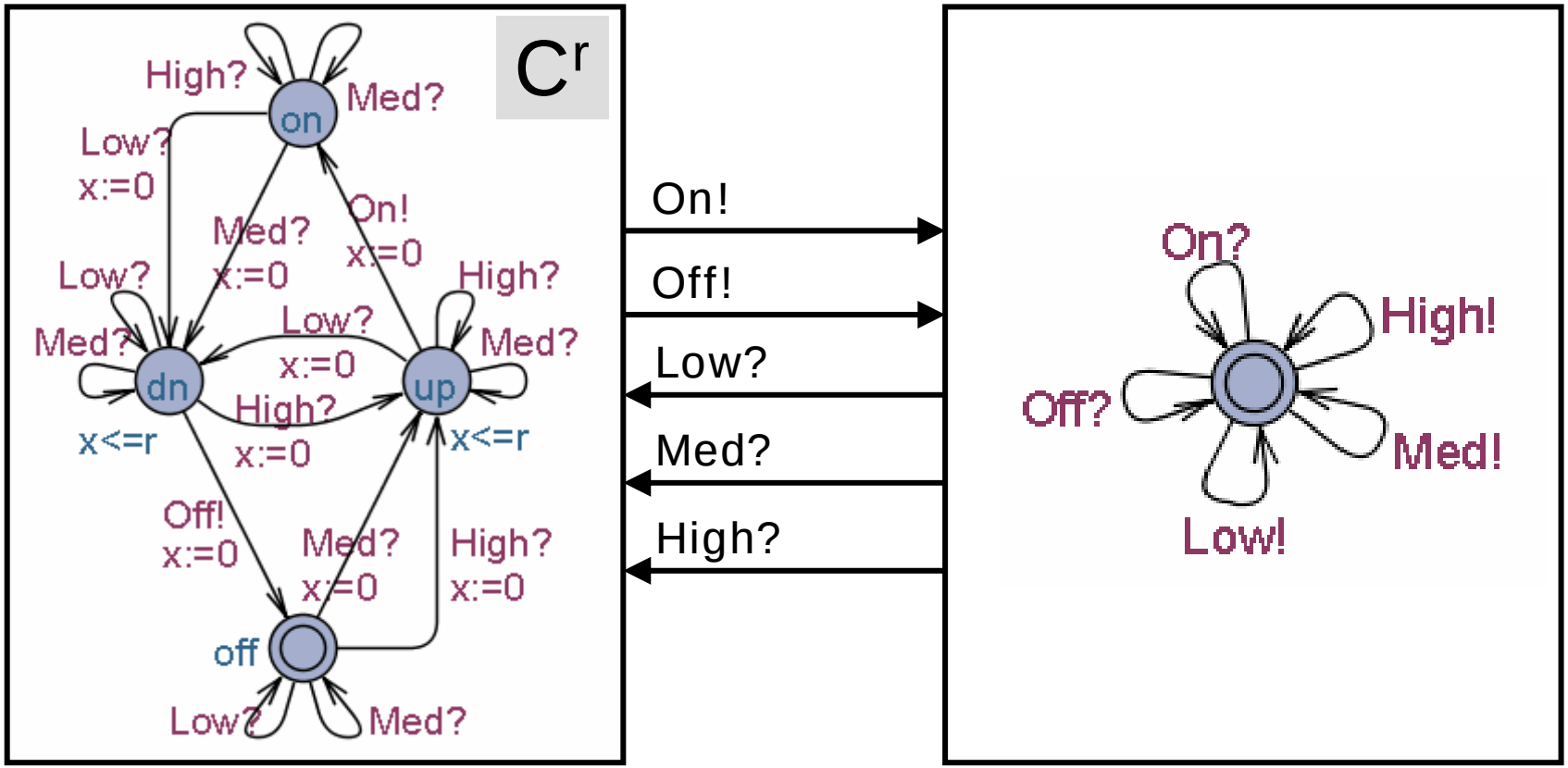
I2 ~~**rt-ioco**~~ S

Real-Time Conformance

- **TTr**(s): the set of *timed traces* from s
  - eg.: σ = `grasp?·50·release?·50`
- **Out**(s after σ) = possible outputs and delays after σ
  - eg. **Out** `(interface after grasp?.220)={touch!,0..270}`
- **i rt-ioco s =def**
  - **$\forall\sigma \in$ TTr(s): Out(i after σ) $\subseteq$ Out(s after σ)**
  - **TTr(i) $\subseteq$ TTr(s)**

- **Intuition**
  - **never produces illegal output, and**
  - **always produces required output in time**

Sample Cooling Controller

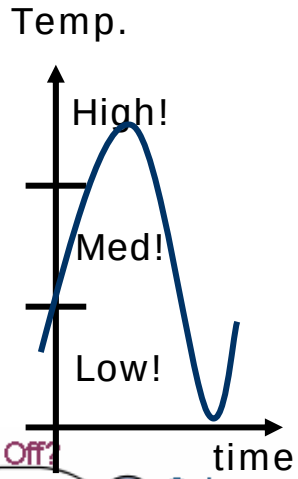


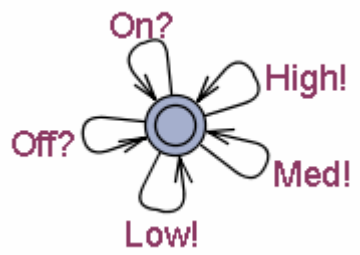
IUT-model

Env-model

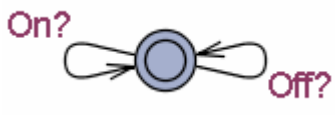
Env. Modeling

- Realism and Guiding
  - 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)

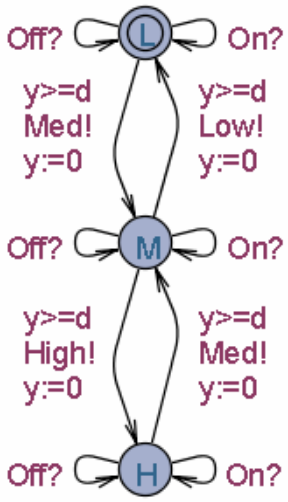




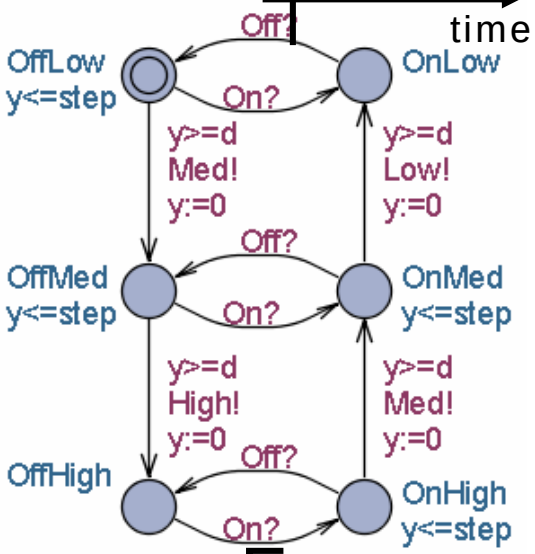
E_M



E_L



E_1

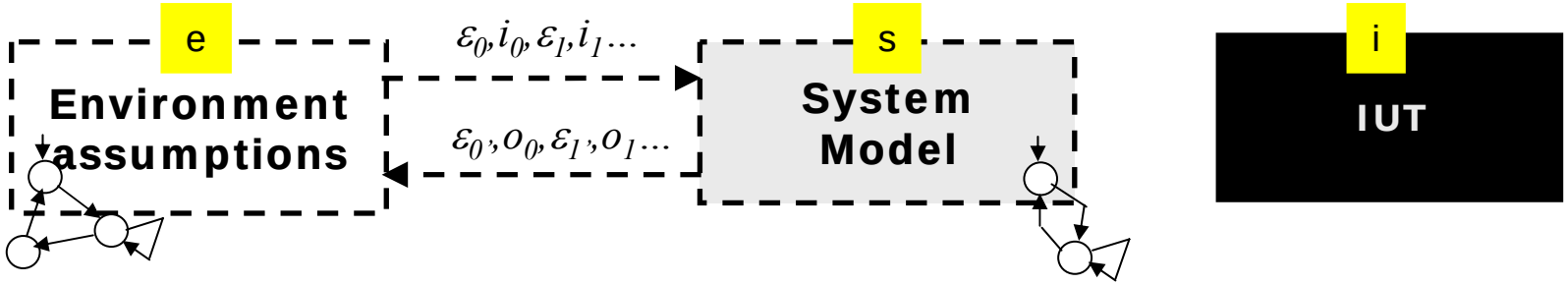


E_2

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

Implementation relation

Relativized real-time io-conformance



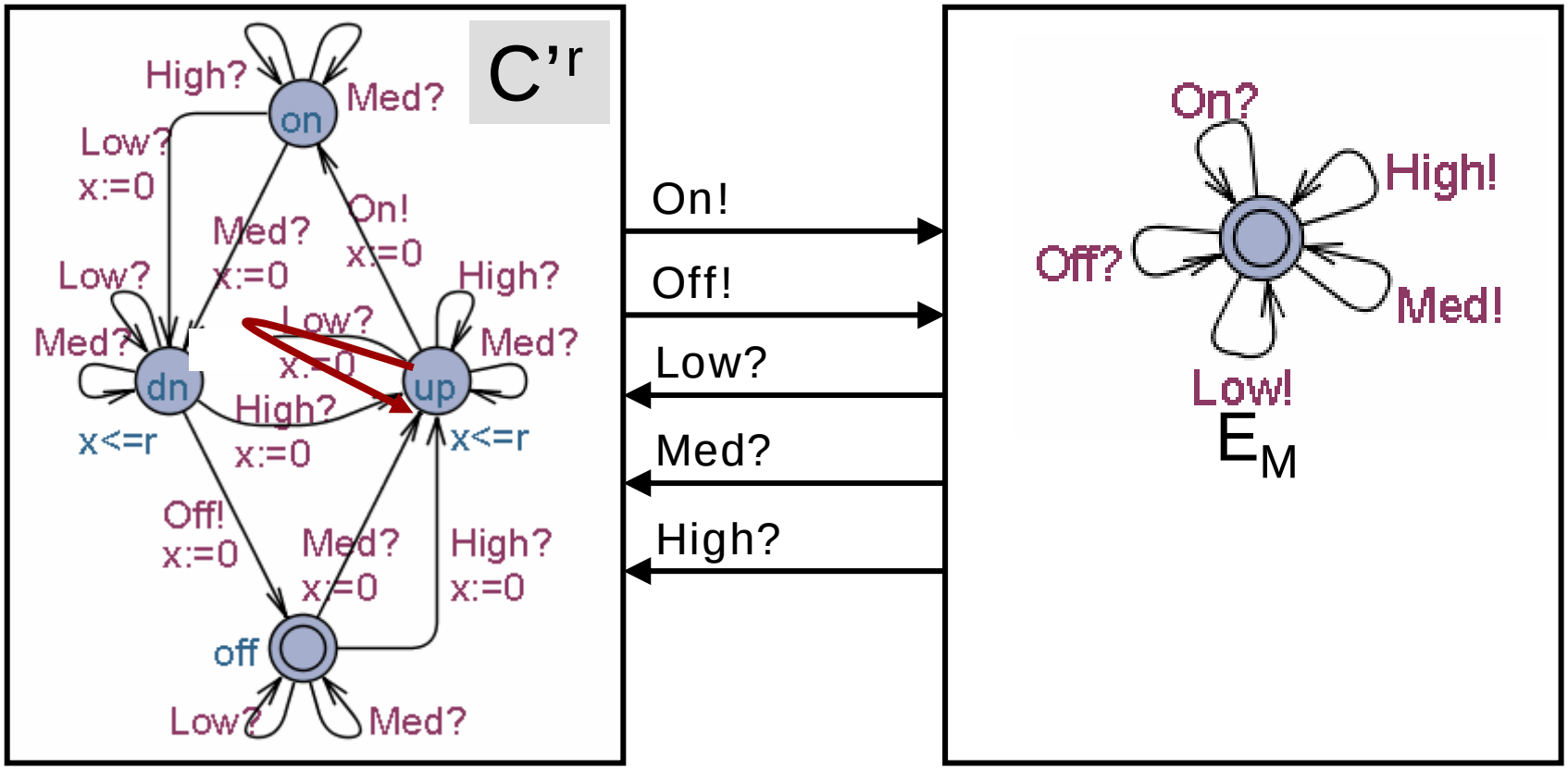
- **Let** *P* **be a set of states**
- **TTr**(*P*): the set of *timed traces* from states in *P*
- *P* **after** σ = the set of states reachable after timed trace σ
- **Out**(*P*) = possible outputs and delays in *P*

- 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)

- **Intuition, for all relevant environment behaviors**
  - **never produces illegal output, and**
  - **always produces required output in time**
- **~timed trace inclusion**

Sample Cooling Controller



IUT

Env-model

C'^r ~~rt-ioco~~ $_{E_M}$ C^r

Test Generation

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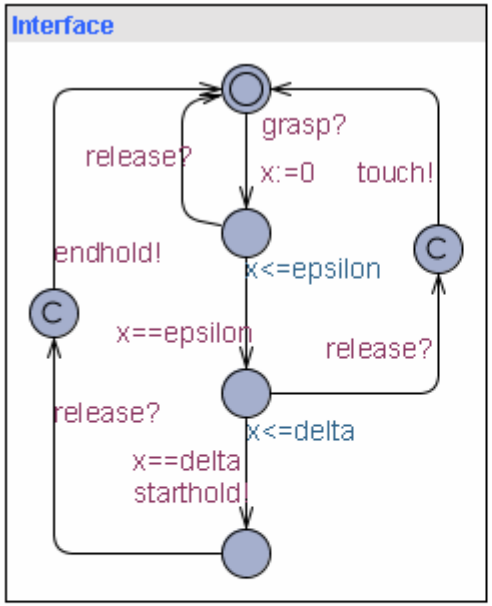
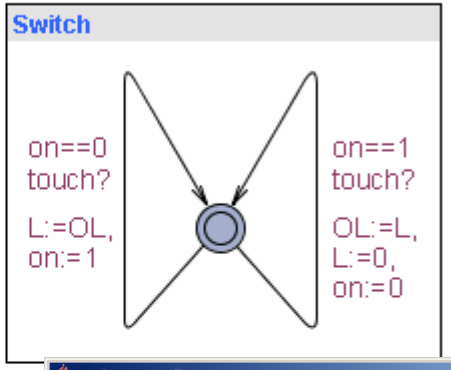
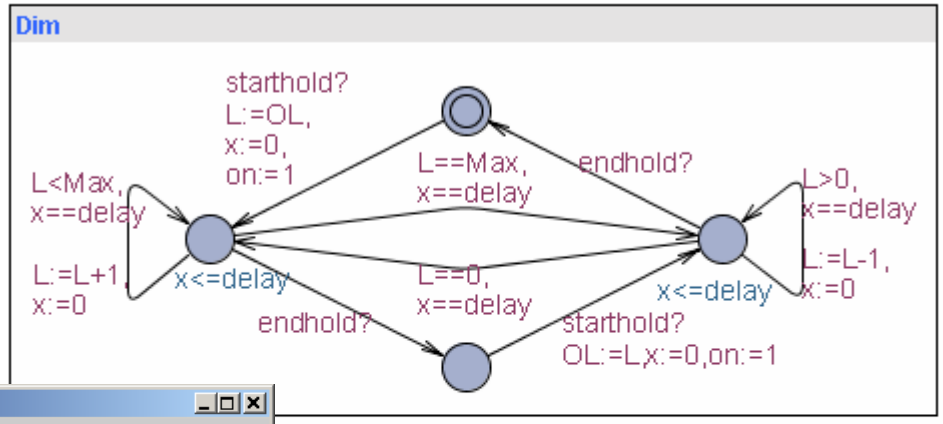
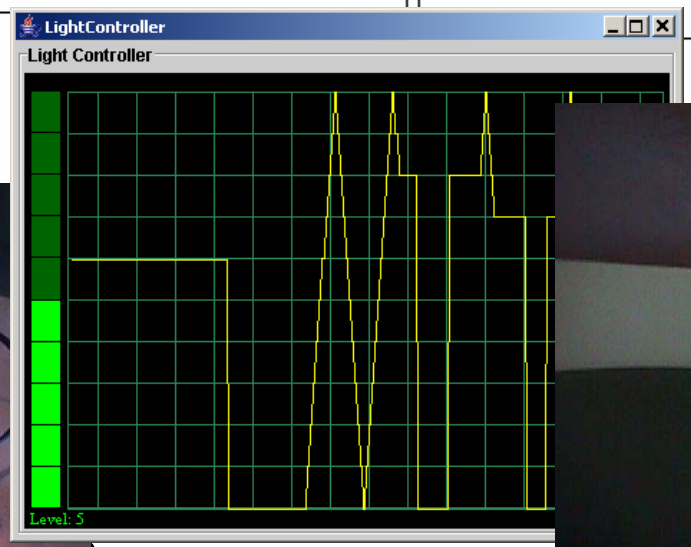
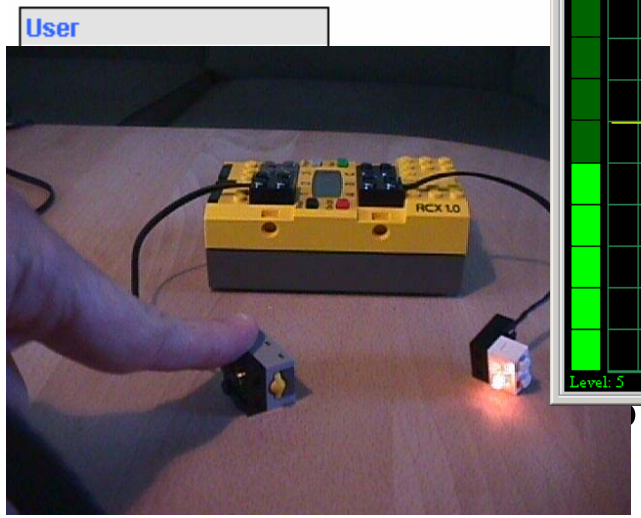
Touch-sensitive Light-Controller











Test Generation Principles

- Test purpose based generation
  - “test that light can become max”
  - Formalize purpose
  - Use model to compute sequence that meets purpose (inputs and expected outputs)
- Model Coverage
  - State-coverage
  - Transition
  - Def-Use pairs
  - ...
- Randomized model interpretation
- Fault-Models
- ONLINE (randomized) testing

Time Optimal Real-Time Test Generation using UPPAAL

Anders Hessel,
Paul Pettersson
Uppsala University
Sweden

Kim Larsen,
Brian Nielsen,
Arne Skou
Aalborg University
Denmark

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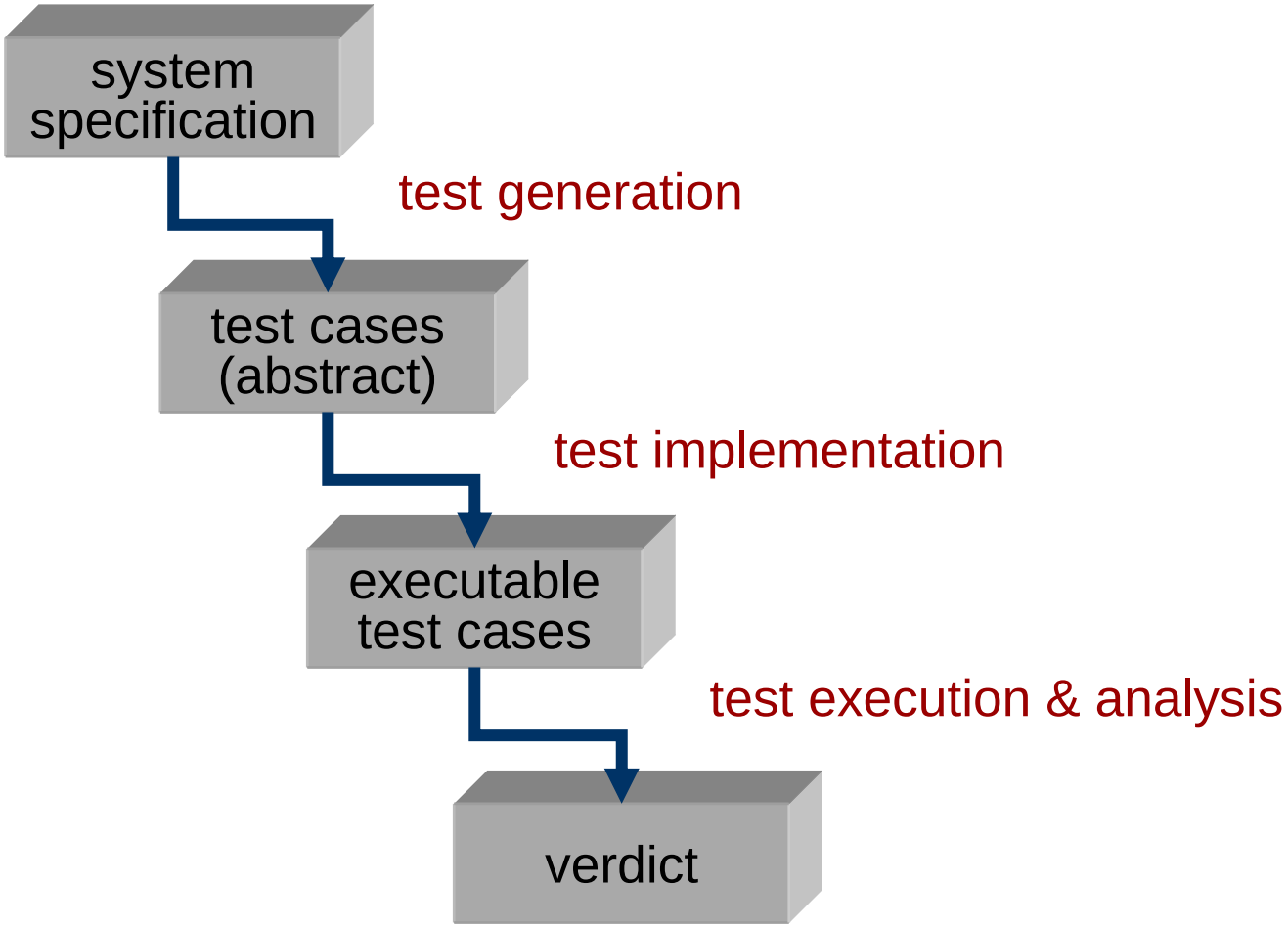
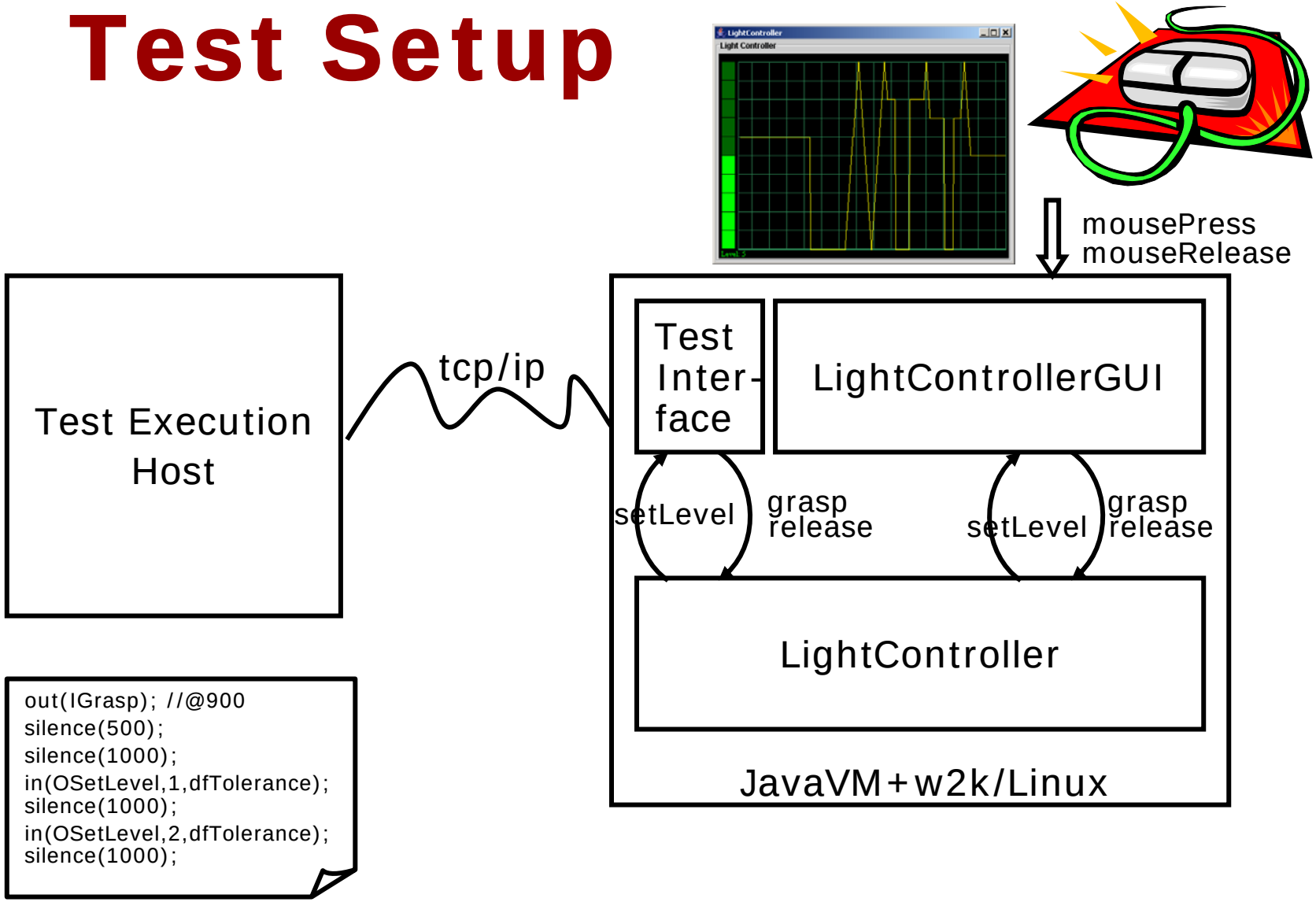
CISS
CENTER FOR INDLEJREDE SOFTWARE SYSTEMER

Testing Process



Test Setup


LightController
Light Controller
mousePress
mouseRelease
Test Execution Host
tcp/ip
Test Inter-face
LightControllerGUI
setLevel
grasp
release
setLevel
grasp
release
LightController
JavaVM+w2k/Linux
out(IGrasp); //@900
silence(500);
silence(1000);
in(OSetLevel,1,dfTolerance);
silence(1000);
in(OSetLevel,2,dfTolerance);
silence(1000);

“Scripts” for LightControl

Events: const IGrasp=0; const int IRelease=1; const int OSetLevel=0;

- void **out**(int eventNo);

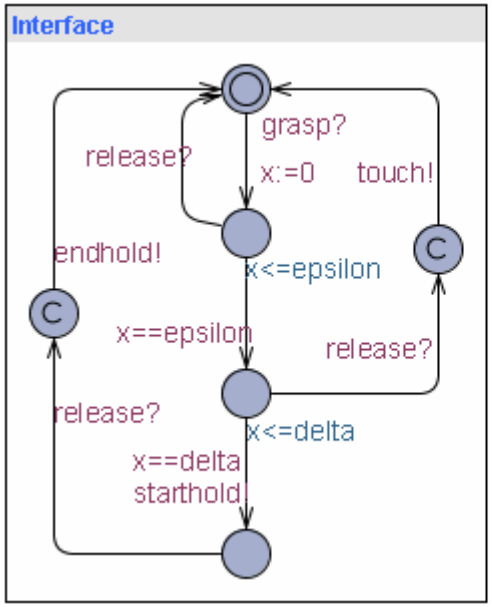
  send eventNo to IUT at now();
- void **silence**(int msDelay);

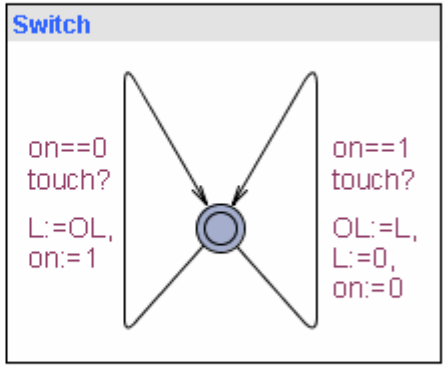
  expect no outputs for msDelay: otherwise fail
- void **in** (int eventNo,int par, int msTolerance);

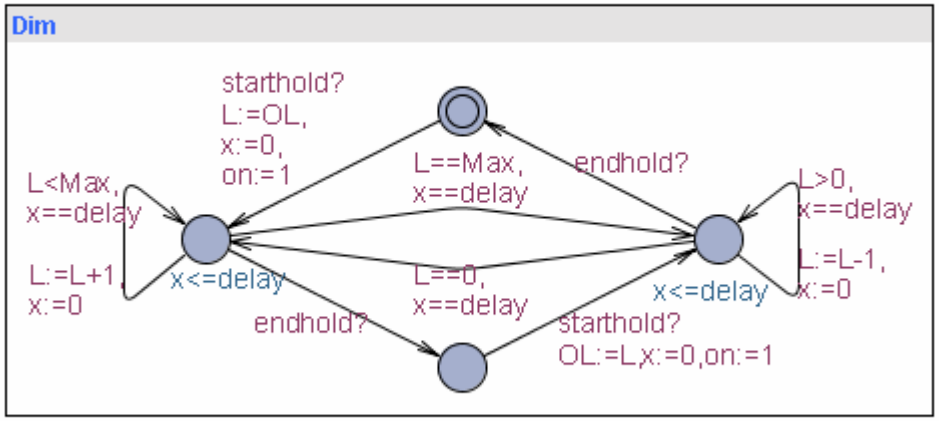
  expect input event(par) before now()+msTolerance otherwise fail
- void **at**(int eventNo, int par, int msTime, int msTolerance);

  expect input eventNo(par) at time msTime from start of test+/- msTolerance

Timed Tests







EXAMPLE test cases for **Interface**

- Epsilon = 200ms
- Delta = 500ms

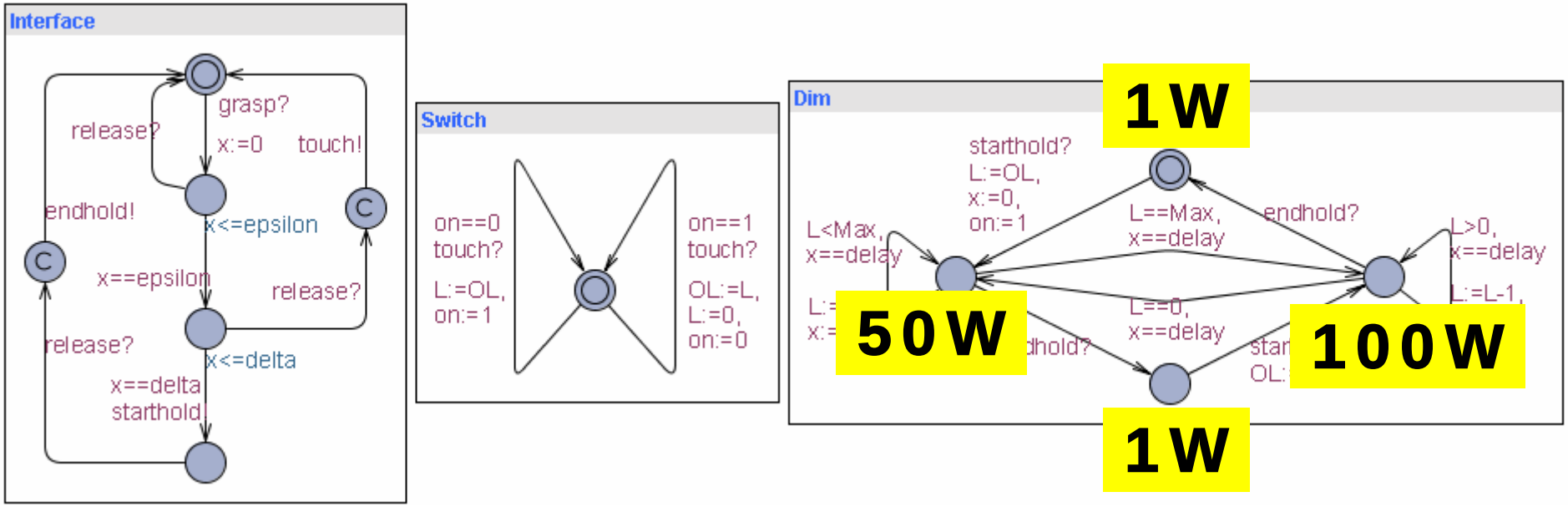
0·grasp!·210·release!·touch?.PASS

0·grasp!·317·release!·touch?·2½·grasp!·220·release!·touch?·PASS

1000·grasp!·517·starthold?·100·release!·endhold?·PASS

INFINITELY MANY SEQUENCES!!!!!!

Optimal Tests

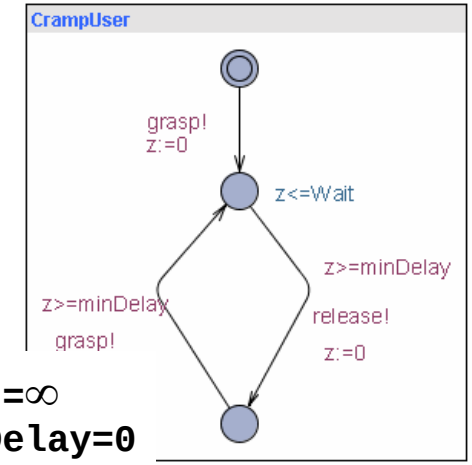


- ***Shortest*** test for max light??
- ***Fastest*** test for max light??
- ***Fastest*** edge-covering test suite??
- Least ***power*** consuming test??

Test Purposes 1

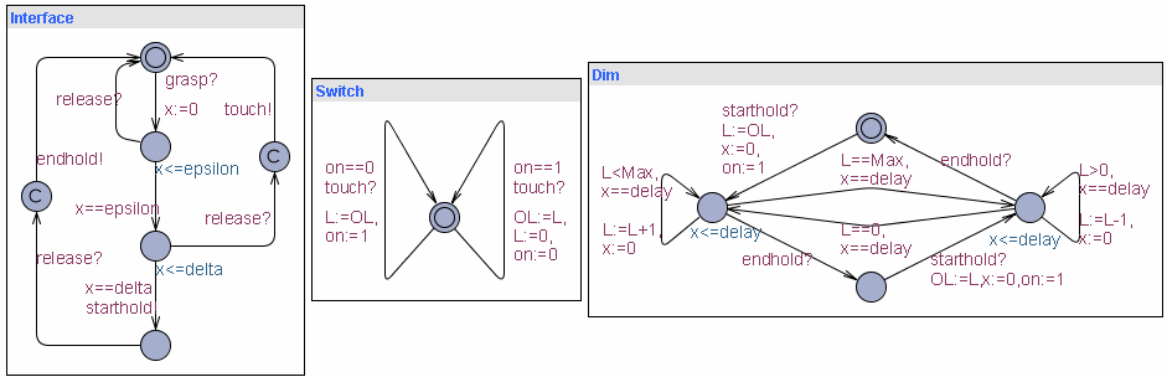
A specific test objective (or observation) the tester wants to make on SUT

Environment model



Wait=∞
minDelay=0

System model



TP1: Check that the light can become bright:

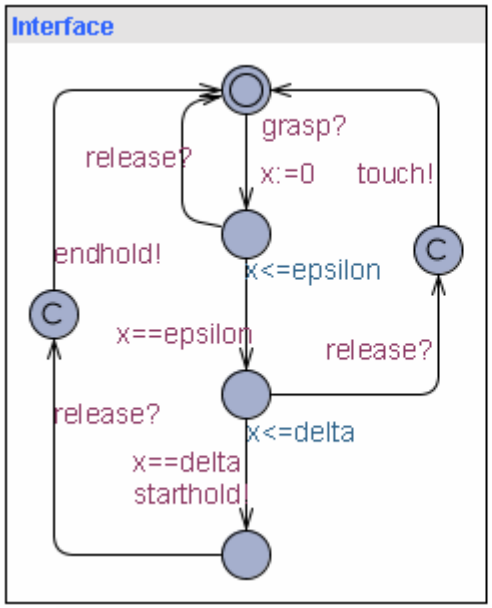
E<> L==10

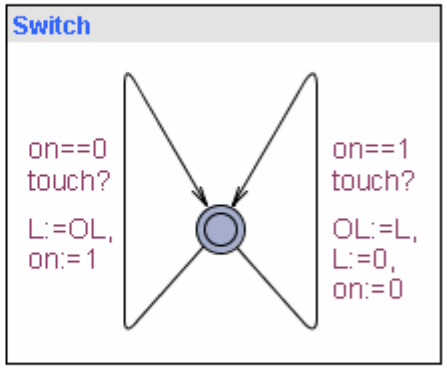
- *Shortest* (and *fastest*) Test:

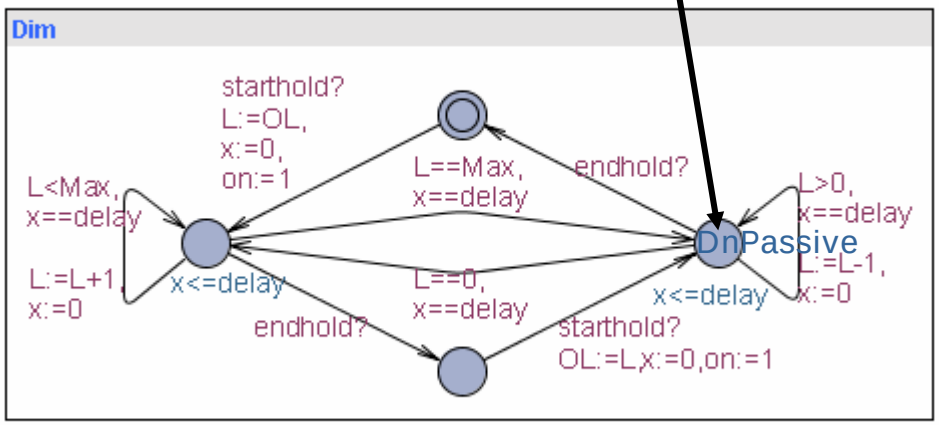
```
out(IGrasp);silence(500);in(OSetLevel,0);silence(1000);
in(OSetLevel,1);silence(1000);in(OSetLevel,2); silence(1000);
in(OSetLevel,3);silence(1000);in(OSetLevel,4);silence(1000);
in(OSetLevel,5);silence(1000);in(OSetLevel,6);silence(1000);
in(OSetLevel,7);silence(1000);in(OSetLevel,8);silence(1000);
in(OSetLevel,9);silence(1000);in(OSetLevel,10);
out(IRelease);
```

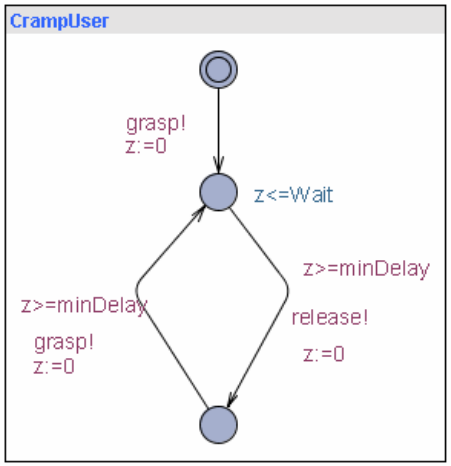
Test Purposes 2

TP2: Check that controller can enter location 'DnPassive':
E<> Dim.DnPassive







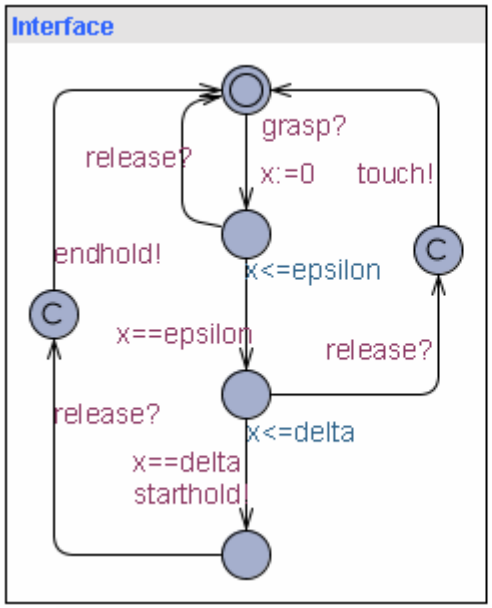


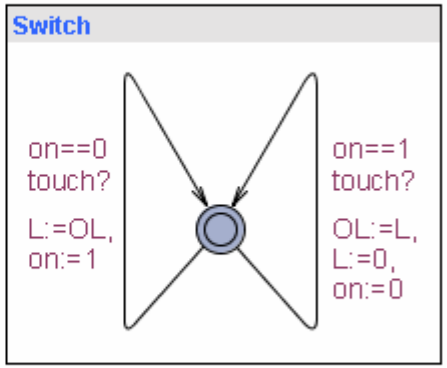
- If delay=1000
- *Shortest* (and *fastest*) Test:

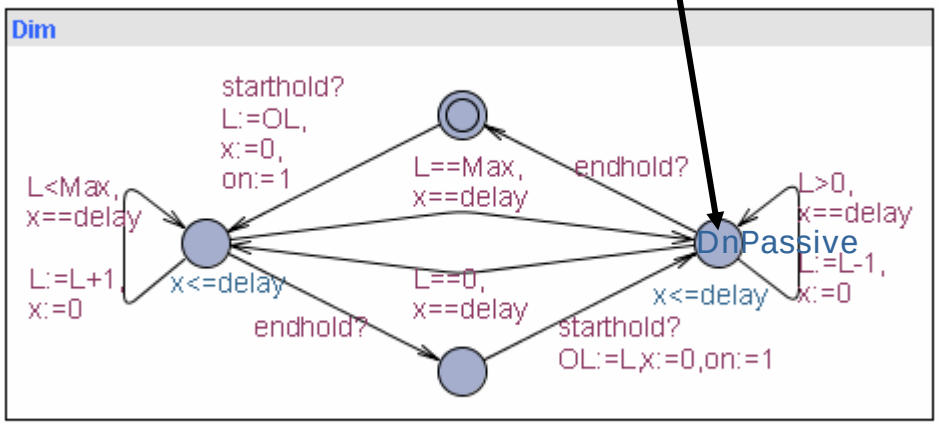
```
out(IGrasp);
silence(500);
in(OSetLevel,0);
out(IRelease);
out(IGrasp);
silence(500);
```

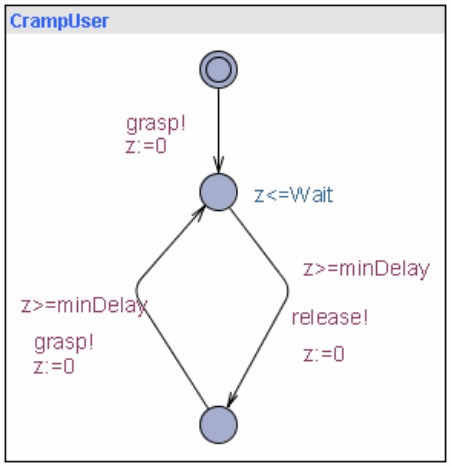
Test Purposes 2

TP2: Check that controller can enter location ‘DnPassive’:
E<> Dim.DnPassive









- If delay=40?
- *Shortest* Test:

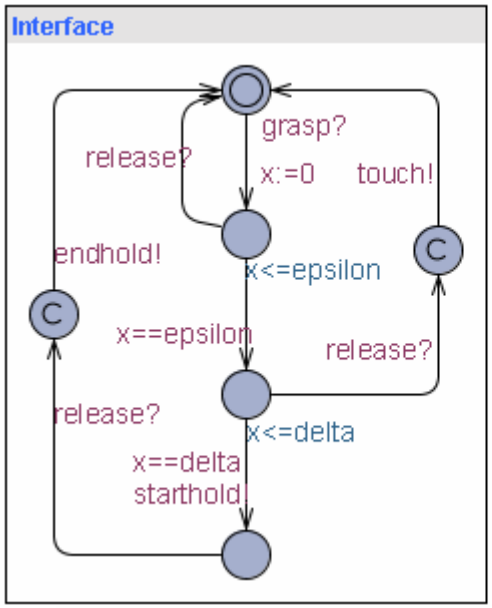
```
out(IGrasp);
silence(500);
in(OSetLevel,0);
out(IRelease);
out(IGrasp);
silence(500);
```

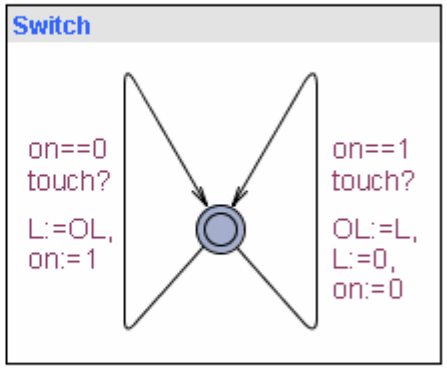
- *Fastest* Test:

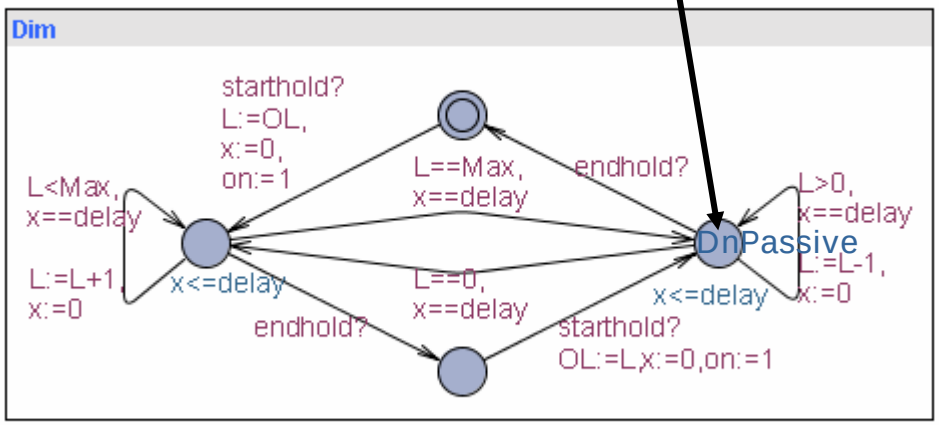
```
out(IGrasp);silence(500);in(OSetLevel,0);silence(40);
in(OSetLevel,1);silence(40);in(OSetLevel,2); silence(40);
in(OSetLevel,3);silence(40);in(OSetLevel,4); silence(40);
in(OSetLevel,5);silence(40);in(OSetLevel,6); silence(40);
in(OSetLevel,7);silence(40);in(OSetLevel,8); silence(40);
in(OSetLevel,9);silence(40);in(OSetLevel,10);silence(40);
```

Test Purposes 2

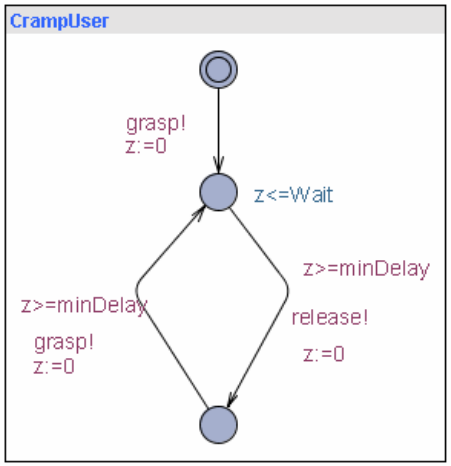
TP2: Check that controller can enter location ‘DnPassive’:
E<> Dim.DnPassive







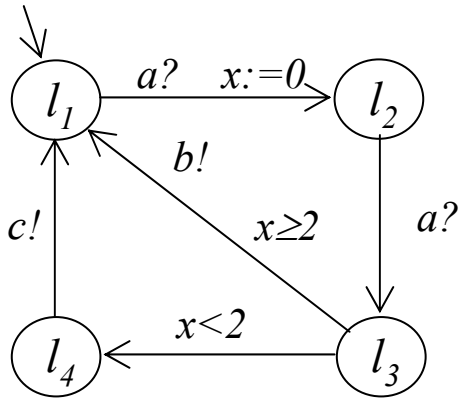
- If Wait=1500 and minDelay=400?



Ask a tool

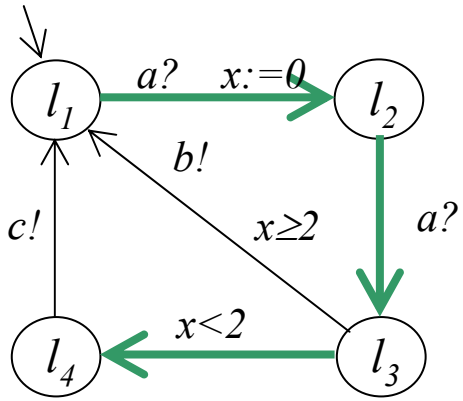
Coverage Based Test Generation

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



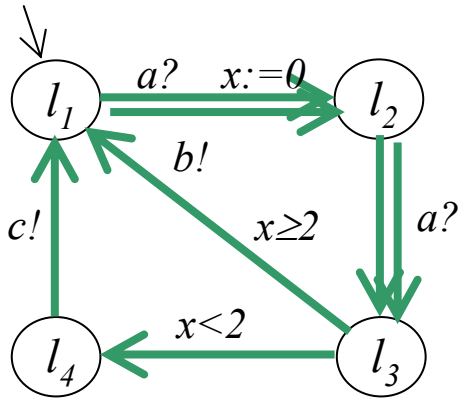
Coverage Based Test Generation

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



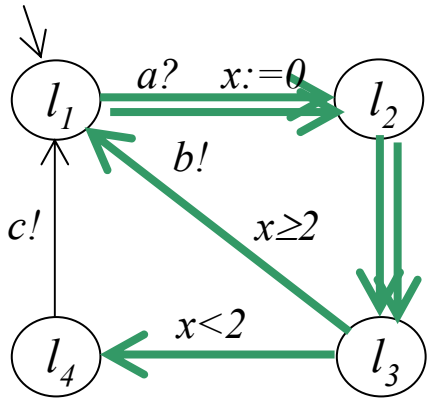
Coverage Based Test Generation

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



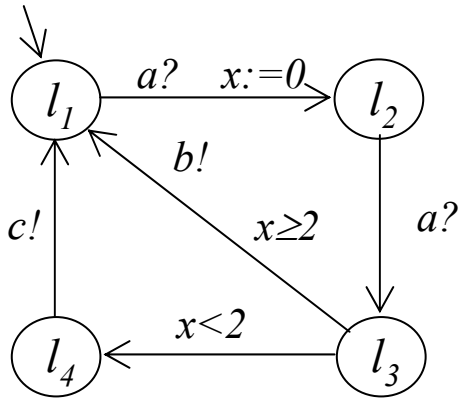
Coverage Based Test Generation

- Multi purpose testing
- Cover measurement
- Examples:
  - Location Coverage,
  - Edge Coverage,
  - **Definition / Use Pair Coverage**



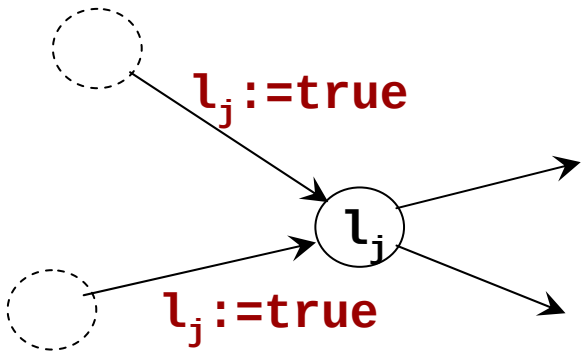
Coverage Based Test Generation

- 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



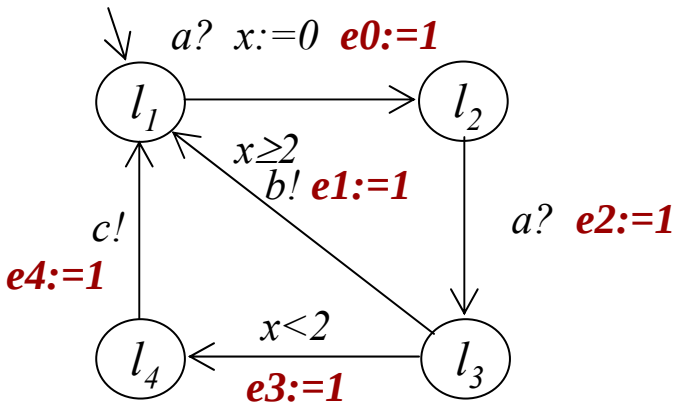
Location Coverage

- 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)



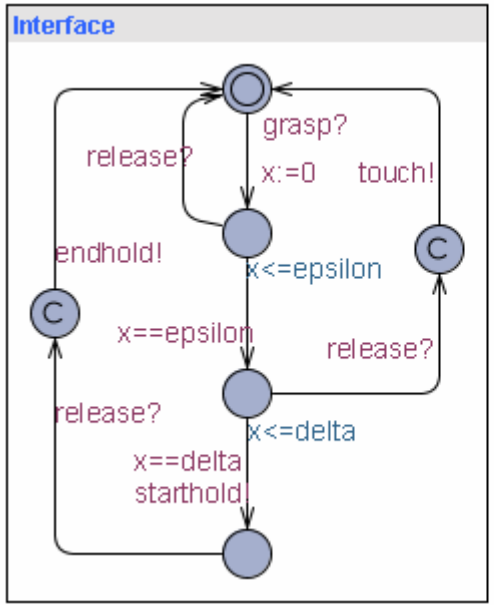
Edge Coverage

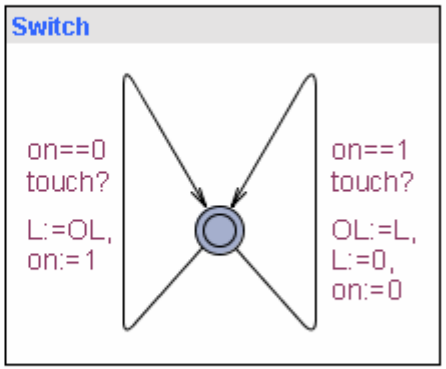
- Test sequence traversing all edges
- Encoding:
  - Enumerate edges $e_0, \ldots, e_n$
  - Add auxiliary variable e_i for each edge
  - Label each edge $e_i := true$
- Check: $EF(\ e_0 = true \wedge \ldots \wedge e_n = true\ )$

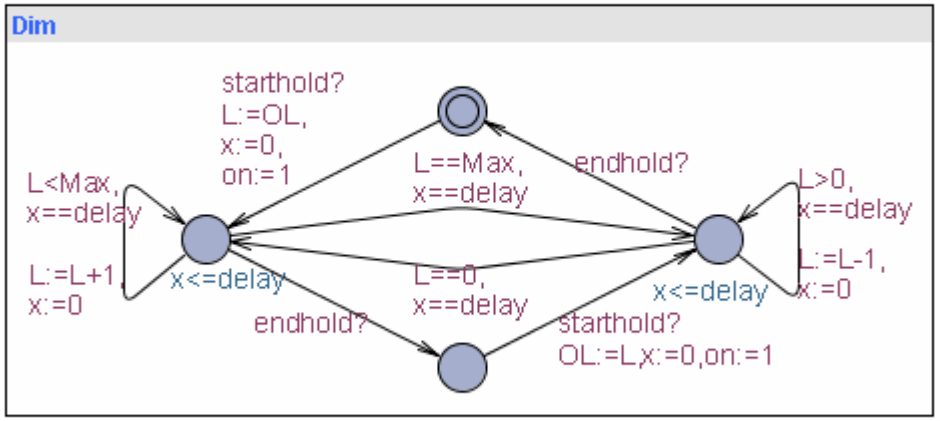


Fastest Edge Coverage

Cost = 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

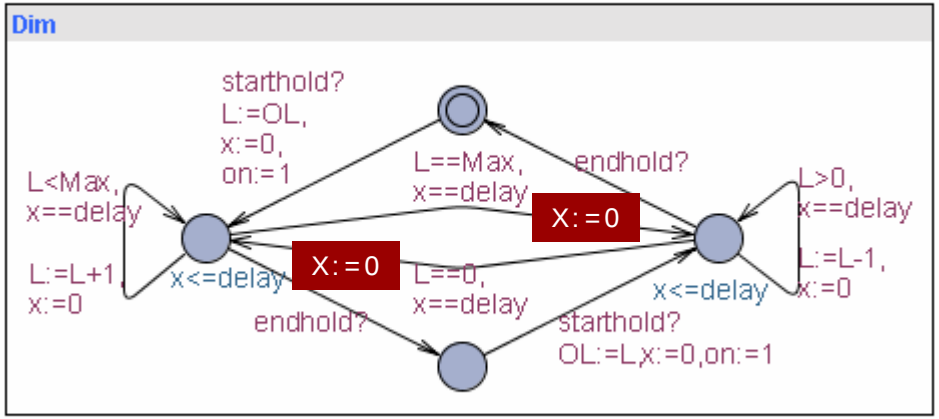
```
//13
out(IGrasp); //@900          // Bring dimmer  PassiveDn->ActiveDN->
silence(500);//hold          // ActiveUP+increase to level 10
silence(1000); in(OSetLevel,1);
silence(1000); in(OSetLevel,2);
silence(1000); in(OSetLevel,3);
silence(1000); in(OSetLevel,4);
silence(1000); in(OSetLevel,5);
silence(1000);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

Mutants

- M1 incorrectly implements switch

```
synchronized public void handleTouch()
  if(lightState==lightOff) {
    setLevel(oldLevel);
    lightState=lightOn;
  }
   else { //was missing
 if(lightState==lightOn){
   oldLevel=level;
   setLevel(0);
   lightState=lightOff;
}
```



- M2 incorrect additional delay in dimmer as if x:=0 was on ActiveUP ↔ActiveDN transitions

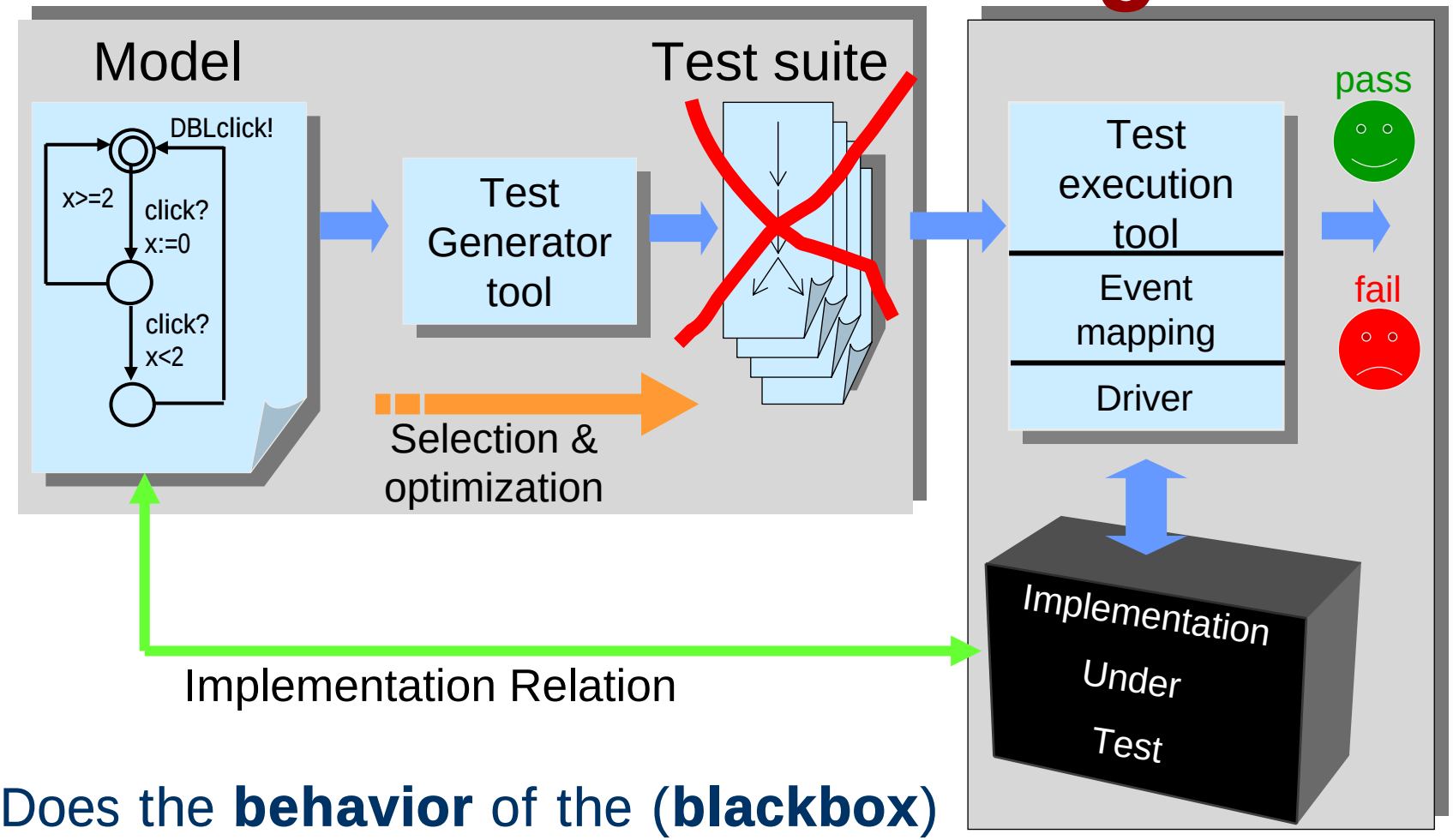
Outcome

Description	Test#	M0	M1	M2
MaxLevel	1	pass	pass	pass
Short ActiveDn	4	pass	pass	pass
Resume	5	Pass	Fail	pass
Edge Cov.	3	Pass	Fail	Fail

Online Testing Of Real-Time Systems

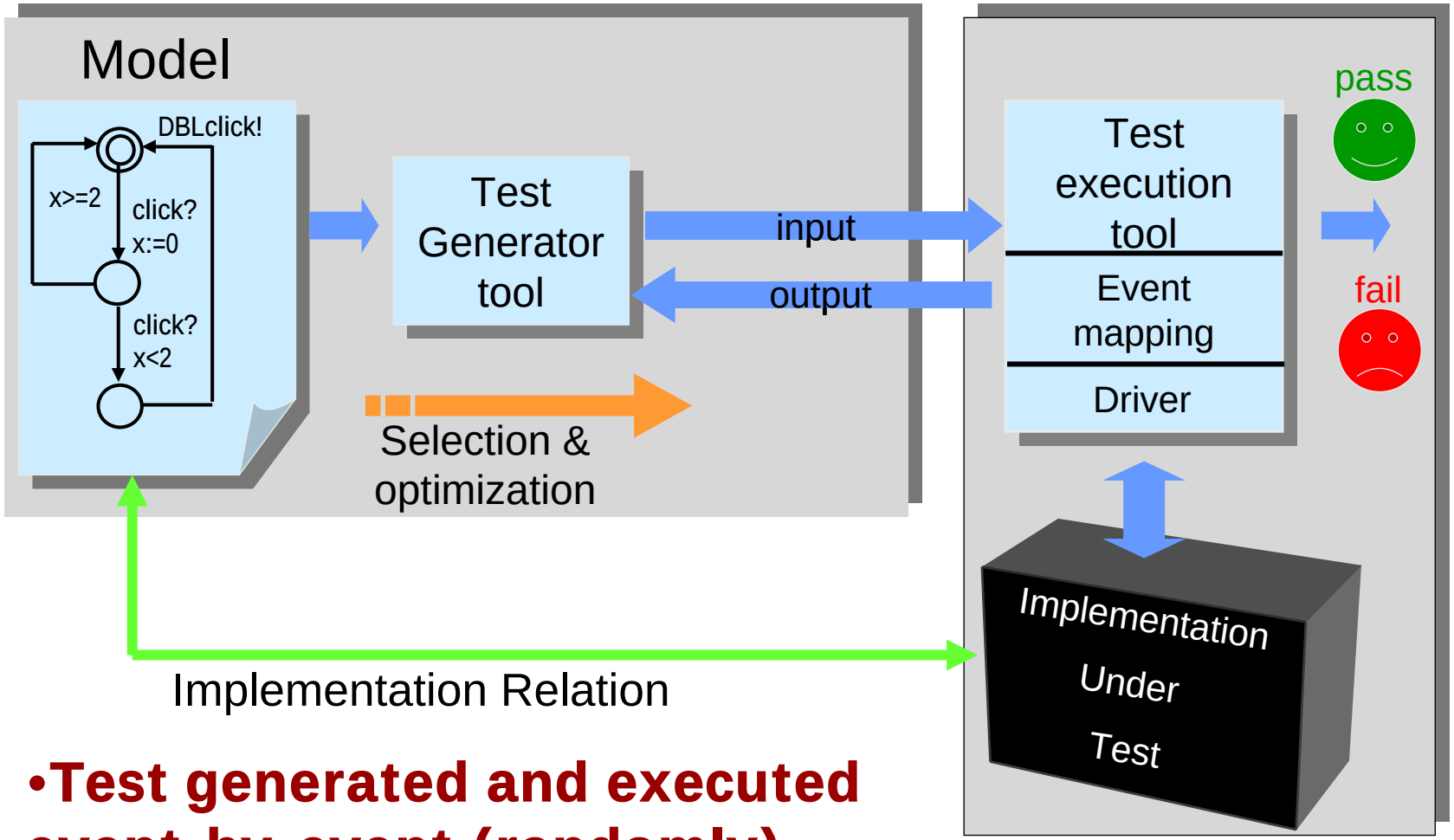
BRICS
Basic Research
in Computer Science

Automated Model Based Conformance Testing



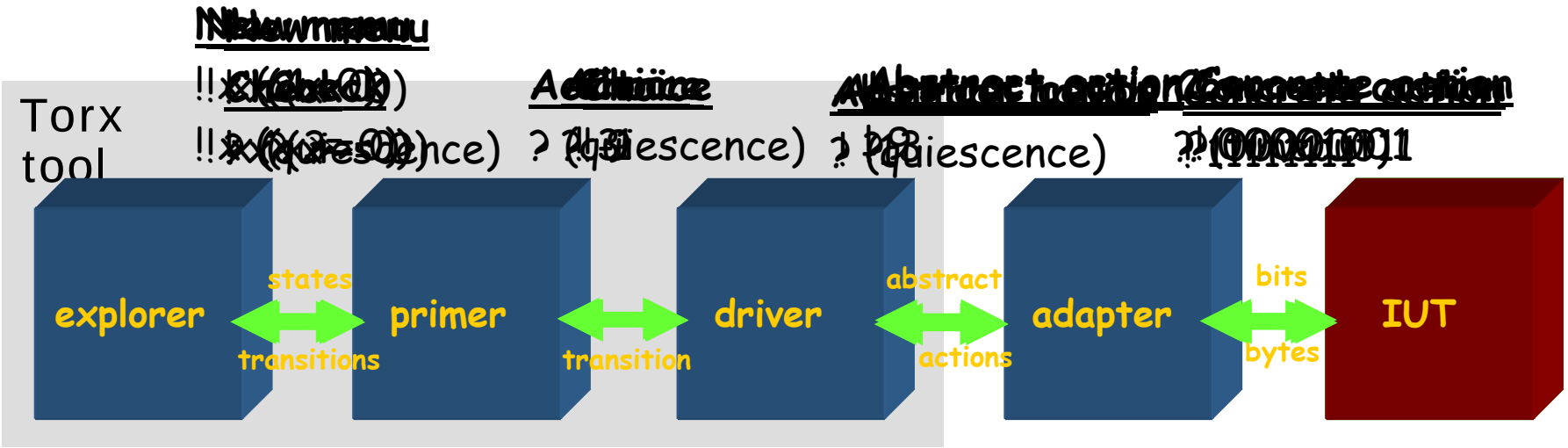
Does the **behavior** of the (**blackbox**) implementation ***comply*** to that of the specification?

Online Testing

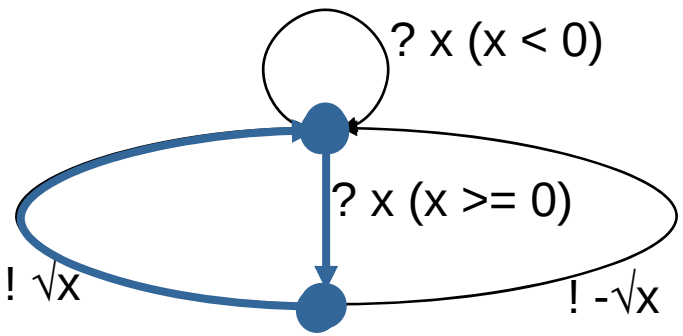


- **Test generated and executed event-by-event (randomly)**
- **A.K.A on-the-fly testing**

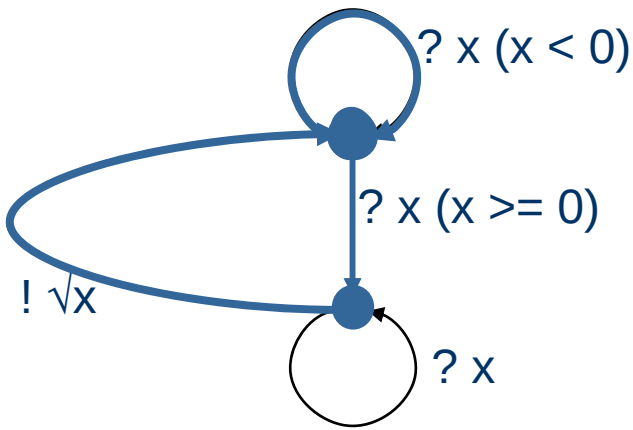
On-The-Fly Testing



specification



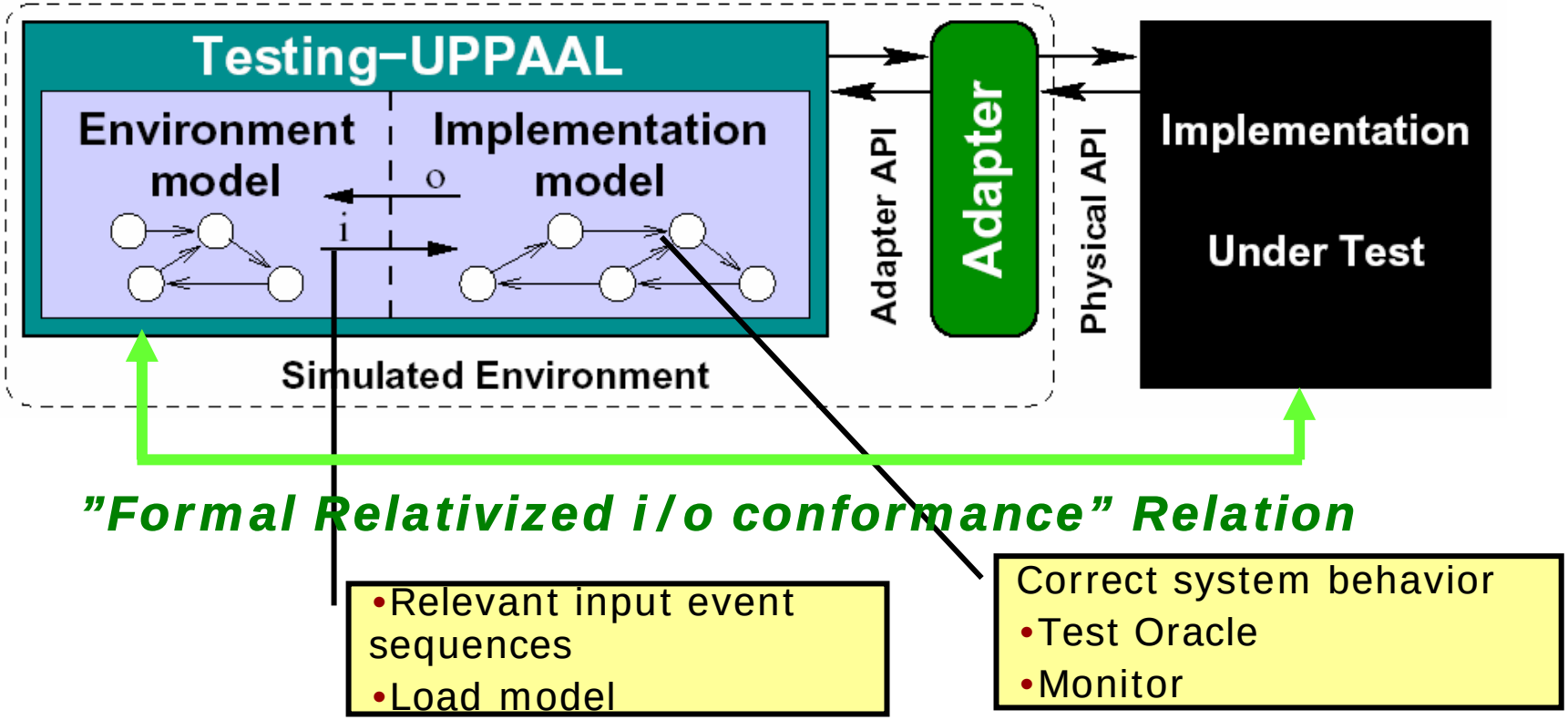
implementation



[Jan Tretmans].

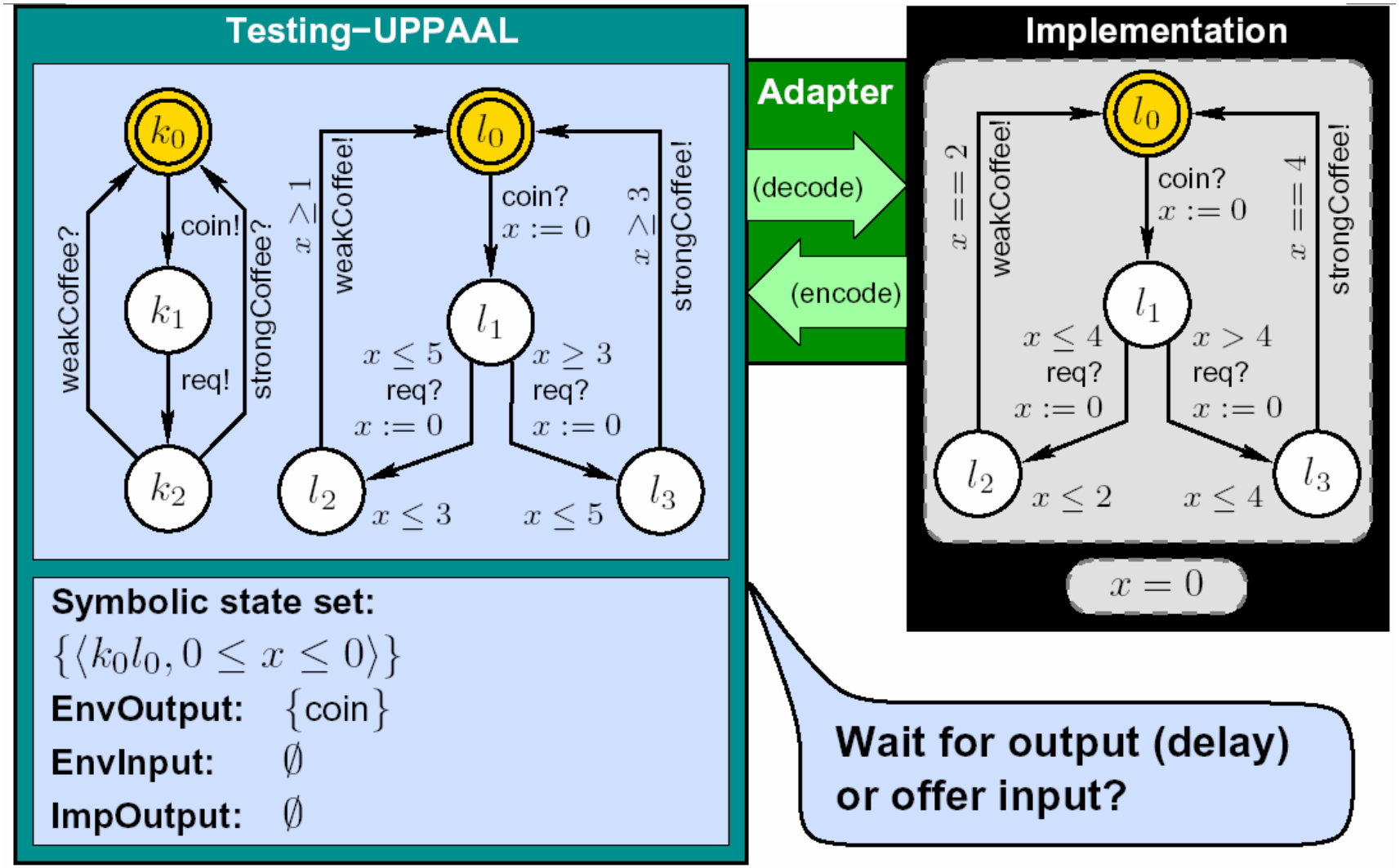
Our Framework

- ***UppAal Timed Automata*** *Network: Env || IUT*

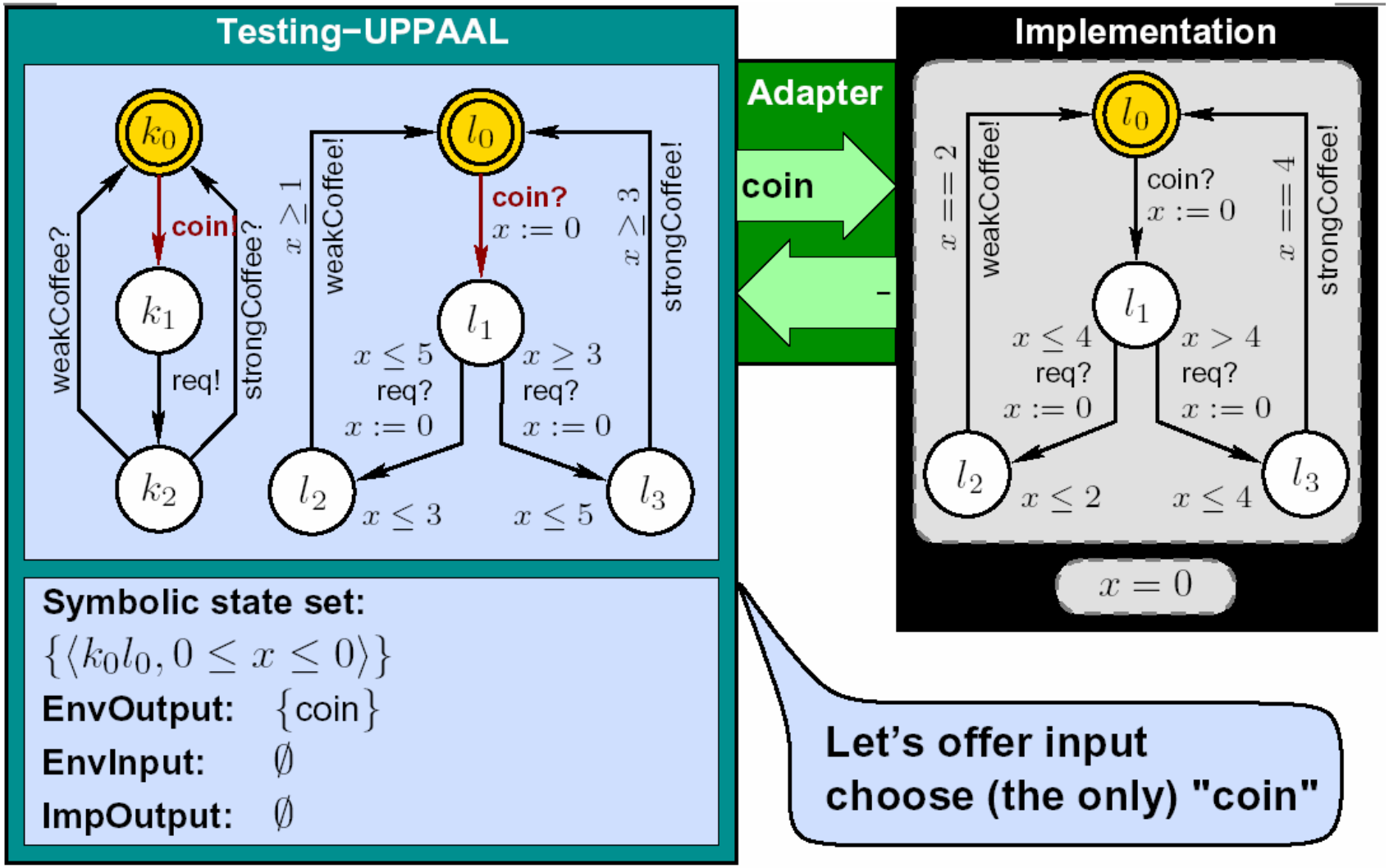


- *Complete and sound algorithm*
- Efficient symbolic reachability algorithms
- **UppAal-TRON:** Testing Real-Time Systems Online
- Release 1.3 http://www.cs.aau.dk/~marius/tron/

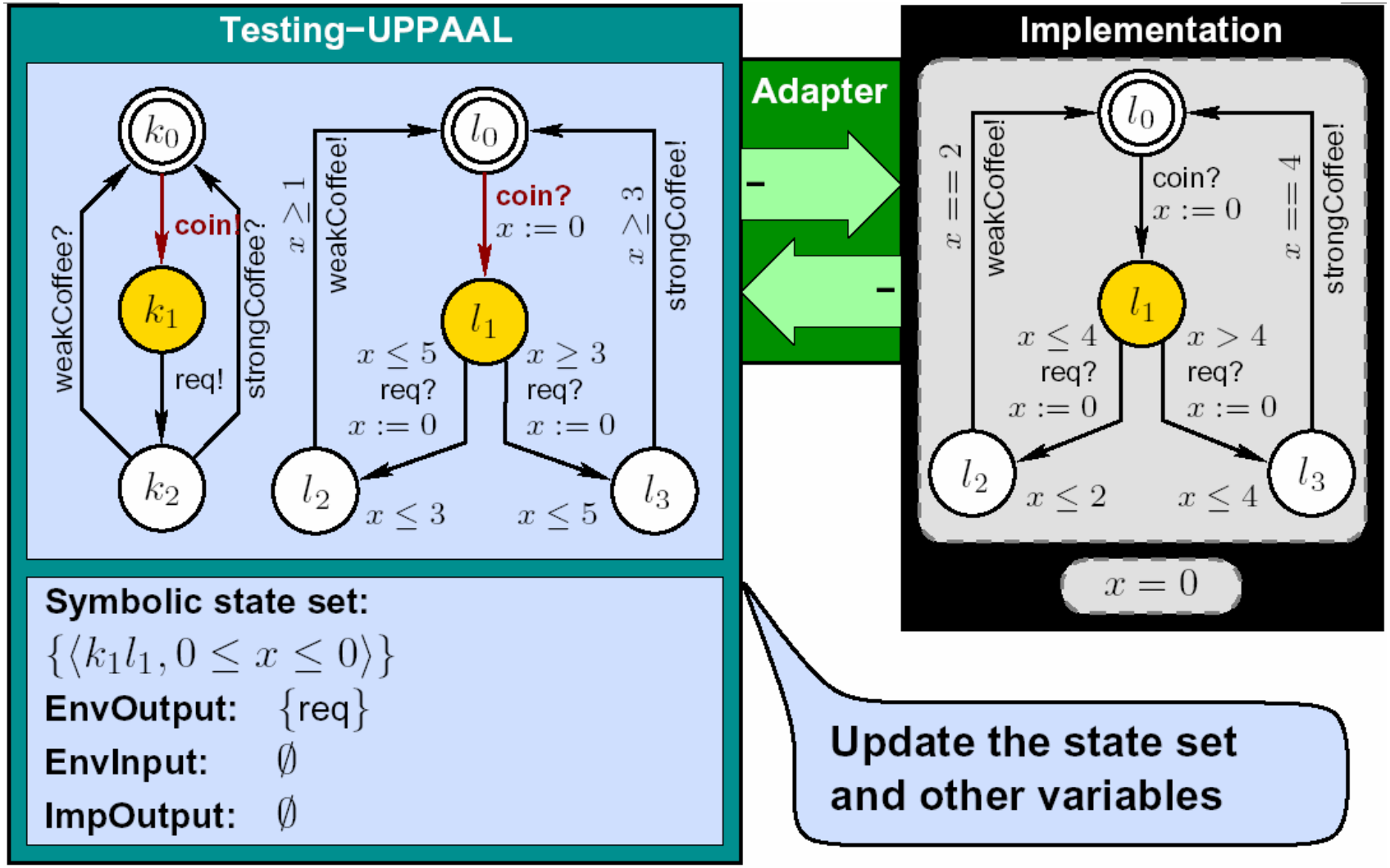
Online Testing



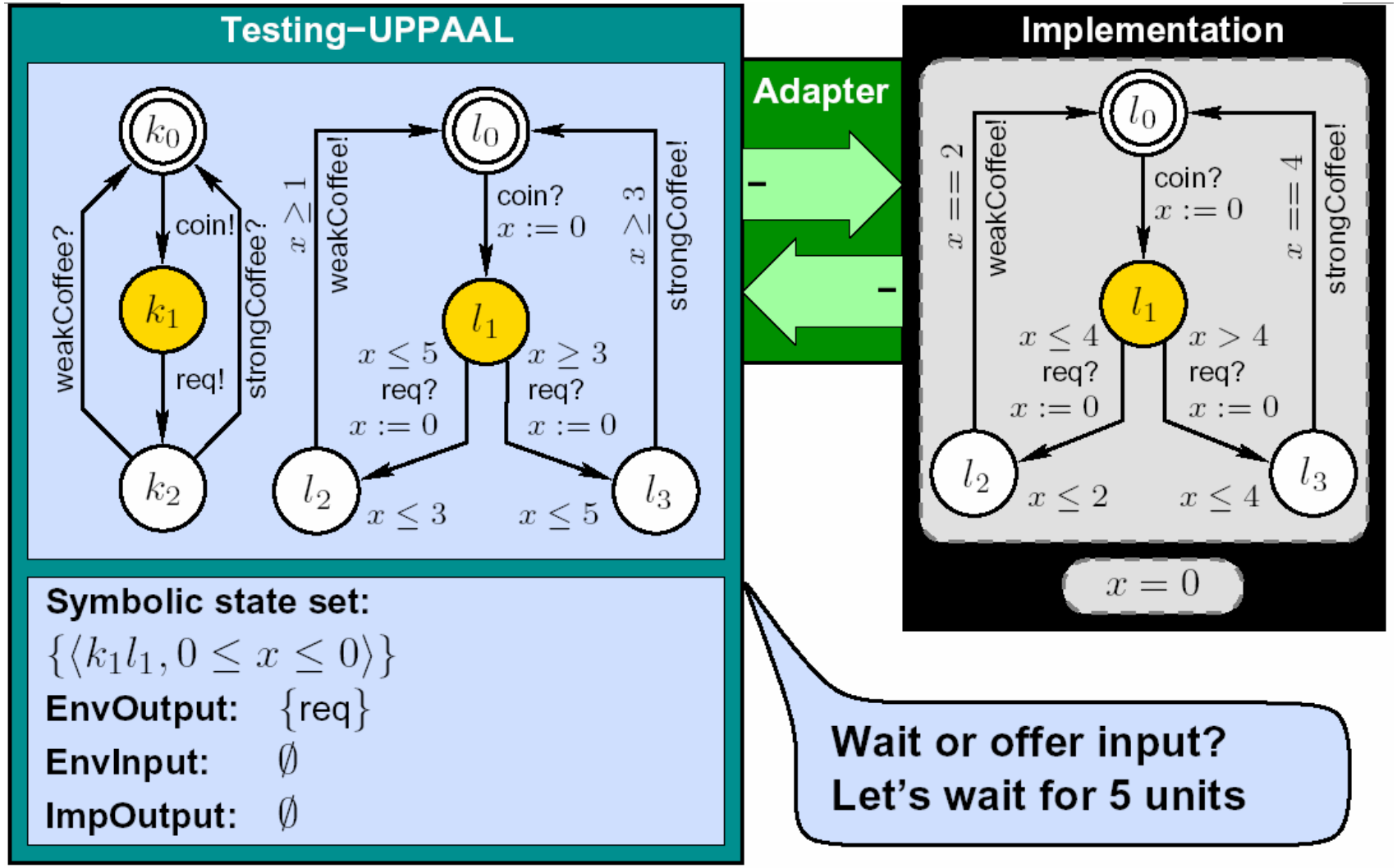
Online Testing



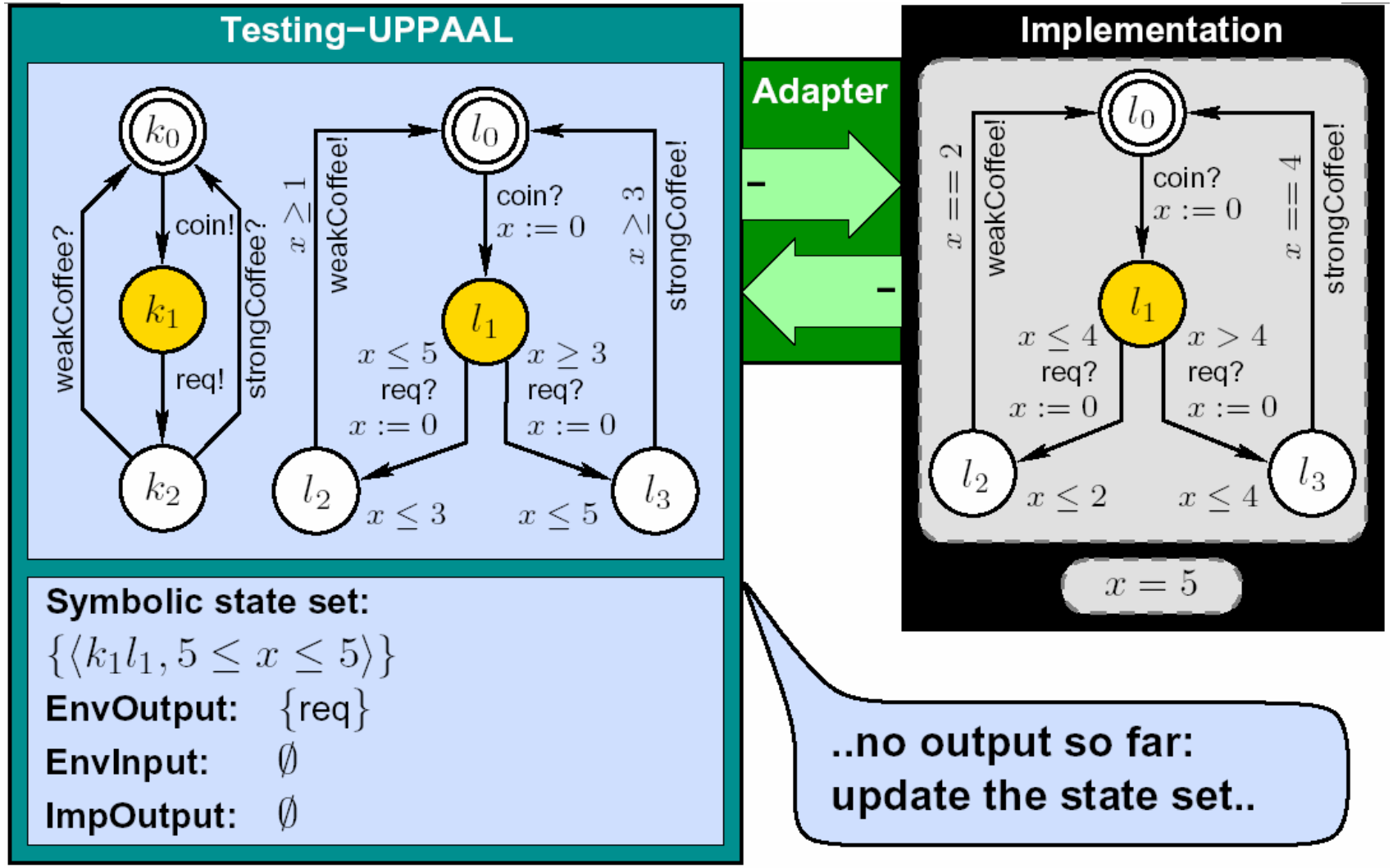
Online Testing



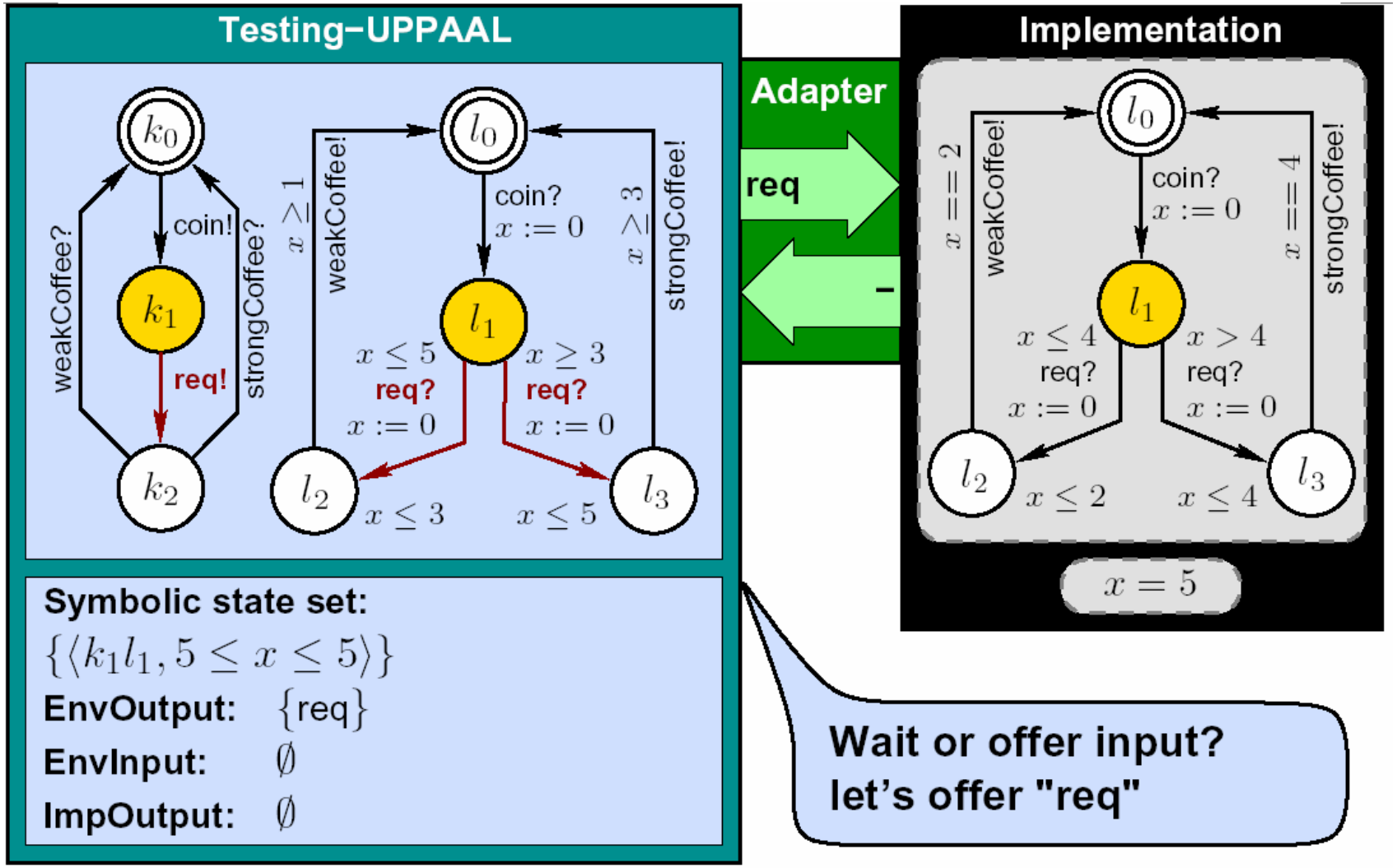
Online Testing



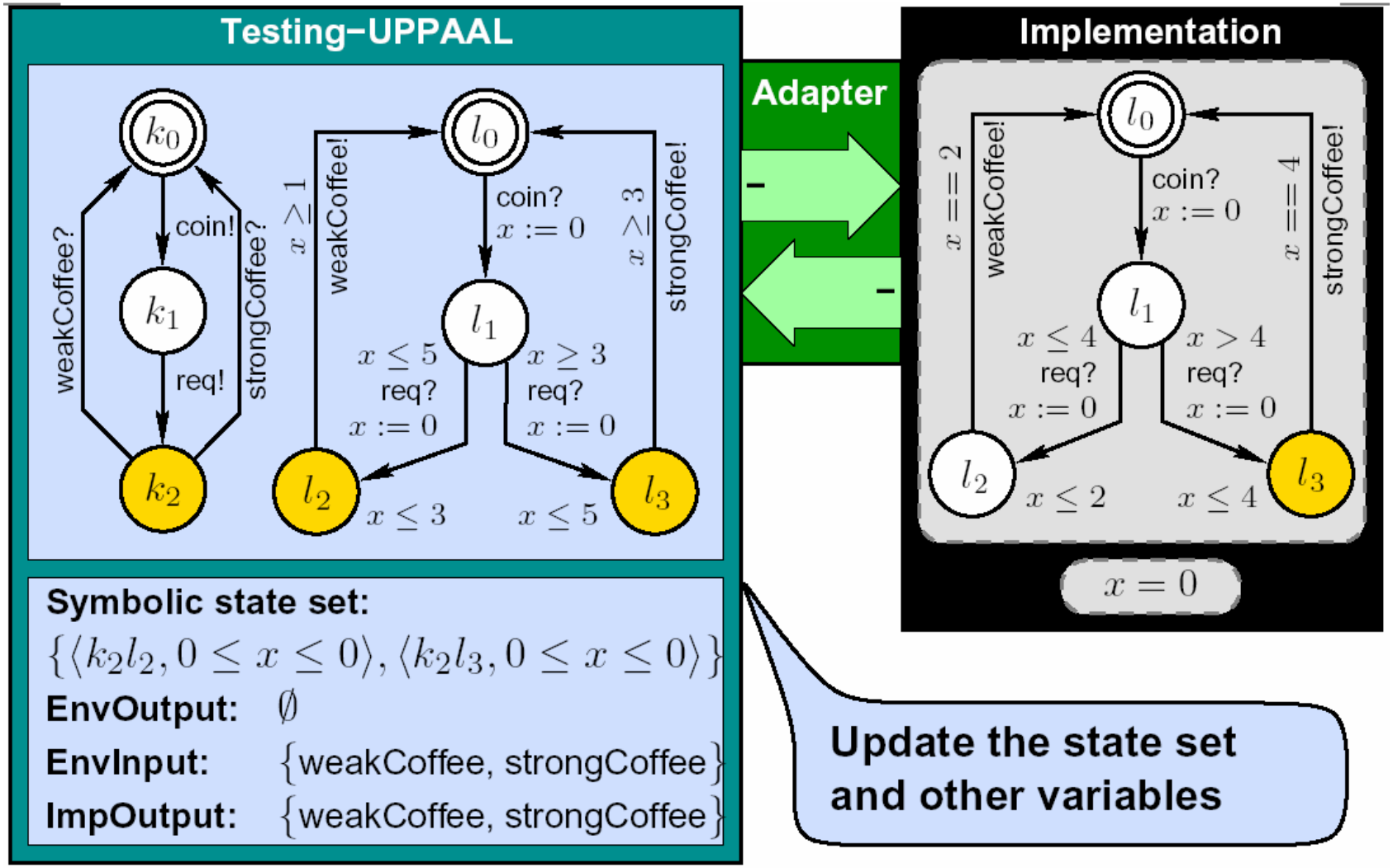
Online Testing



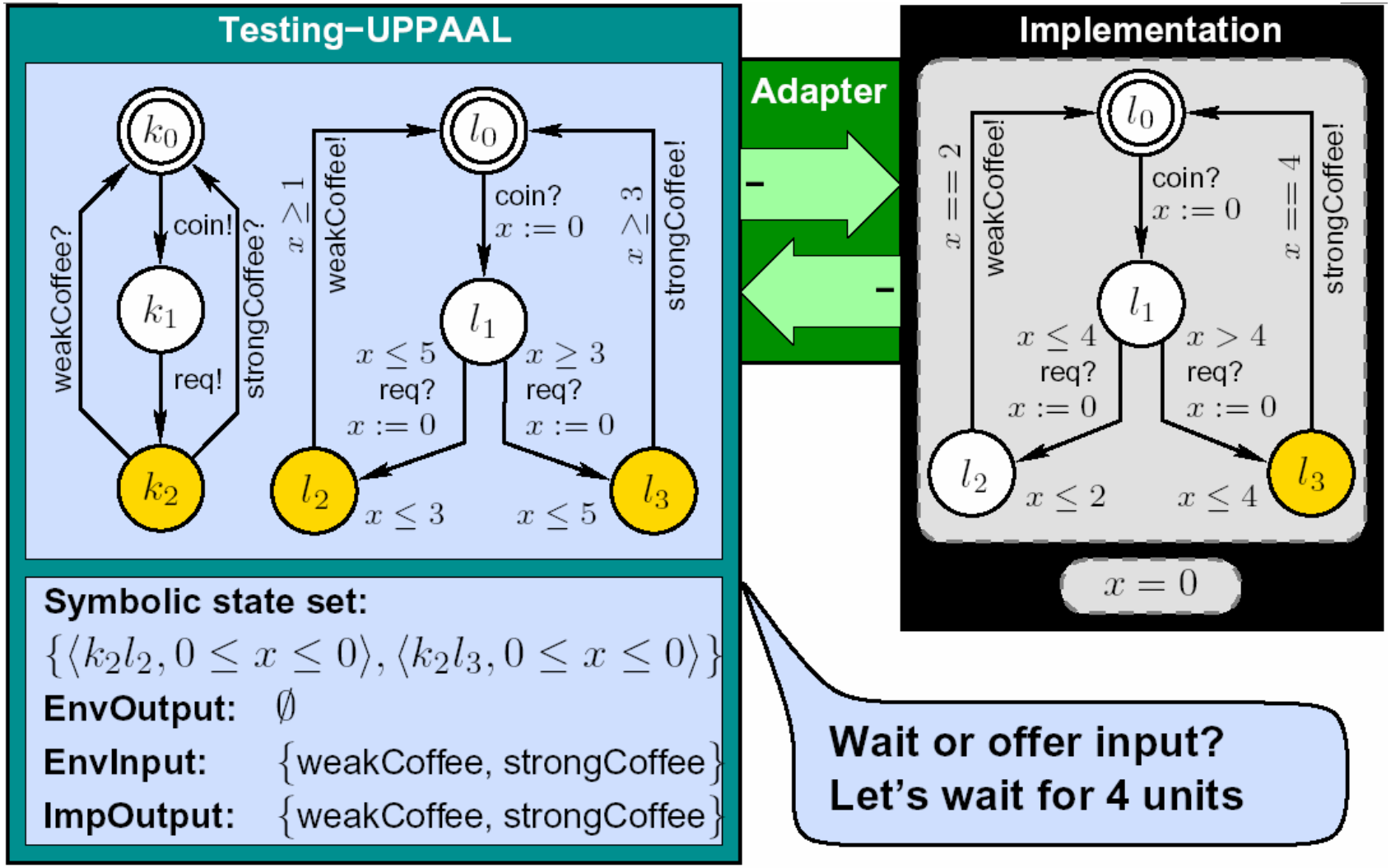
Online Testing



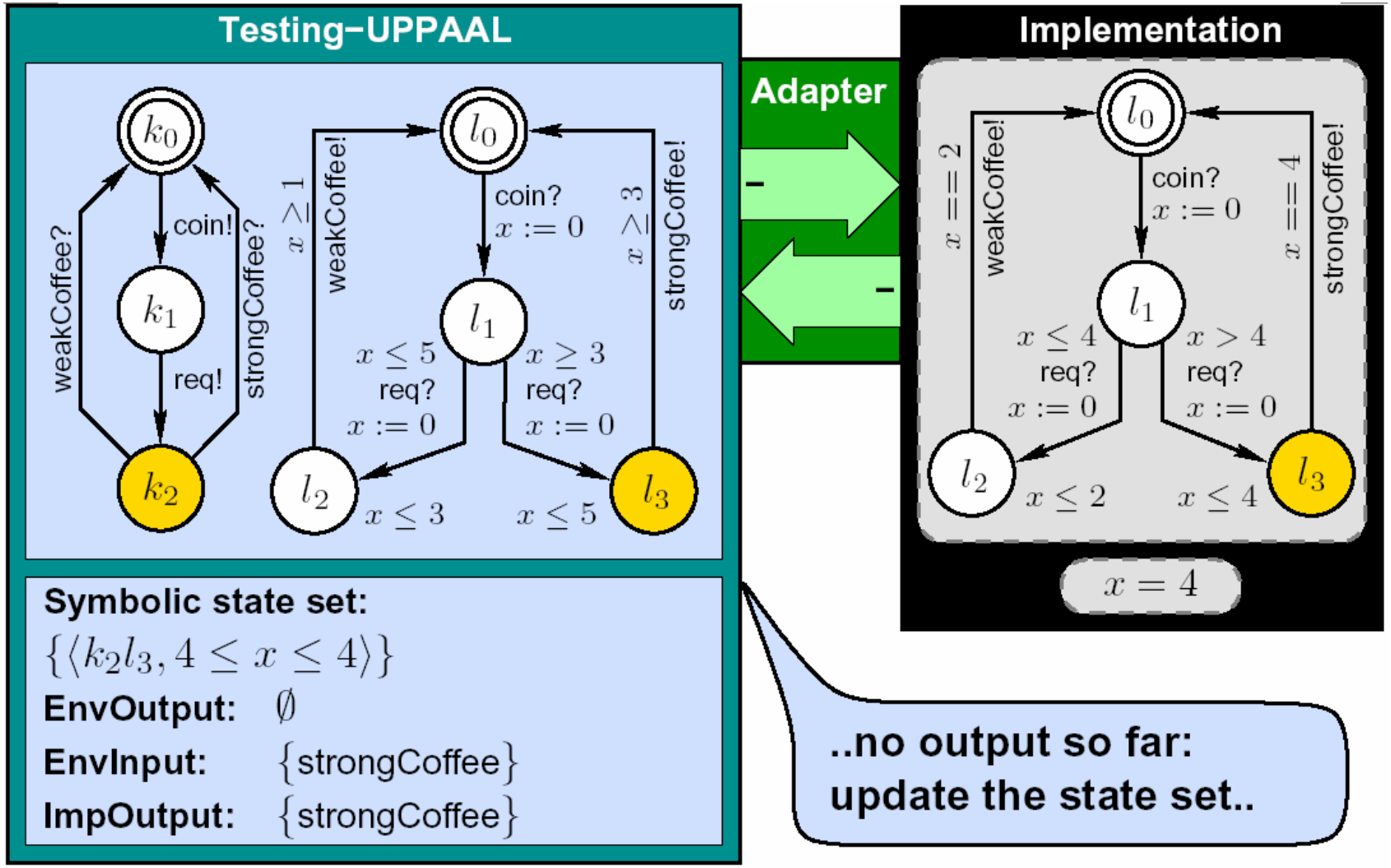
Online Testing



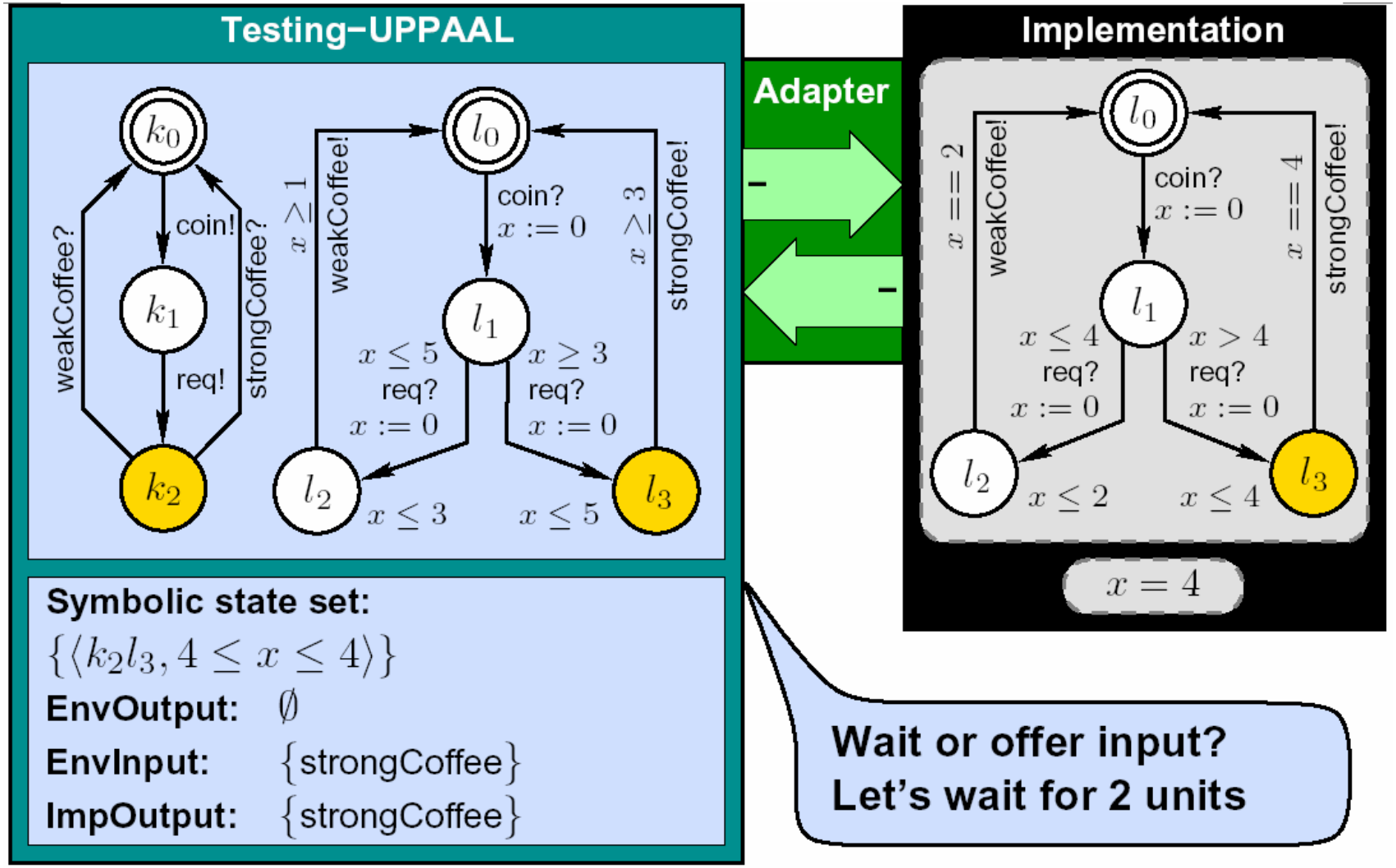
Online Testing



Online Testing



Online Testing



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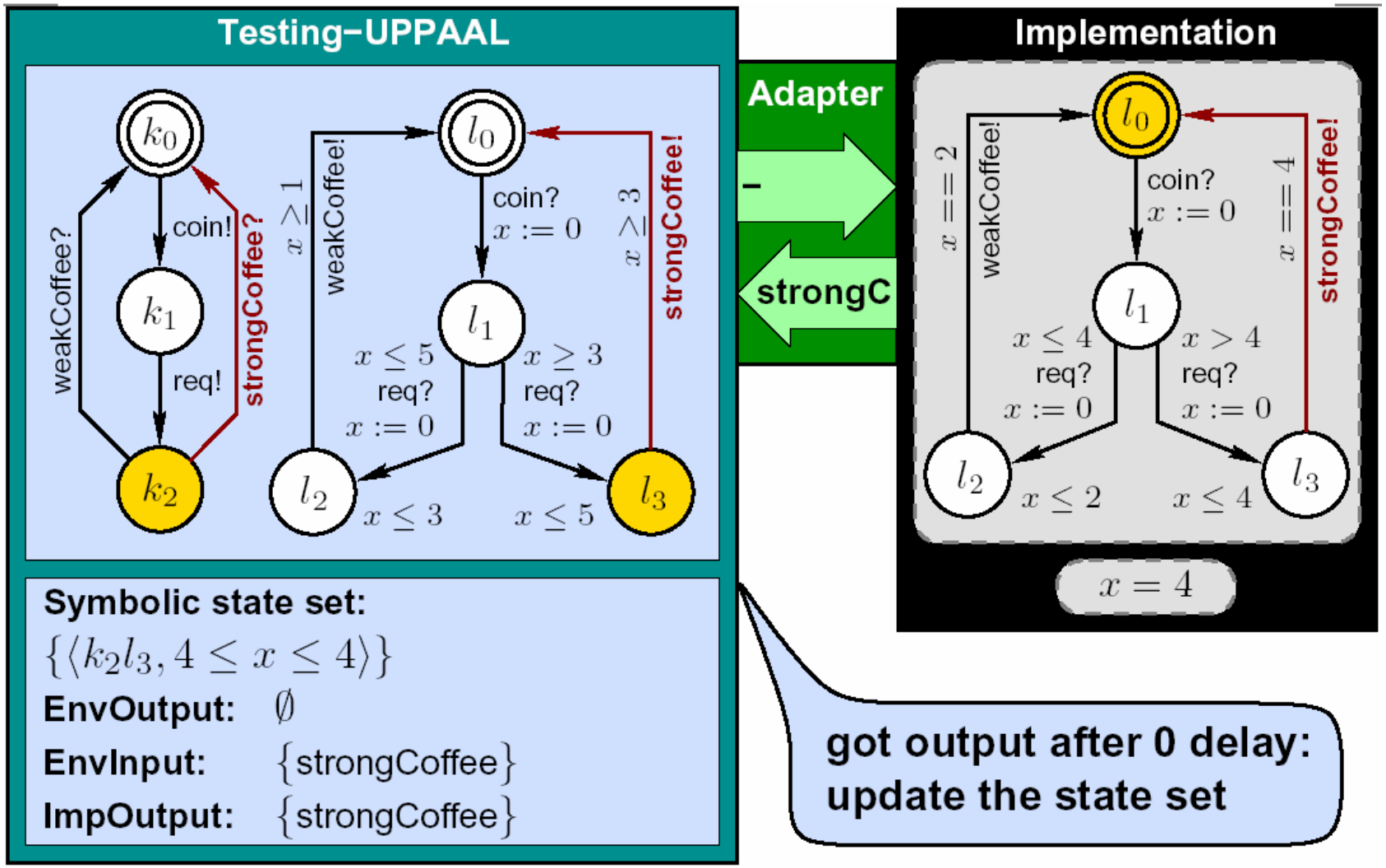

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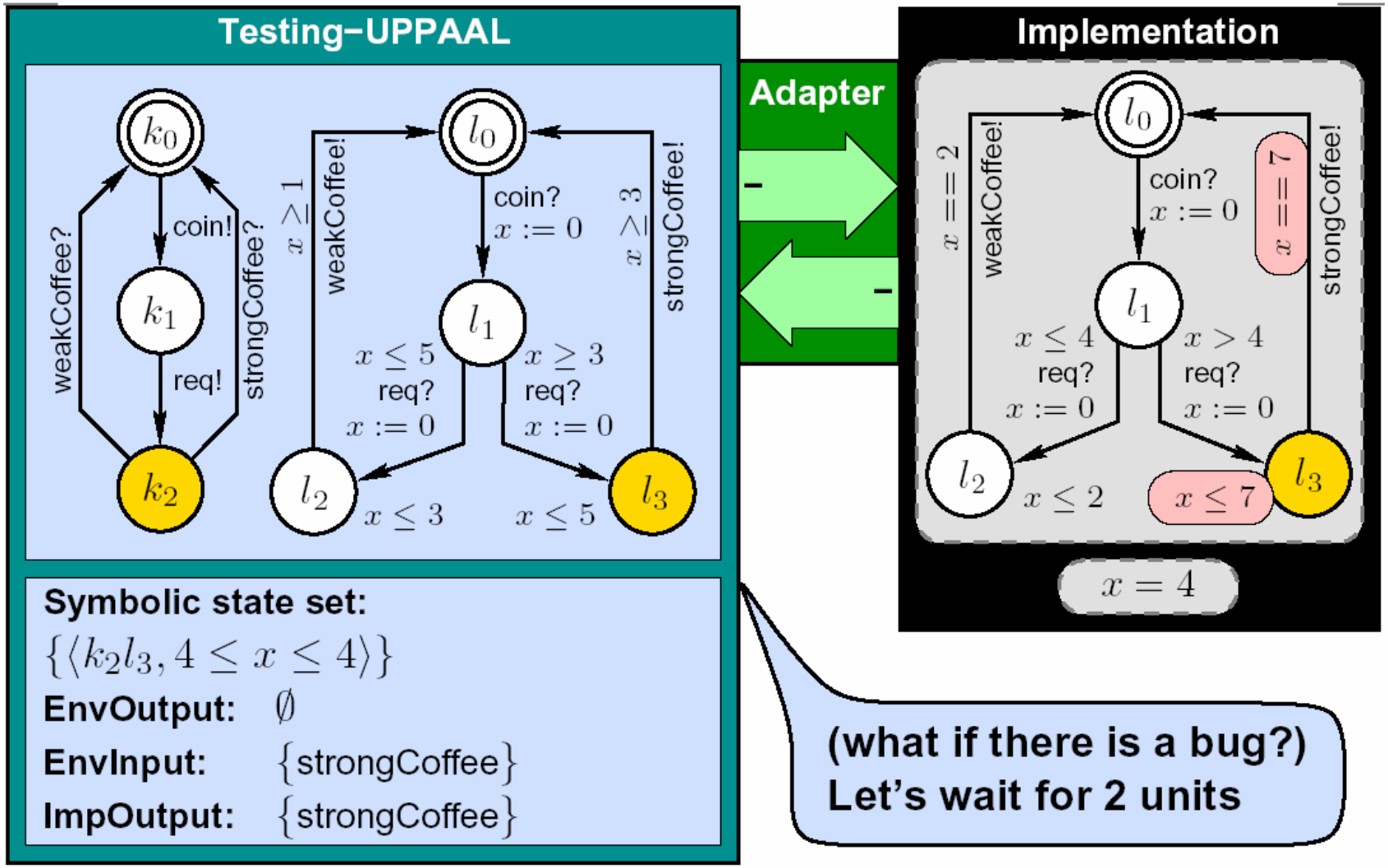
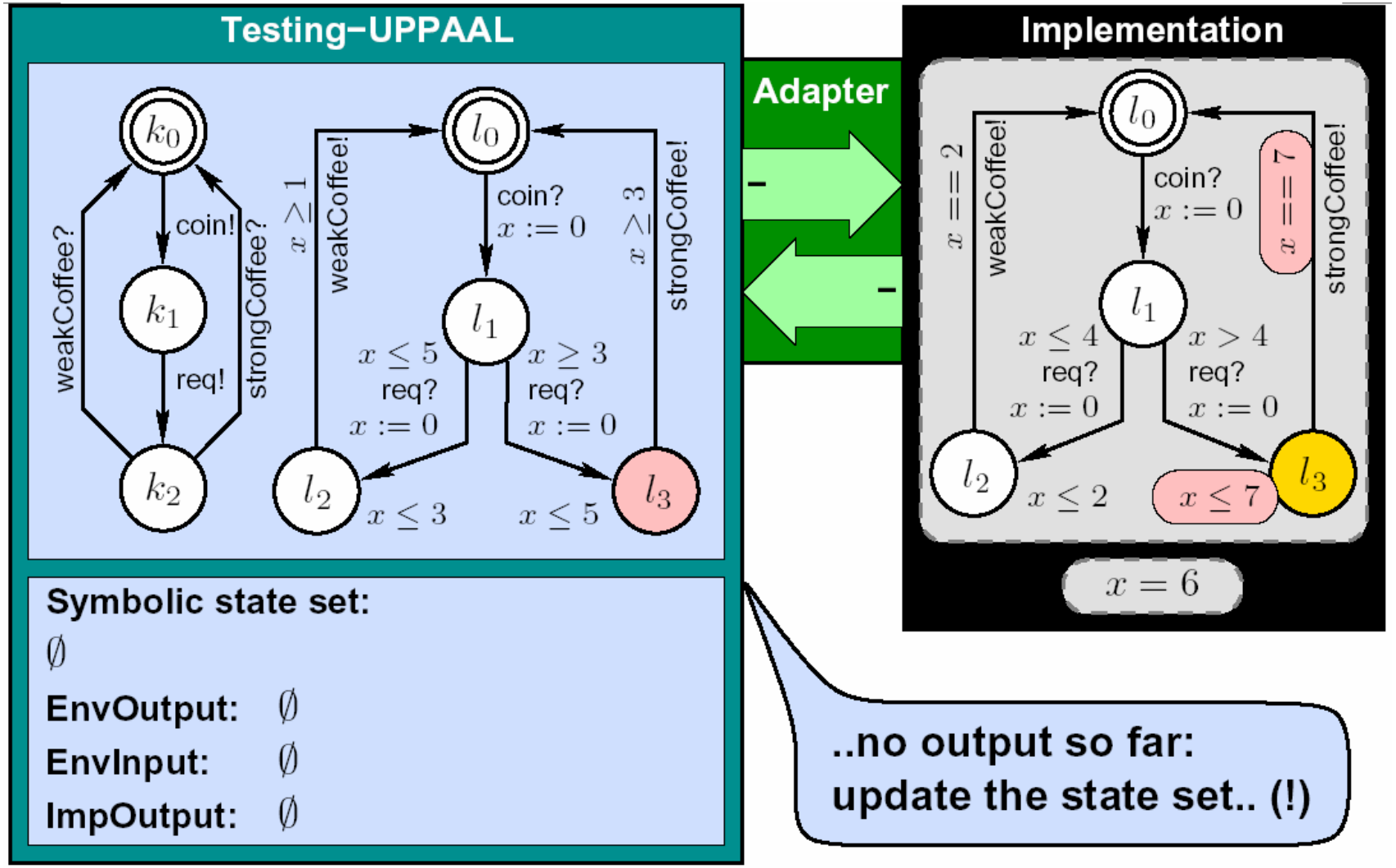
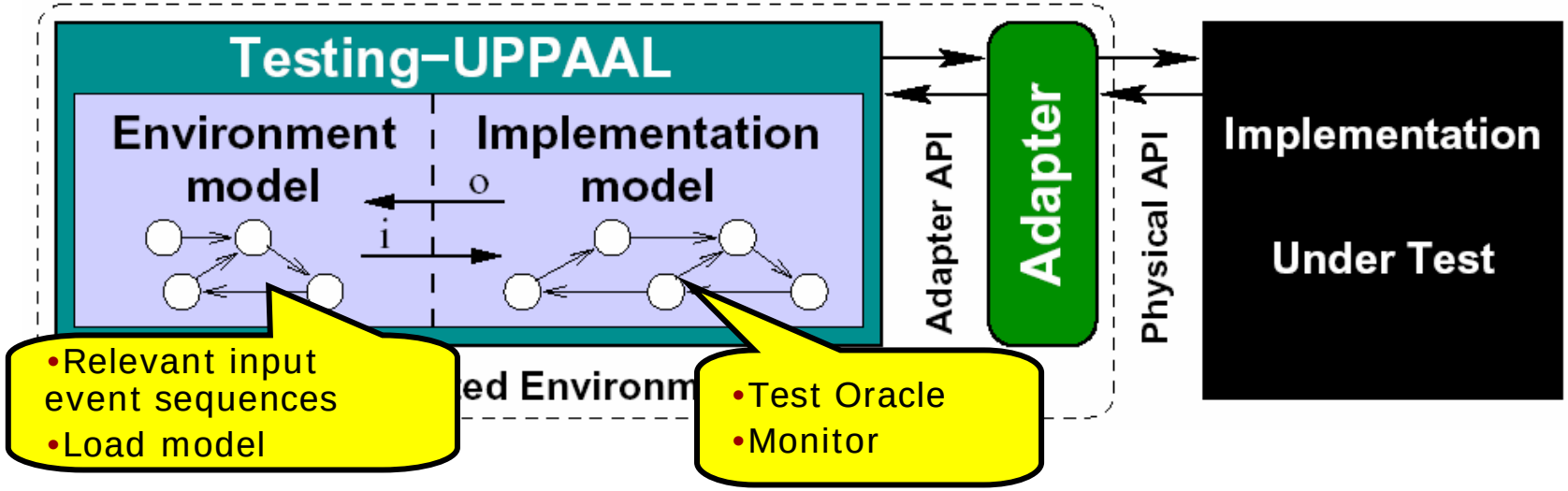


Online Testing



Test Specification



User Supplied Test Specification

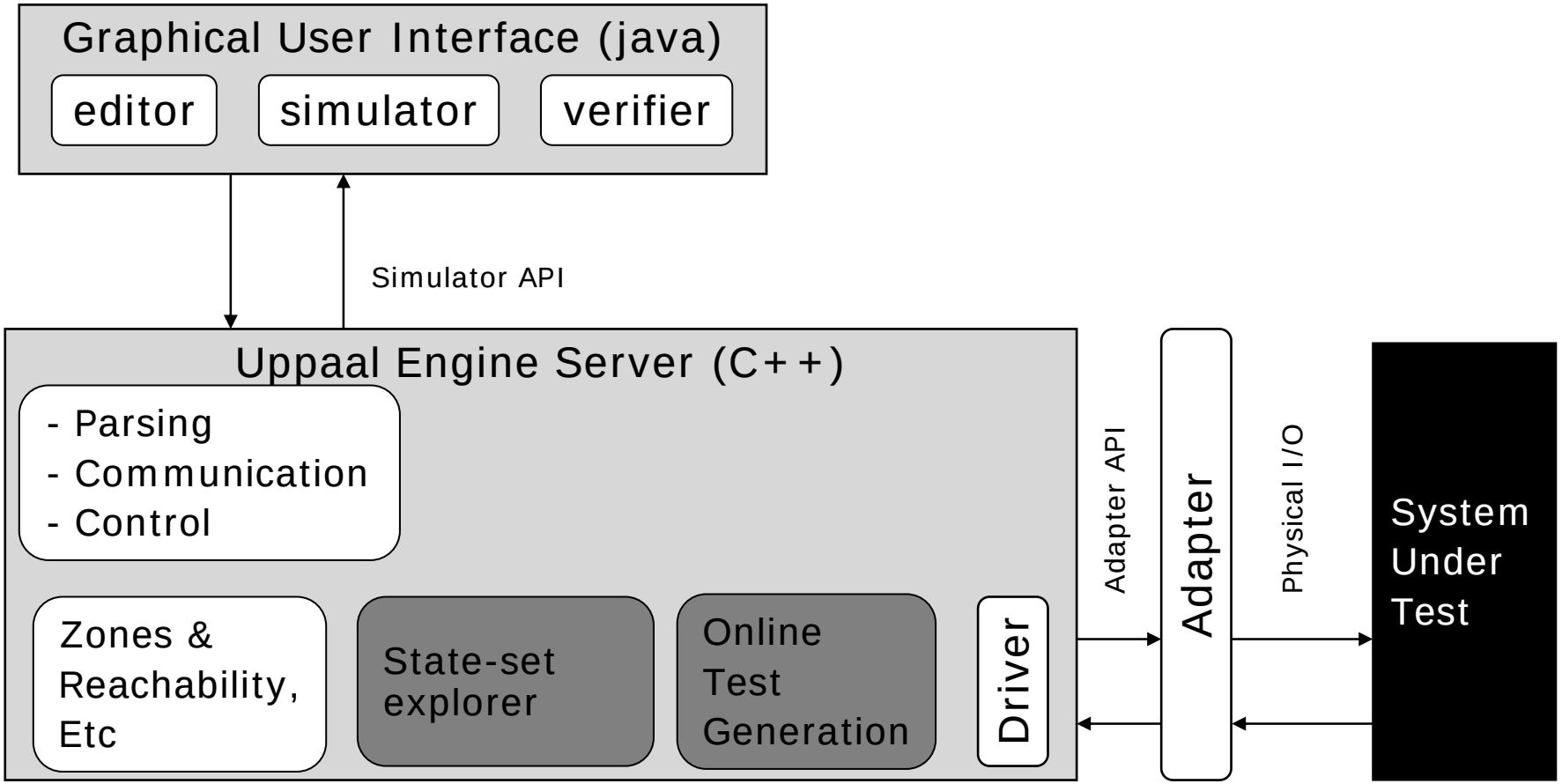
- *Closed TA Network* partitioned into *Env* and *IUT*.
  - IUT model weakly input input enabled
  - Model of *Environment*
- Designate *observable input* and *output* actions.
- Specify amount of real time per one time-unit in model.

Online Algorithm

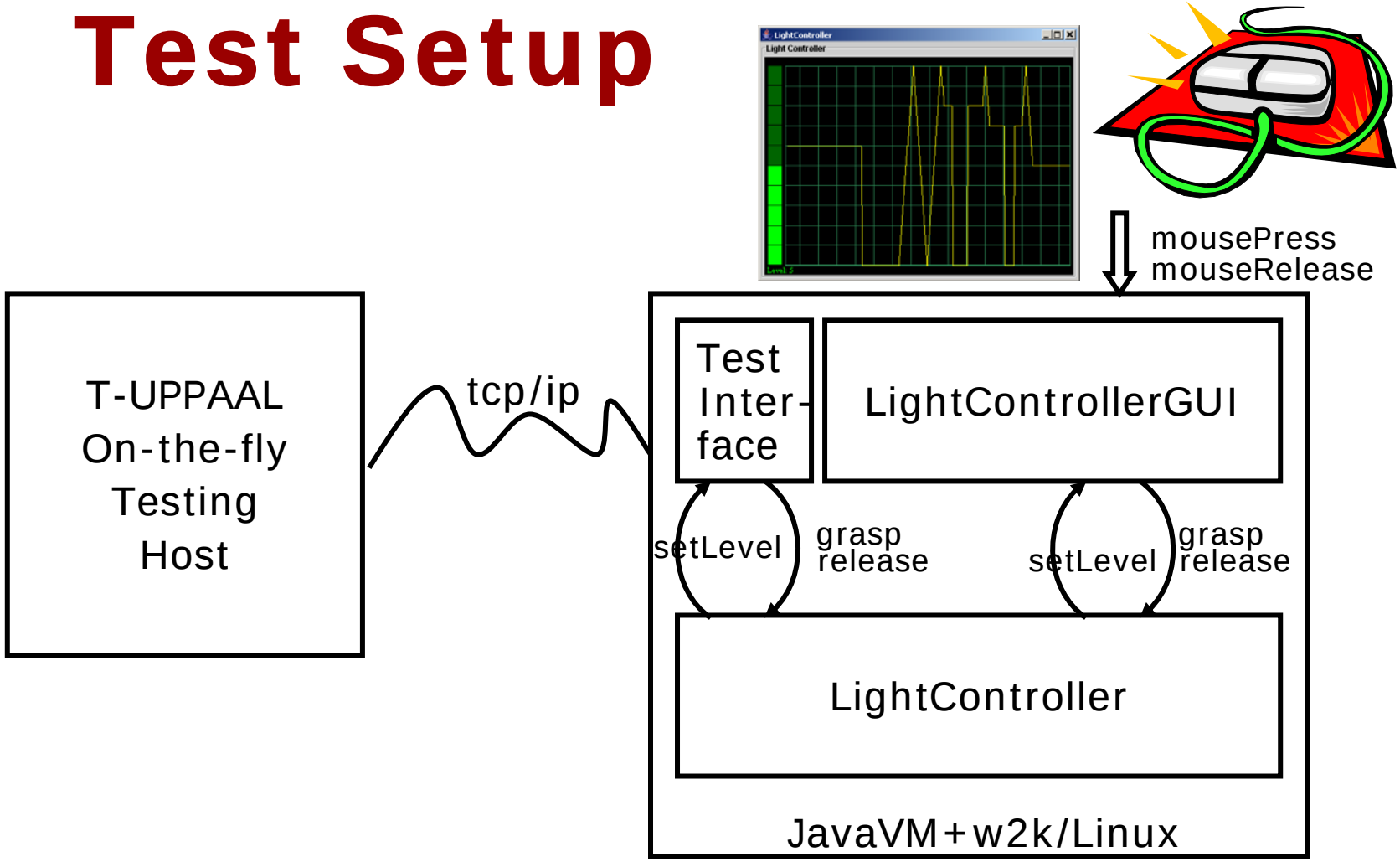
Algorithm *TestGenExec (TestSpec)* **returns** {**pass**, **fail**, **inconclusive**)

```
S:={⟨l0,0⟩}, continueTesting:= true
While continueTesting do either
    1.  i:=ChooseAction(EnvOutput(S)) // Offer an input
        send i to SUT
        Z:=After(S,i)
    2.  δ=chooseDelay(S)              // Delay and wait for output
        Wait(δ)
            if o occurred after δ' ≤ δ then
                S:=After(S, δ')
                1.  if o ∉ ImpOutput(S) then return fail
                2.  if o ∉ EnvInput(S) then return inconclusive
                S:=After(S,o)
            else                      // no output within δ time
                S:=After(S, δ)
                if S=∅ then return fail
    3.  continueTesting := false      // terminate
return pass
```

T-UppAal: implementation



Test Setup


LightController
Light Controller
mousePress
mouseRelease
T-UPPAAL
On-the-fly
Testing
Host
tcp/ip
Test
Inter-
face
LightControllerGUI
setLevel
grasp
release
setLevel
grasp
release
LightController
JavaVM+w2k/Linux

Danfoss EKC Case

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)

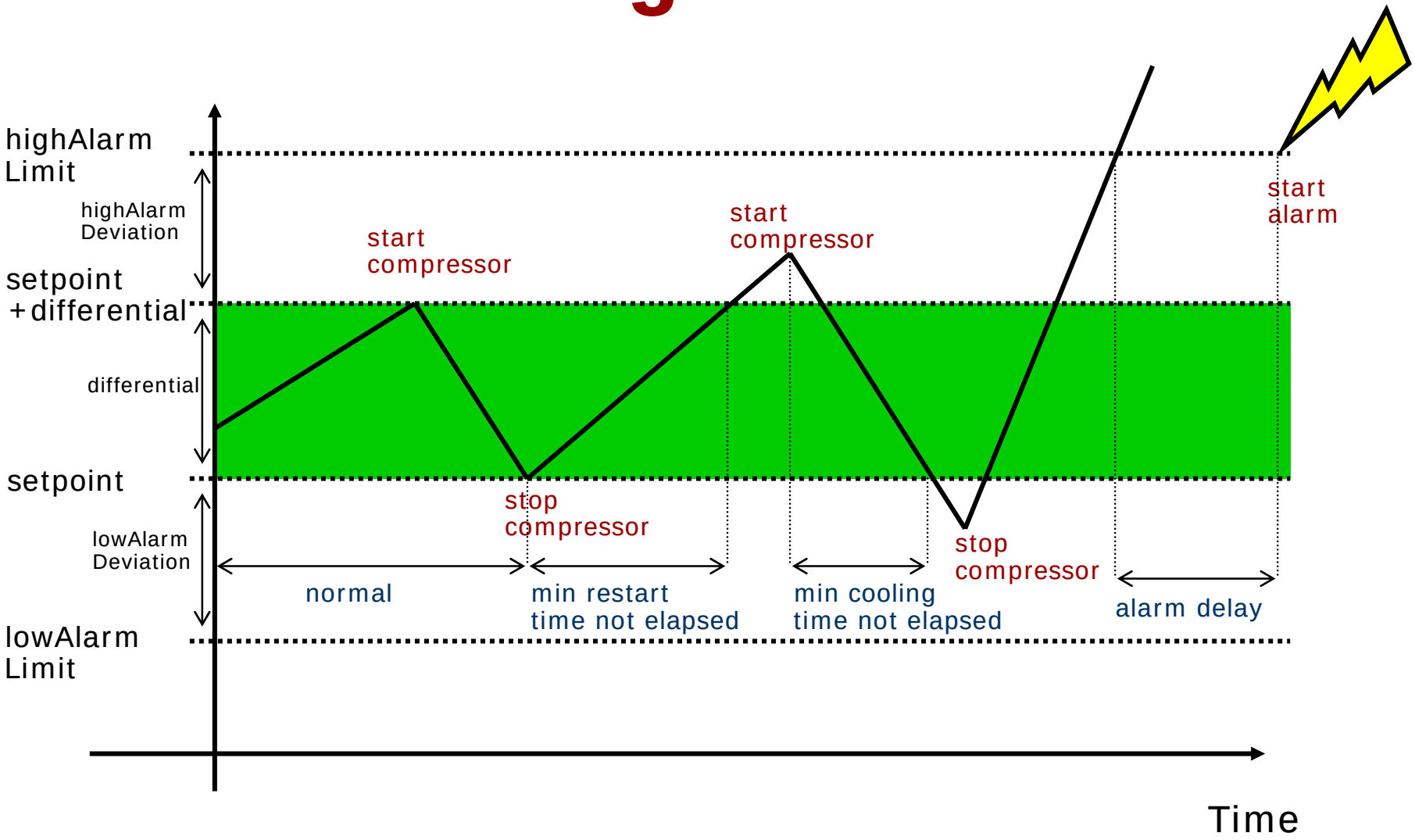
Display Output

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

- Optional real-time clock or LON network module

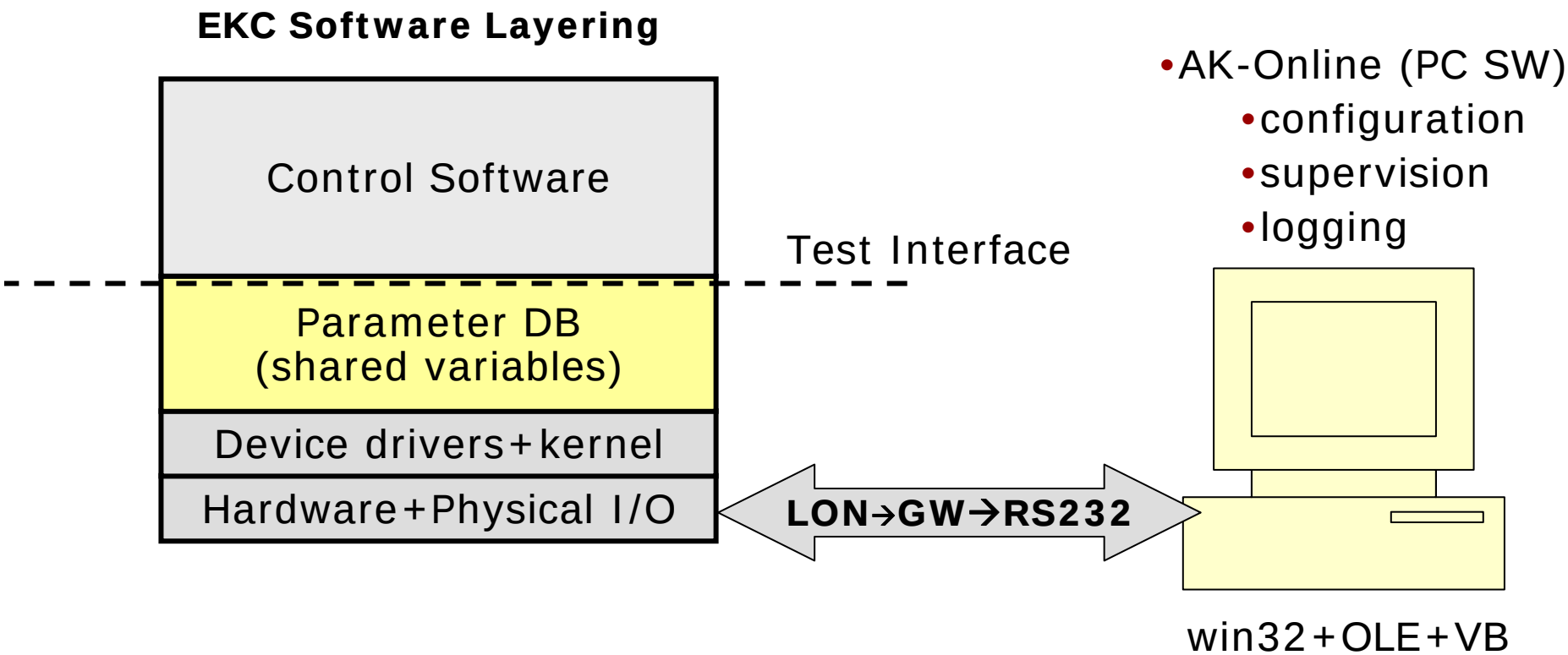
Industrial Cooling Plants

Basic Refrigeration Control

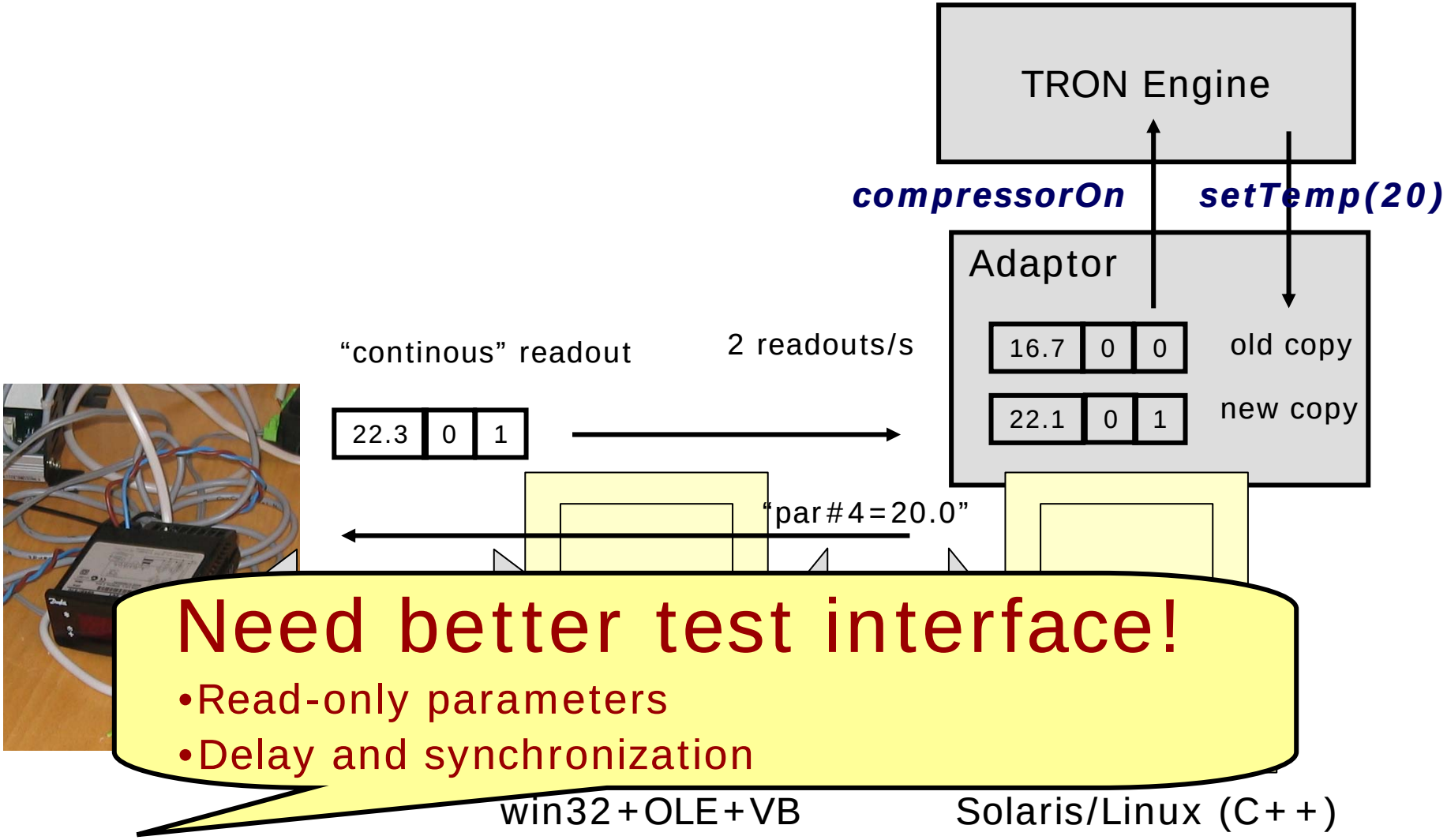


EKC Adaptation 1

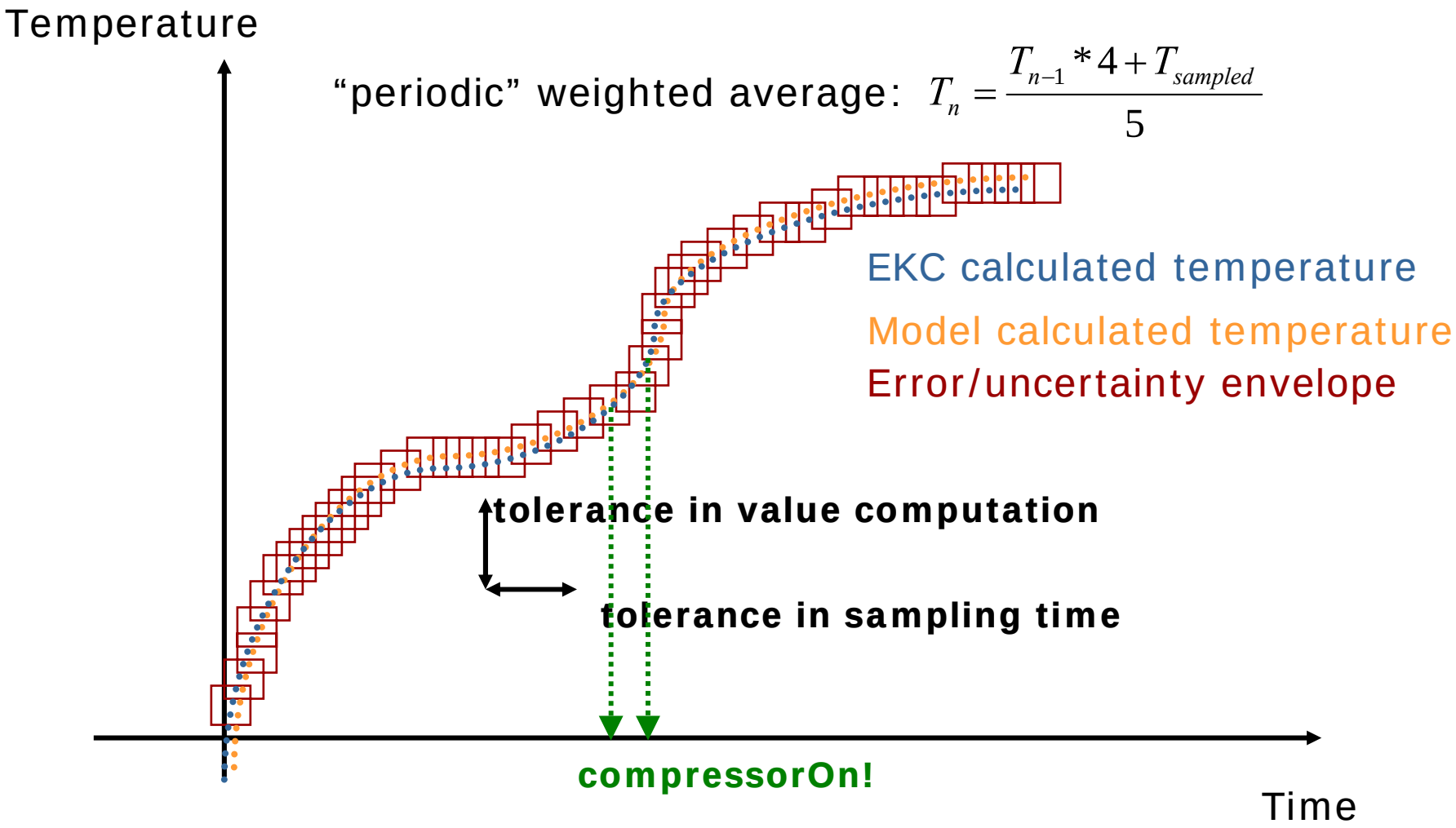
- **Read and write parameter "database"**
- **47 parameters**



EKC Adaptation 2

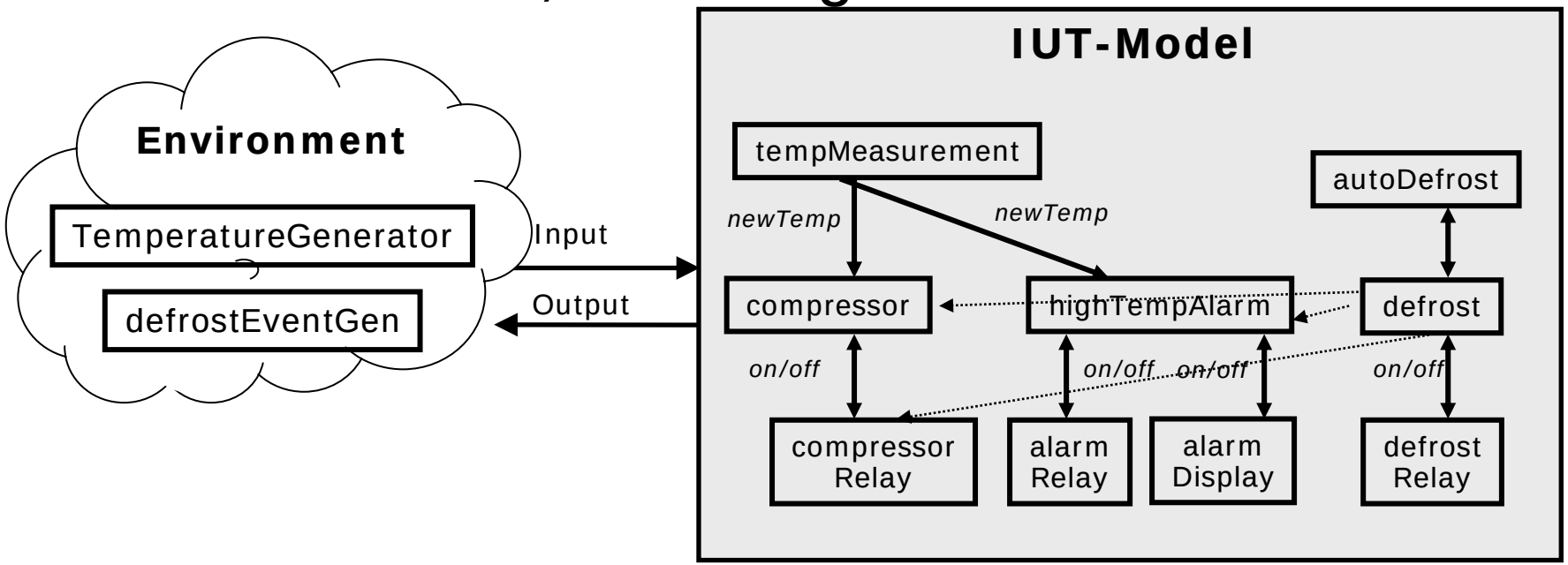


Temperature Tracking



Main Model Components

- 18 concurrent timed automata
- 14 clocks, 14 integers



Reverse Engineering

- Unclear and incomplete specifications
- Method of Working
  1. Formulate hypothesis model
  2. Test
  3. **FAIL**-verdict ⇒ Refine model
  4. **(PASS)** ⇒ Confirm with Danfoss
- Detects differences between actual and modeled behavior
- ***Indicates promising error-detection capability***
- 4 examples

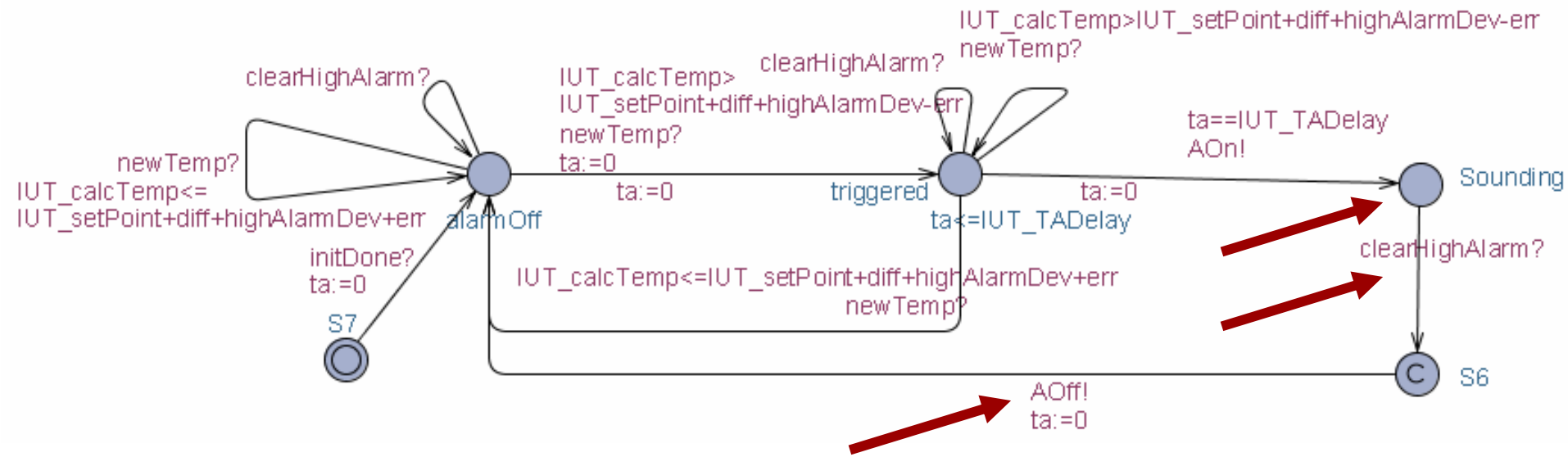
Ex1: Control Period

- Control actions issued when ”calculatedTemp” crosses thresholds

“periodic” weighted average: $$T_n = \frac{T_{n-1} * 4 + T_{sampled}}{5}$$

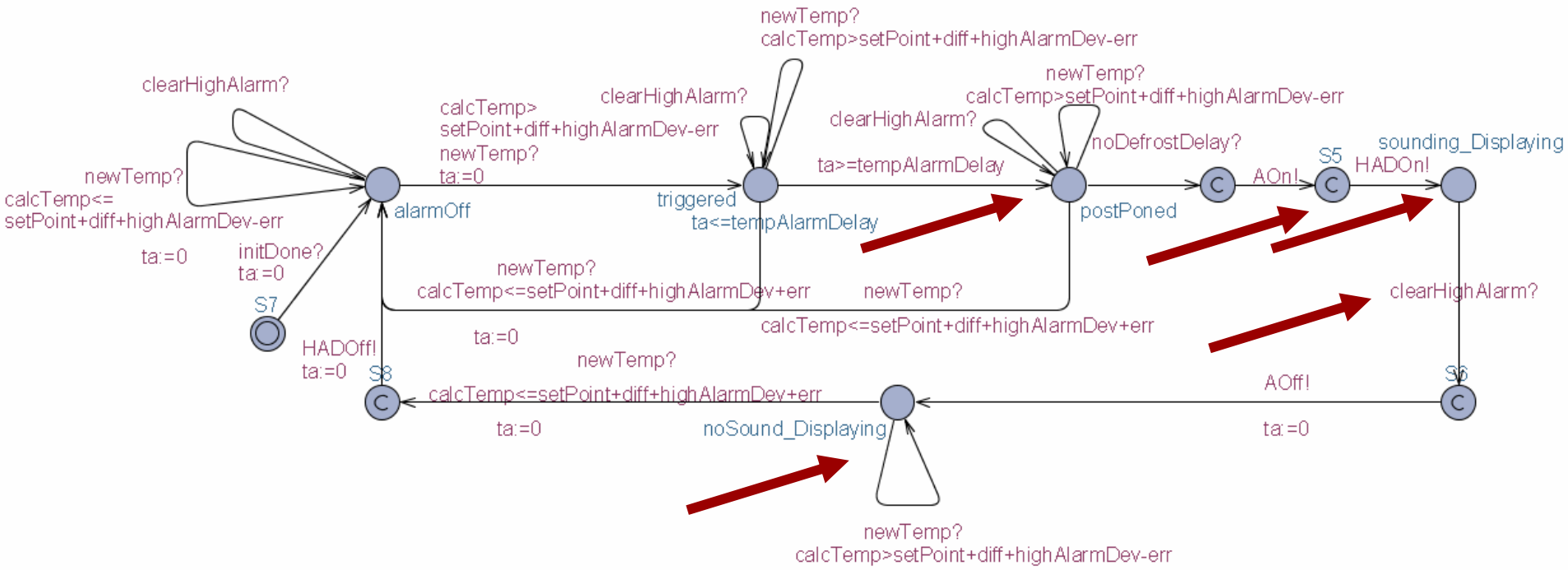
- No requirements on period given
- Tested to be 1.2 seconds

Ex2: High Alarm Monitor v1



Clearing the alarm do not switch off alarm state, only alarm relay

Ex2: High Alarm Monitor v2



- Add HighAlarmDisplay action
- Add location for “noSound, but alarmDisplaying”
- (Postpone alarms after defrosting)

Ex3: Defrosting and Alarms

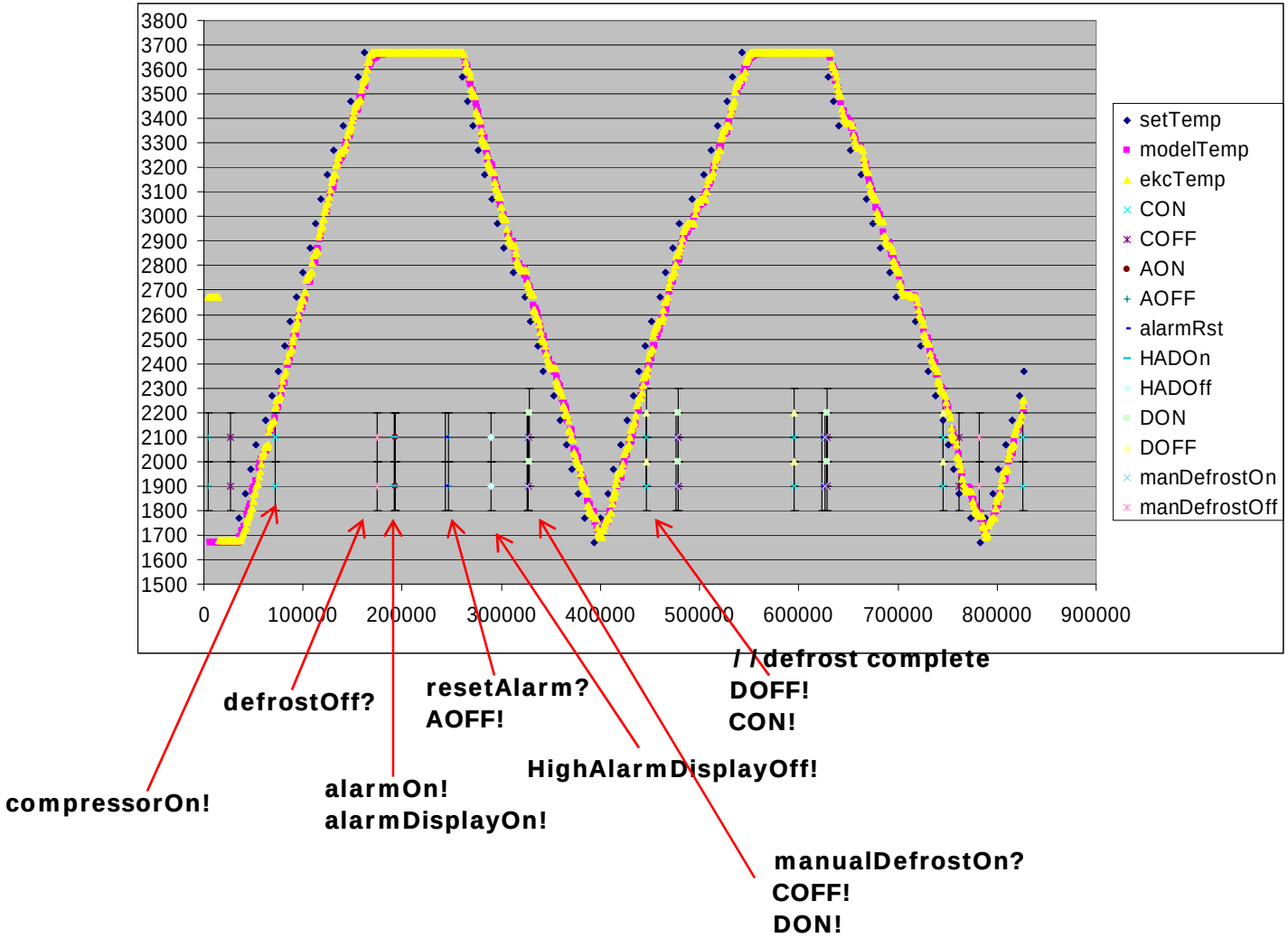
- When defrosting the temperature rises
- Postpone high temperature alarms during defrost
- System parameter alarmDelayAfterDefrost
- Several Interpretations
  1. Postpone alarmDelayAfterDefrost+alarmDelay after defrost?
  2. Postpone alarmDelayAfterDefrost+alarmDelay after highTemp detected?
  3. Postpone alarmdelayAfterDefrost until temperature becomes low; then use alarmDelay
- Option 3 applies!

Ex4: Defrost TimeTolerance

- Defrost relays engaged earlier and disengaged later than expected
- Assumed 2 seconds tolerance
- Defrosting takes long time
- Implementation uses a low resolution timer (10 seconds)

Example Test Run

(log visualization)



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