Model Based Testing : principles and applications in the context of timed systems

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Outline

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Introduction on testing

Why testing?

- Systems getting more and more complex
  $\rightarrow$ potentially more bugs
- A failure may cost a lot (human and financial)
  $\rightarrow$ earlier detection implies weaker consequences

Limitations

- "Testing can only be used to show the presence of bugs, but never to show their absence" (Dijkstra)
  $\rightarrow$ need to make some assumptions
  $\rightarrow$ Objective : increase the confidence in the system

Different kinds of testing

black box / white box

- white box : most elements of the system are known, especially source code (structural testing)
- black box : implementation is considered as an unknown black box; only interfaces are known
  $\rightarrow$ test generation based on the specification (functional testing)

What do we intend to test

User testing, performance testing, conformance testing, interoperability testing, robustness testing, etc...

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$\rightarrow$ Testing that a black-box implementation (IUT) of a system behaves correctly wrt. its functional specification Spec.

Conformance testing of reactive systems

Reactive system

System which reacts to its environment through its interfaces.

- Environment: human, software, hardware
- Necessary to think about :
  - Controllability : "how the tester can lead the test"
  - Observability : "how the tester can get information"

→ definition of Points of Control and Observation (PCO).

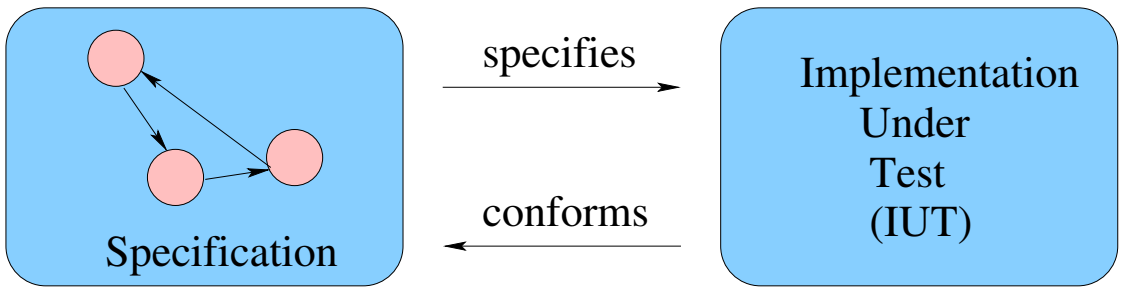
→ definition of a test architecture

Model Based Testing

Industrial practice: manual design of test suites from informal specifications

Model Based Testing

Model Based Testing (MBT) → testing with the ability to detect *faults* which do not conform to a model called specification.



⇒ possible automation for test generation, test execution, test evaluation (verdict)
⇒ Formal Methods

Model Based Testing (2)

- Test cases are generated from the Model
- Problems :
  - need to find a "good" model of the specification
  - what does specify mean?
  - what does conform mean?
- Implementation is supposed to be equivalent to a formal model (but Implementation is unknown)
- Need to define a conformance relation between the Specification and the Implementation

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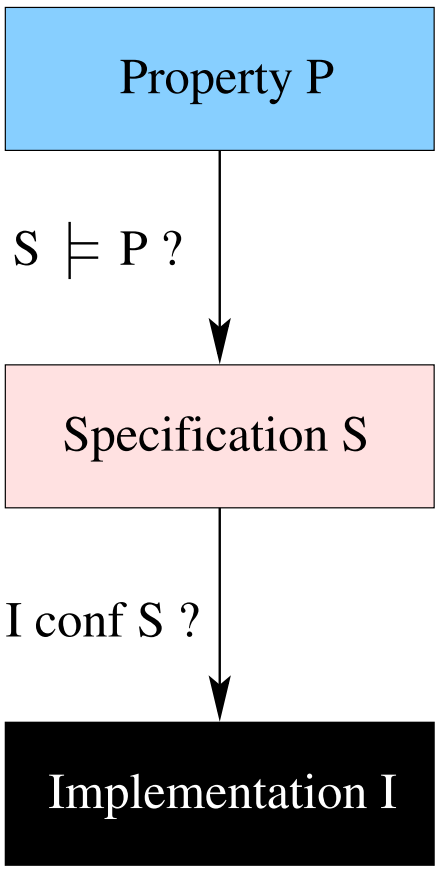
At the beginning...

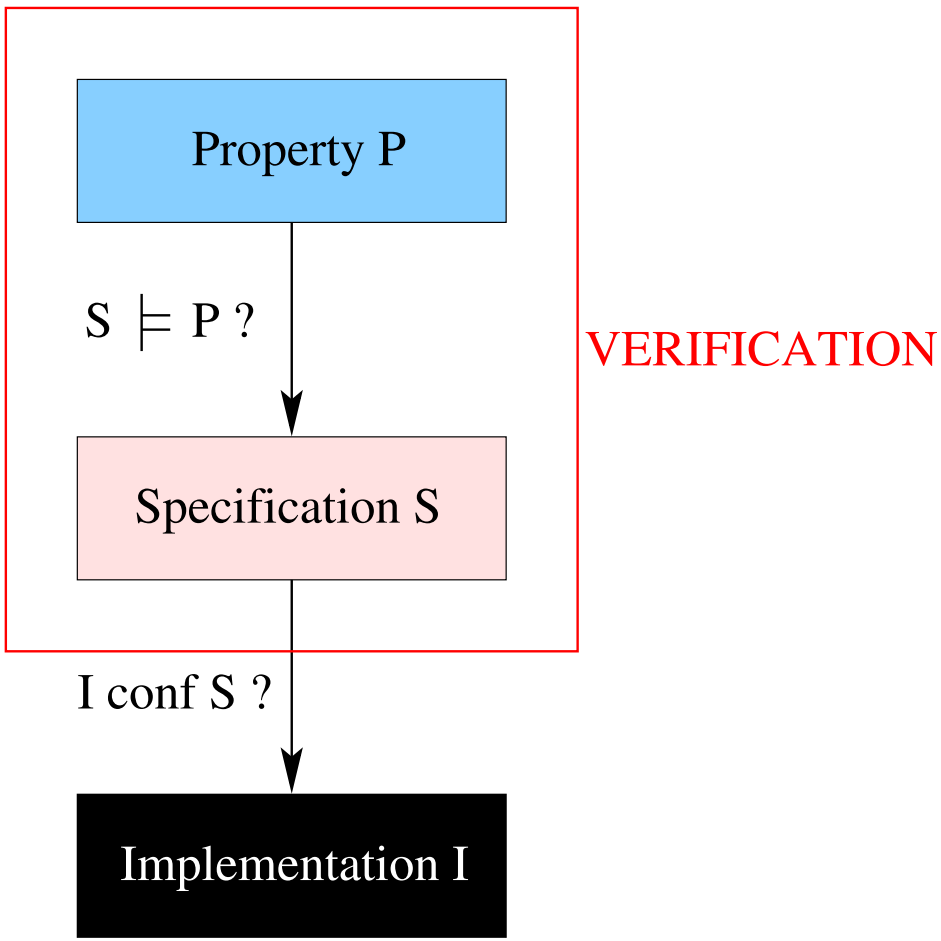
Two main approaches of MBT :

- Finite State Machines
- Labeled Transition Systems

General schema



General schema



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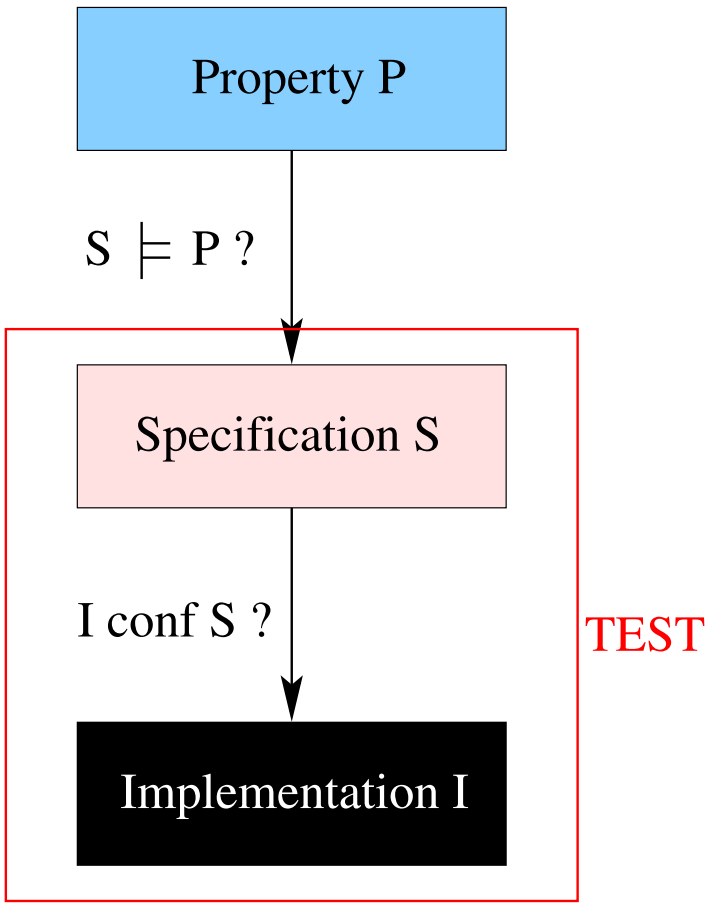

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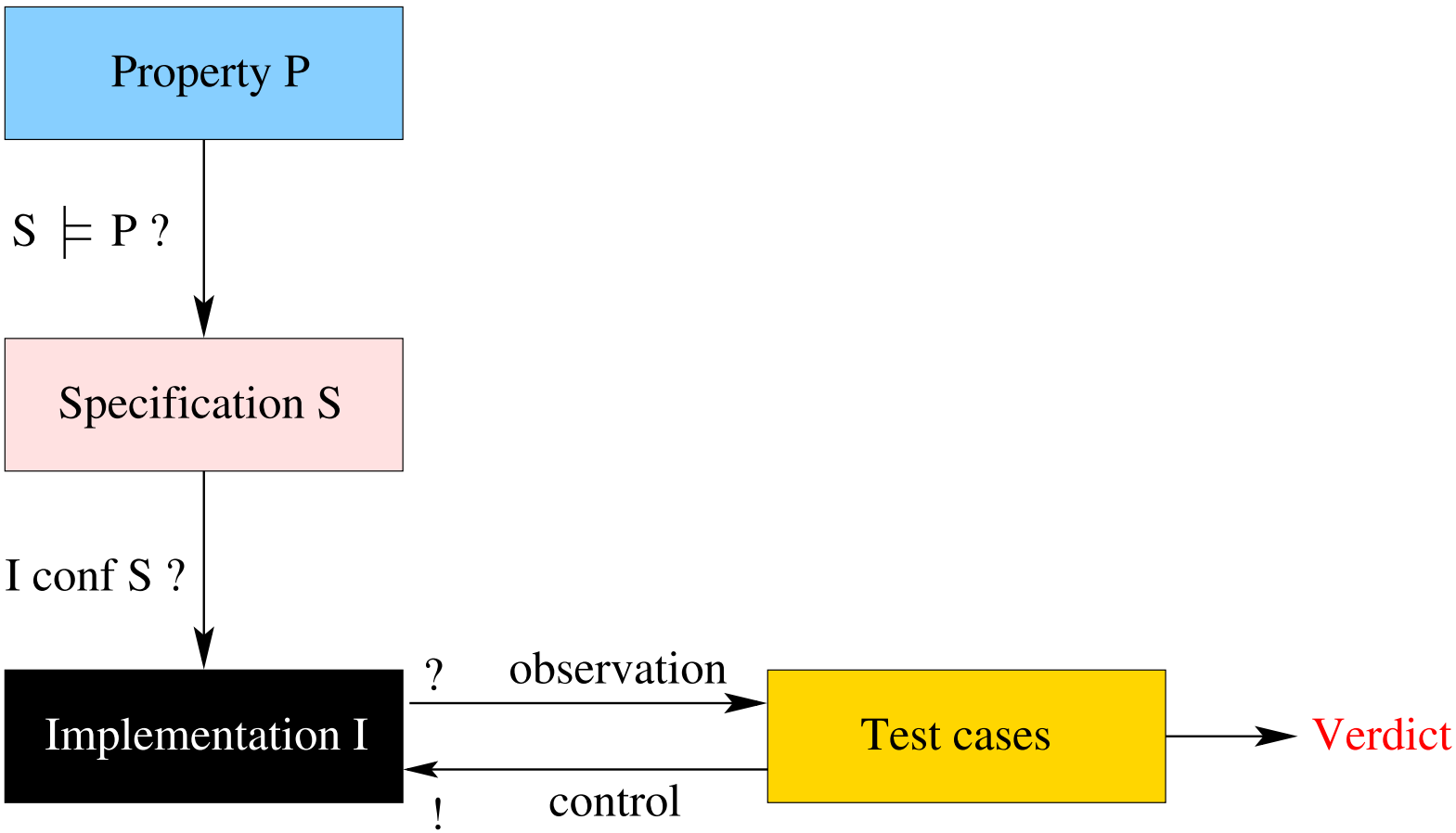

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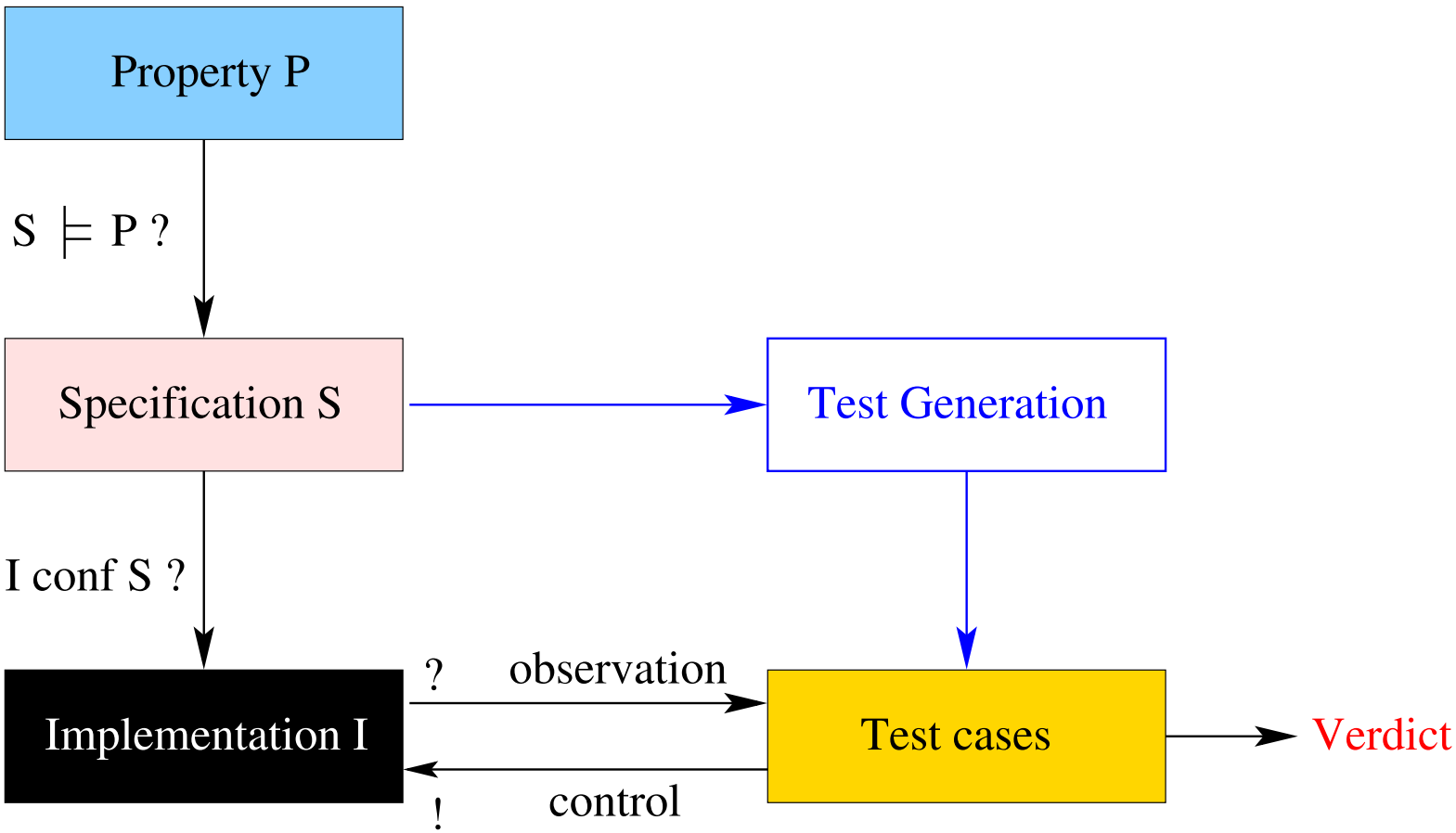

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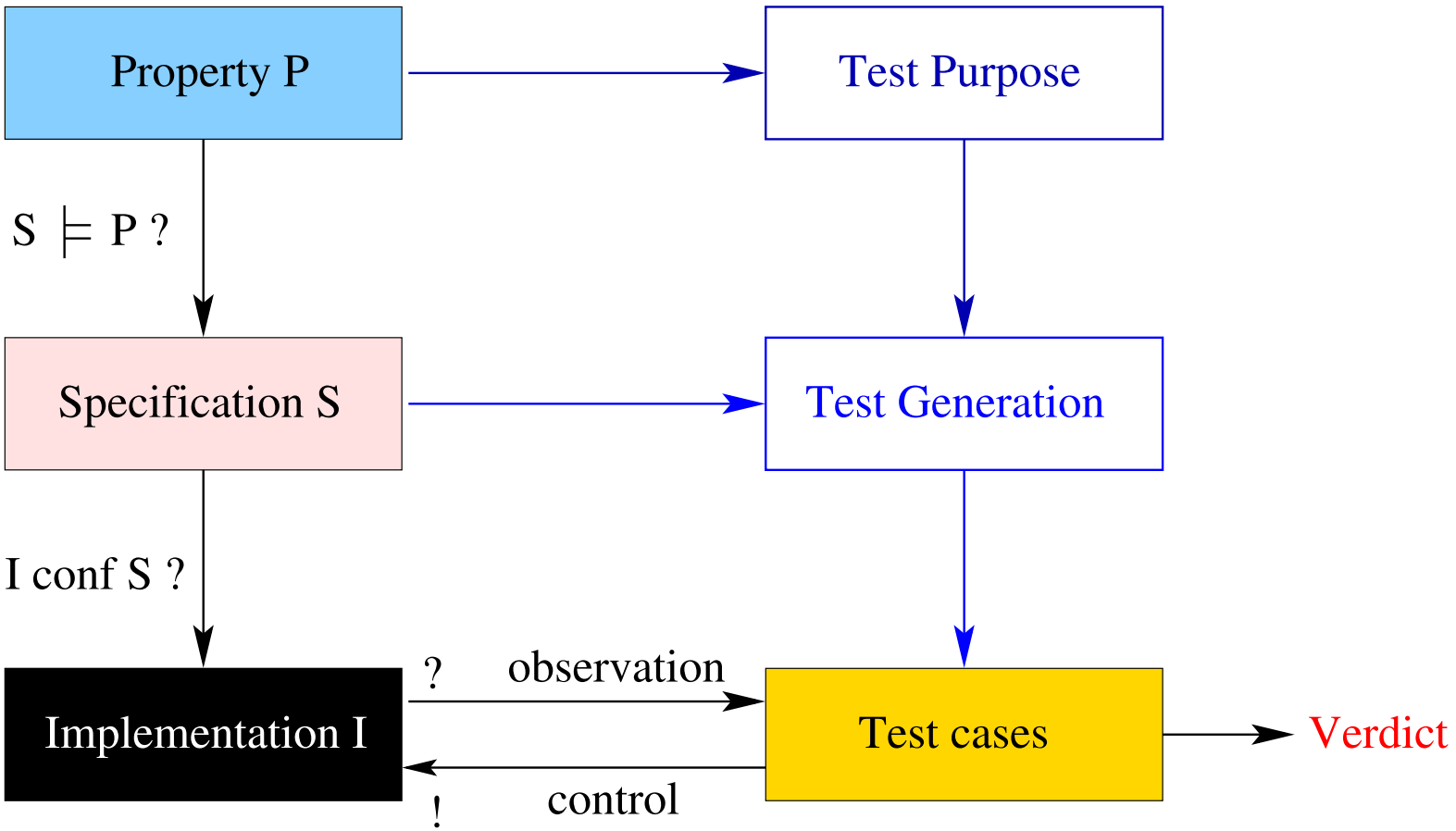


Main ingredients of a testing theory

Specification, implementation and conformance

Specification: model of requested behaviors,

Implementations: model of *observable* real behavior (unknown)

Conformance relation: formalizes "IUT conforms to Spec"

Tests cases and their executions

Test cases, test suites: model of tests (control/observation)

Test execution: interaction test $\leftrightarrow$ IUT, produced **observations**, associated **verdicts** (e.g. pass, fail)

Test suite properties: "IUT passes TS" $\leftrightarrow$ "IUT conf S"

Test generation

Algorithms : tests = testgen(Spec (+ TestPurpose))

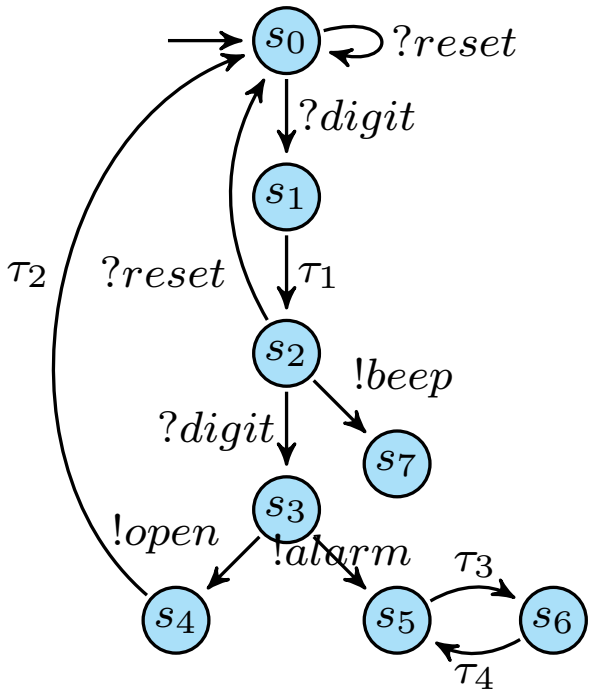
Outline

References

Part essentially based on :

- [Tre96] J. Tretmans, "Test generation with inputs, outputs, and repetitive quiescence," *Software–Concepts and Tools*, vol. 17, pp. 103–120, 1996.
- [JJ04] C. Jard and T. Jéron, "Tgv: theory, principles and algorithms, a tool for the automatic synthesis of conformance test cases for non-deterministic reactive systems," *Software Tools for Technology Transfer (STTT)*, 10 2004.
- [Jer04] T. Jéron, "Contribution à la génération automatique de tests pour les systèmes réactifs," 2004, habilitation à Diriger des Recherches - Université de Rennes 1.

Input Output Labelled Transition System (IOLTS)



$M = (Q^M, A^M, \longrightarrow_M, q_0^M)$ with :

- Q^M set of states
- $q_0^M \in Q^M$ initial state
- A^M action alphabet,
  - A_I^M input alphabet (with ?)
  - A_O^M output alphabet (with !)
  - I^M internal actions (τ_k)
- $\longrightarrow_M \subseteq Q^M \times A^M \times Q^M$ transition relation

$A_{VIS}^M = A_I^M \cup A_O^M$ set of visible actions

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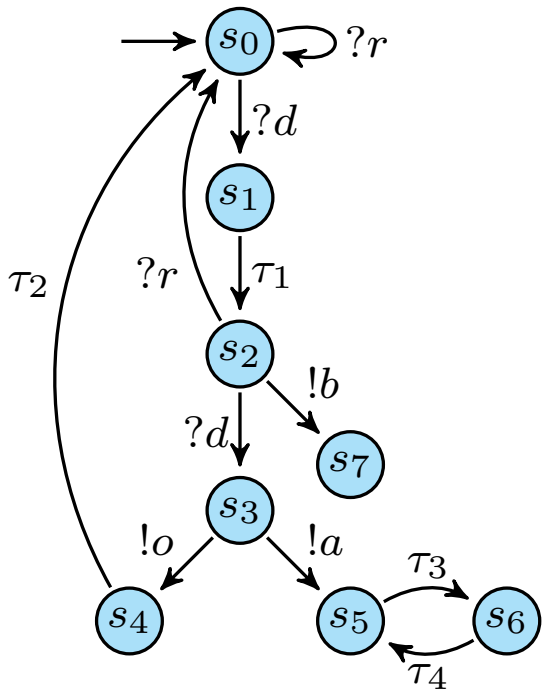

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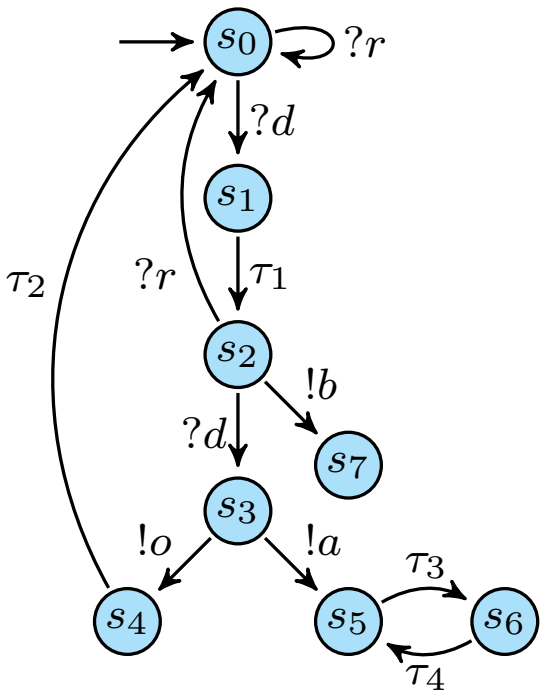
Runs / Traces



Runs: alternate sequences of states and actions fireable btw those states

$s_0 \xrightarrow{?d} s_1 \xrightarrow{\tau_1} s_2 \xrightarrow{?d} s_3 \xrightarrow{!o} s_4 \in Runs(M)$

$Traces$: projections of $Runs$ on visible actions:

$Traces(M) = \{\varepsilon, ?d, ?r, ?d.?r, ?r.?d, ?d.!b, ...\}$

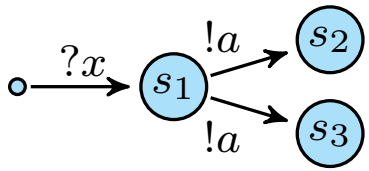
P after σ: set of states reachable from P after observation σ:

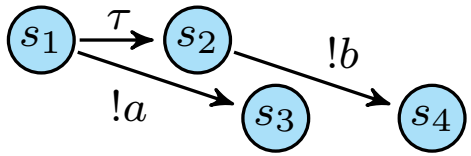
$\{s_2\}$ after $?d.!o = \{s_0, s_4\}$

$\{s_0\}$ after $?d, !a = \emptyset$

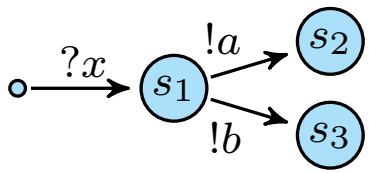
M after $\sigma \triangleq \{q_0\}$ after σ

Non-determinism





Not to be confused with uncontrolled choice



M is deterministic if it has no internal action,
and $\forall q, q', q'' \in Q, \forall a \in A_{VIS}, (q \xrightarrow{a} q' \wedge q \xrightarrow{a} q'') \Rightarrow q' = q''$

Determinization: $det(M) = (2^Q, A_{VIS}, \longrightarrow_{det}, q_0 \text{ after } \epsilon)$ with
$P \xrightarrow{a}_{det} P' \Leftrightarrow P, P' \in 2^Q, a \in A_{VIS}$ and $P' = P$ after a.

$$Traces(M) = Traces(det(M))$$

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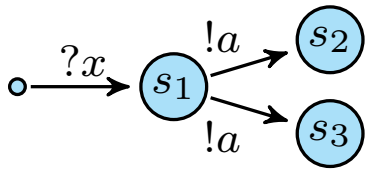

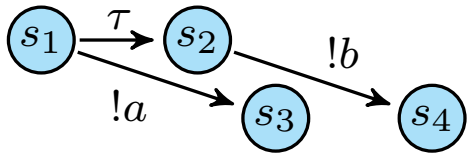

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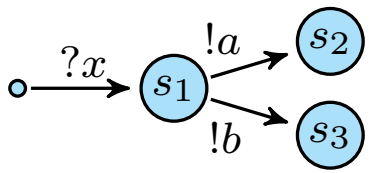

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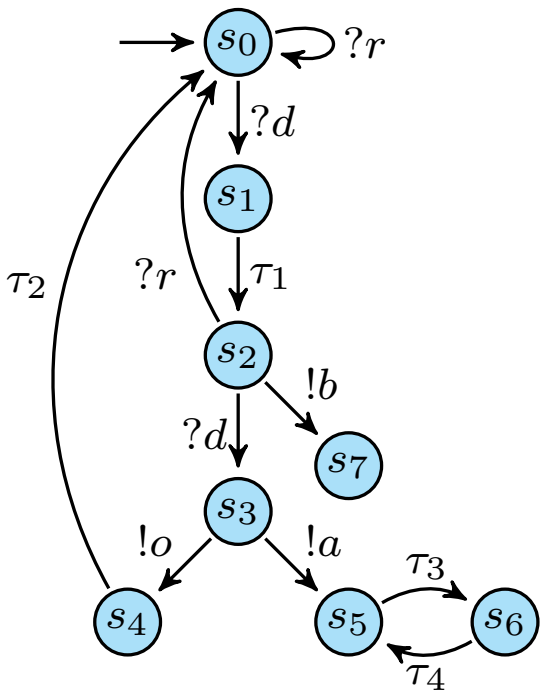
Observation of quiescence

In testing practice, one can observe traces of the IUT, but also its quiescences with timers.
Only quiescences of IUT unspecified in S should be rejected.



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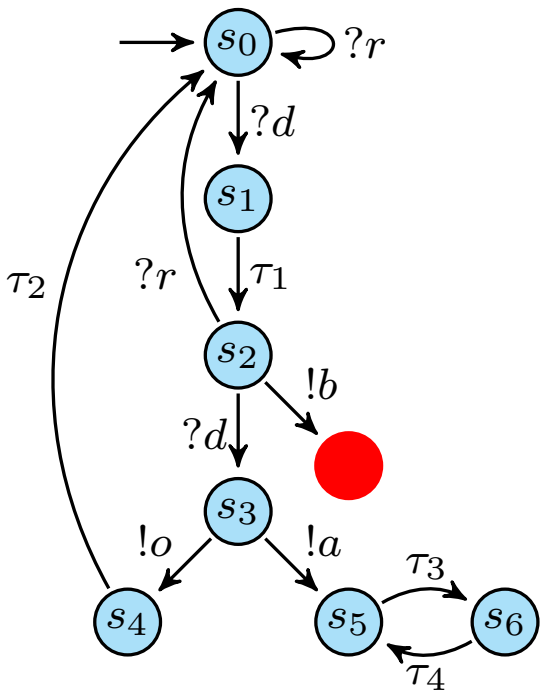

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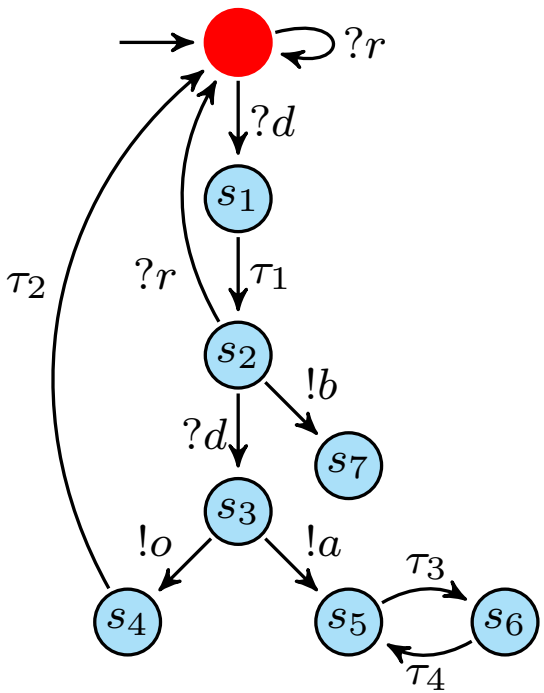

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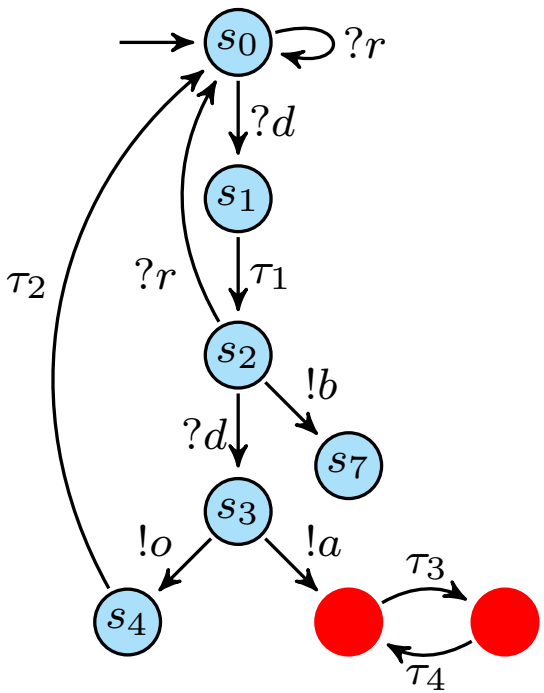

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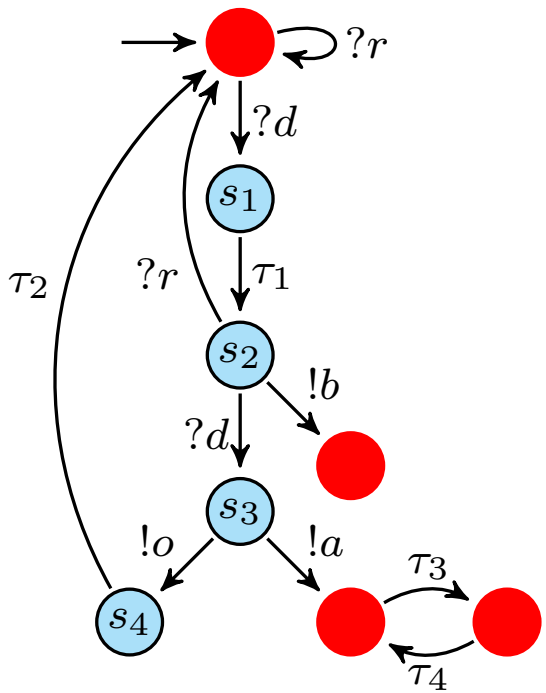

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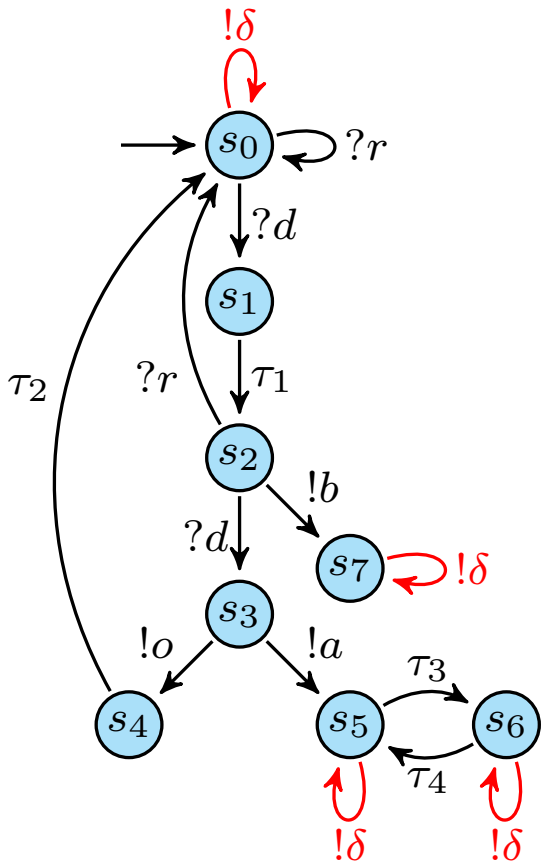
$$quiescent(M) = deadlock(M) \cup livelock(M) \cup outputlock(M)$$

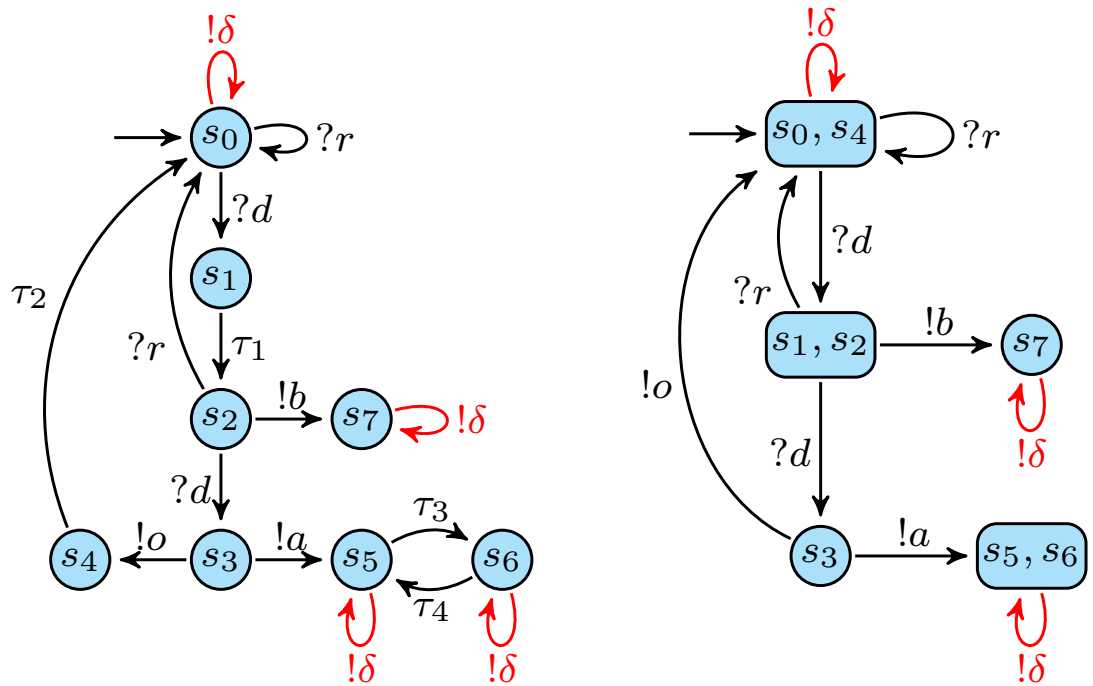
Suspension automaton

Quiescence : special output δ

The suspension ioLTS of $M = (Q, A, \longrightarrow, q_0)$ is an ioLTS $\Delta(M) = (Q, A \cup \{\delta\}, \longrightarrow_{\Delta(M)}, q_0)$ where $\longrightarrow_{\Delta(M)} = \longrightarrow \cup \{q \longrightarrow_\delta q | q \in quiescent(M)\}$.



Suspension traces



$\Delta(S)$ $det(\Delta(S))$

Suspension traces

$$STraces(M) \triangleq Traces(\Delta(M)) = Traces(det(\Delta(M)))$$

$STraces(S)$ and $STraces(I)$ represent visible behaviors of S and I for testing $\Rightarrow$ a base for the definition of conformance.

Testing framework

Specification : ioLTS $S = (Q^{\mathsf{S}}, A^{\mathsf{S}}, \longrightarrow_{\mathsf{S}}, s_0^{\mathsf{S}})$

Implementation : ioLTS $IUT = (Q^{\mathsf{IUT}}, A^{\mathsf{IUT}}, \longrightarrow_{\mathsf{IUT}}, s_0^{\mathsf{IUT}})$

Unknown implementation, except for its interface, identical to S's

Hyp.: IUT is input-complete : In any state, IUT accepts any input, possibly after internal actions.

Conformance relation

The conformance relation defines the set of implementations IUT conforming to S.

Conformance

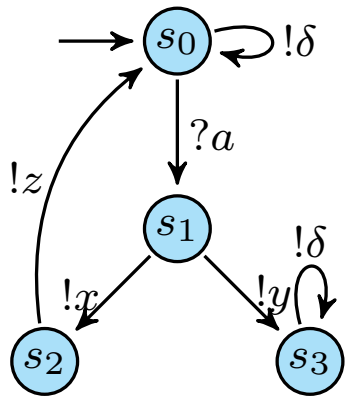
$$IUT \textbf{ ioco } S \triangleq \forall \sigma \in STraces(S), Out(\Delta(IUT) \text{ after } \sigma) \subseteq Out(\Delta(S) \text{ after } \sigma)$$

with $Out(P) \triangleq \Gamma(P) \cap A_O^\delta$ [a]: set of outputs $\wedge$ quiescences in P.

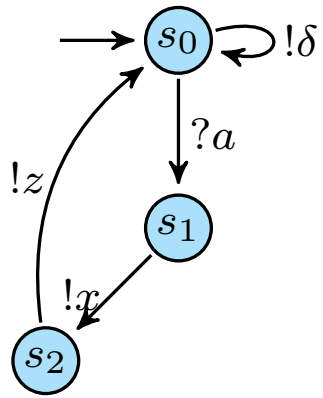
[a] A_O^δ is equivalent notation for A_O since δ is an output of $\Delta(S)$ and $\Delta(IUT)$

Intuition : IUT conforms to S iff after any suspension trace of S and IUT, all outputs and quiescences of IUT are specified by S.

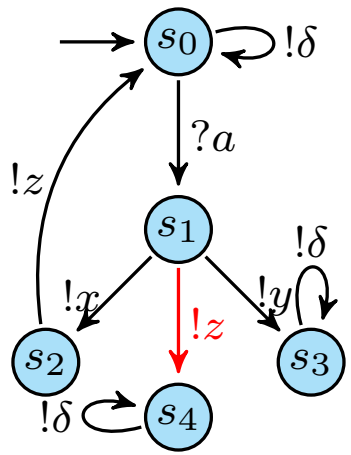
ioco: example



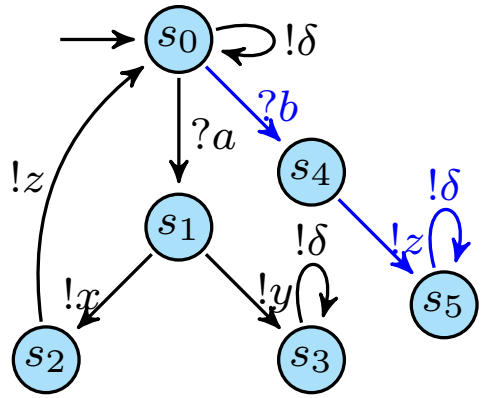
specification $\Delta(S)$



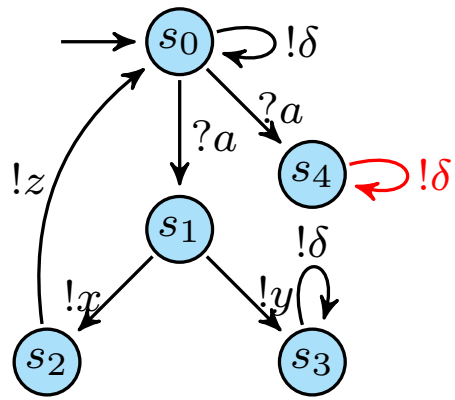
I_1: Implem. choice



I_3: Unspec. output



I_2: Implem. of a partial spec.



I_4 : Unspec. quiescence

Canonical Tester

From S (more precisely from $det(\Delta(S)) = (Q^{\mathsf{d}}, A^{\mathsf{d}}, \longrightarrow_{\mathsf{d}}, q_0^{\mathsf{d}})$), build an ioLTS $Can(S) = (Q^{\mathsf{c}}, A^{\mathsf{c}}, \longrightarrow_{\mathsf{c}}, q_0^{\mathsf{c}})$ $\rightarrow$ the most general ioLTS permitting to detect non-conformance of implementation IUT.

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- $Q^c = Q^d \cup \{\textbf{Fail}\}$ and $q_0^c = q_0^d$
- $A^c = A_I^c \cup A_O^c$ where $A_I^c = A_O^d$ and $A_O^c = A_I^d$ input / output inversion
- $\longrightarrow_c = \longrightarrow_d \cup \{q \xrightarrow{a}_c \textbf{Fail} \mid q \in Q^d, a \in A_I^c \wedge \neg(q \xrightarrow{a}_d)\}$, all non-specified outputs lead to **Fail**.

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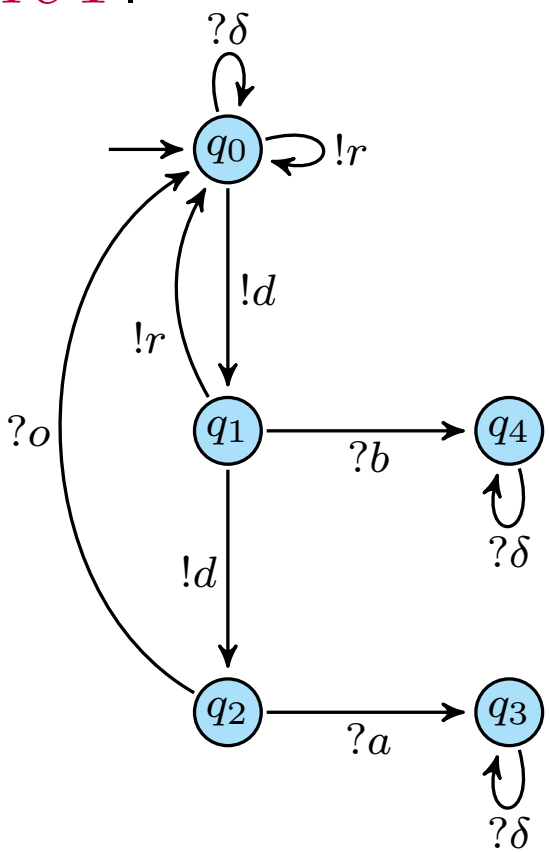

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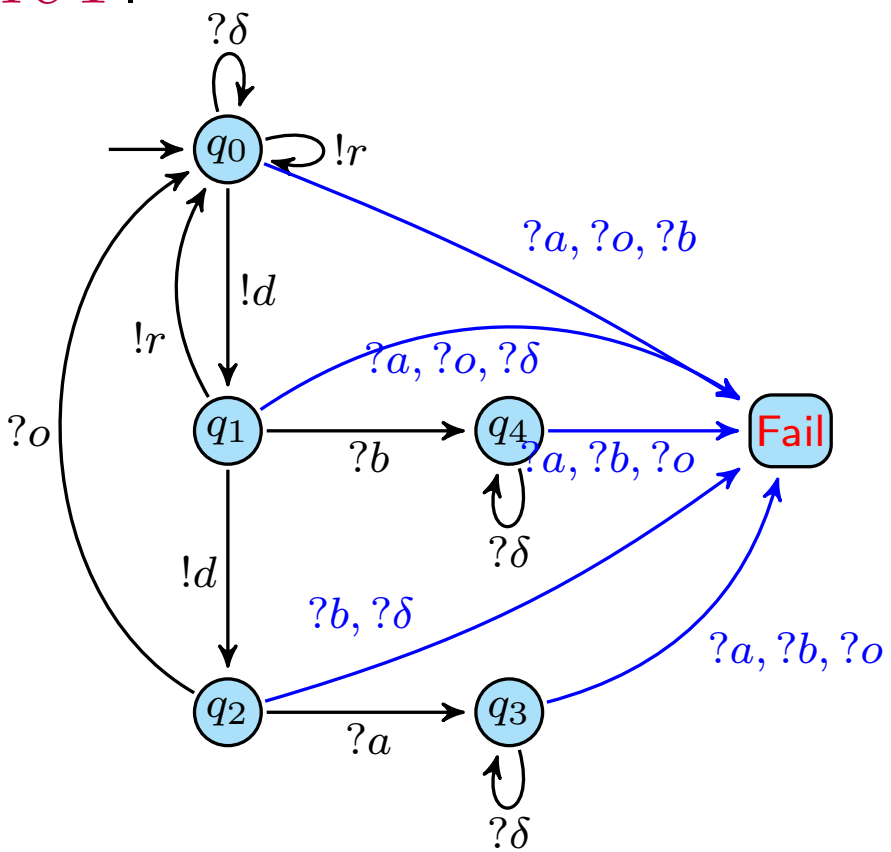

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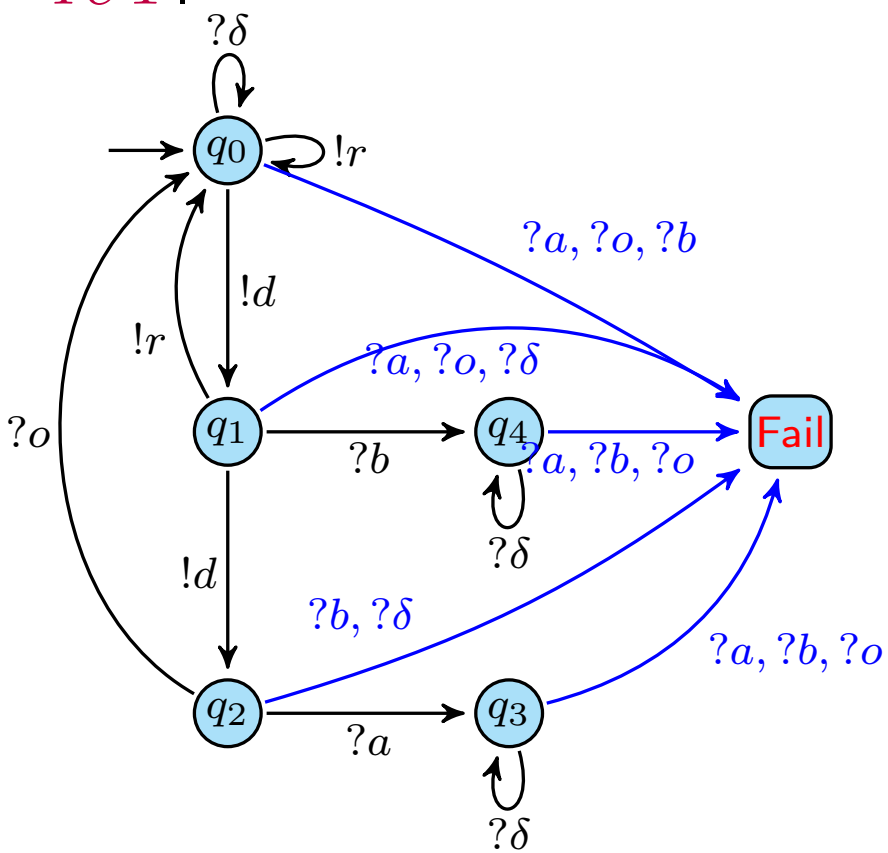
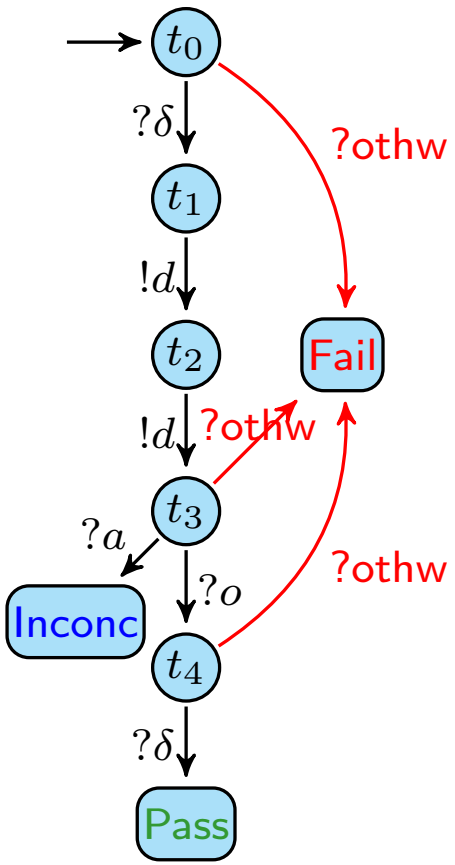


IUT **ioco** $S \iff$
$STraces(IUT) \cap$
$Traces_{\mathsf{Fail}}(Can(S)) = \emptyset$

Test cases

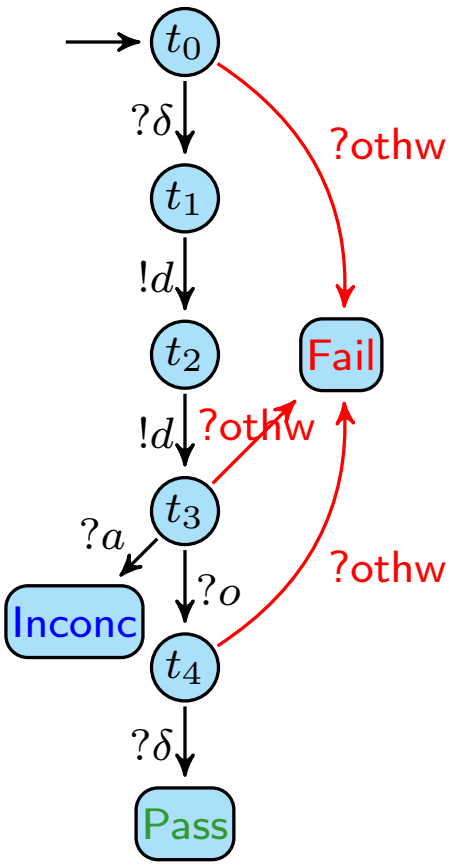
A test case is a deterministic ioLTS $(Q^{\mathsf{TC}}, A^{\mathsf{TC}}, \longrightarrow_{\mathsf{TC}}, t_0^{\mathsf{TC}})$, equipped with **verdict** states: Pass, Fail and Inconc s.t.

- $A_O^{\mathsf{TC}} = A_I^{\mathsf{S}}$ and $A_I^{\mathsf{TC}} = A_O^{\mathsf{S}} \cup \{\delta\}$ (input / output inversion)
- TC is controllable, i.e. never have to choose btw. several outputs or btw. inputs and outputs : $\forall q \in Q^{\mathsf{TC}}, (\exists a \in A_O^{\mathsf{TC}}, q \xrightarrow{a}_{\mathsf{TC}} \Rightarrow \forall b \in A^{\mathsf{TC}}, (b \neq a \Rightarrow q \not\xrightarrow{b}_{\mathsf{TC}}))$
- All states permitting an input, are input-complete, except verdict states.

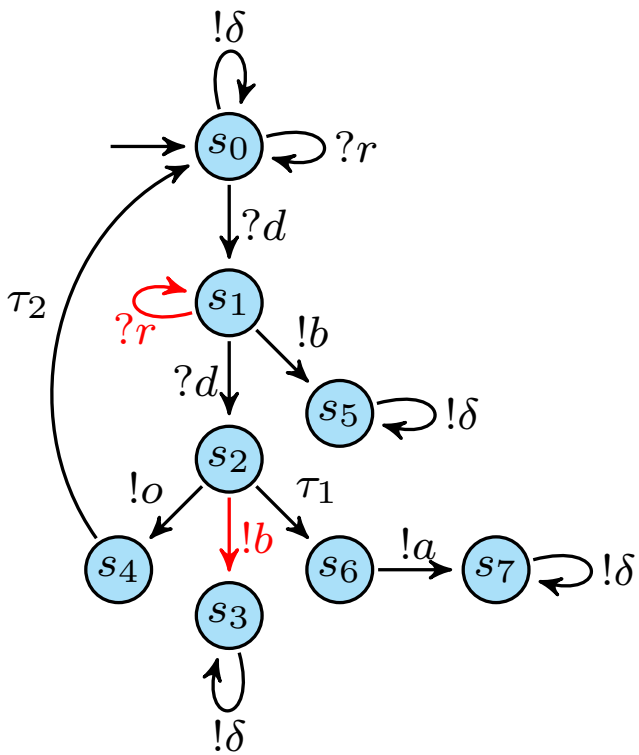


Test execution

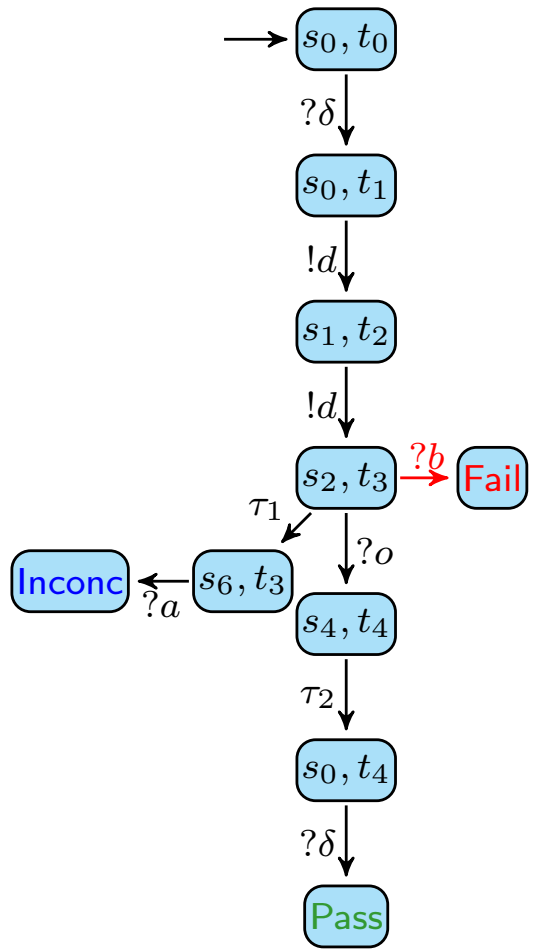
Modelled by the parallel composition $TC \| \Delta(IUT)$ synchronizing on common visible actions



$TC1$



$\Delta(IUT)$



$TC1 \| \Delta(IUT)$

Properties of test suites

TC fails IUT iff an execution of $TC \| \Delta(IUT)$ reaches **Fail**

Expresses a *possibility* for rejection.

Due to non-controllable choices of IUT, a single test case applied on a single Implementation can produce all different verdicts !

Soundness, Exhaustiveness, Completeness

A set of test cases TS is

- *Sound* $\triangleq$
  $\forall IUT : (IUT \textbf{ ioco } S \implies \forall TC \in TS : \neg(TC \ fails \ IUT))$,
  i.e. only non-conformant IUT may be rejected by a $TC \in TS$.
- *Exhaustive* $\triangleq$
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- Complete = Sound and Exhaustive

Test selection

Objective : Find an algorithm taking as input a finite state ioLTS S, and satisfying the following properties:

- produces only sound test suites
- is limit-exhaustive i.e. the infinite suite of test cases that can be produced is exhaustive

Two techniques :

1. Non-deterministic selection (à la TorX)
2. Selection guided by a test purpose (à la TGV)

Non-deterministic selection

Algorithm: partial unfolding of $Can(S)$

Start in q_0^c. After any trace σ in $Can(S)$

- if $Can(S)$ after $\sigma \subseteq$ **Fail**, emit a Fail verdict
- otherwise make a choice between
  - produce a Pass verdict and stop,
  - consider all inputs of $Can(S)$ after σ and continue.
  - choose one output in those of $Can(S)$ after σ and continue.

Properties

TS = all possible Test cases generated with this algorithm :
TS is sound and limit-exhaustive

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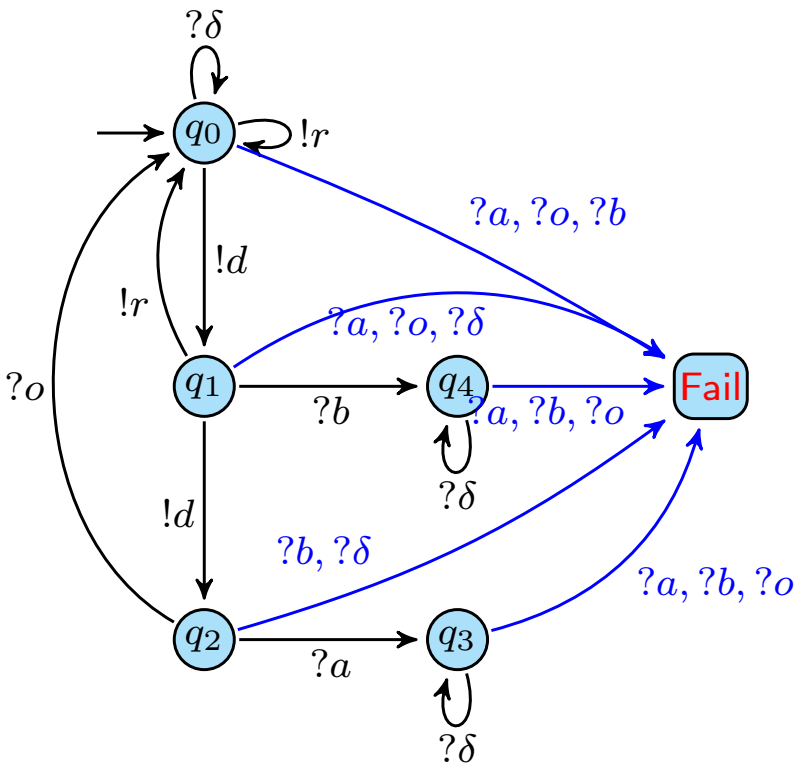
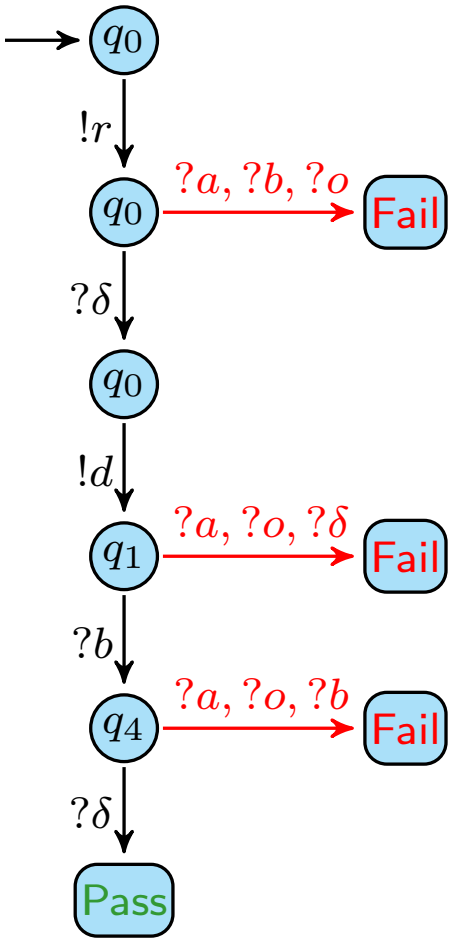
Examples

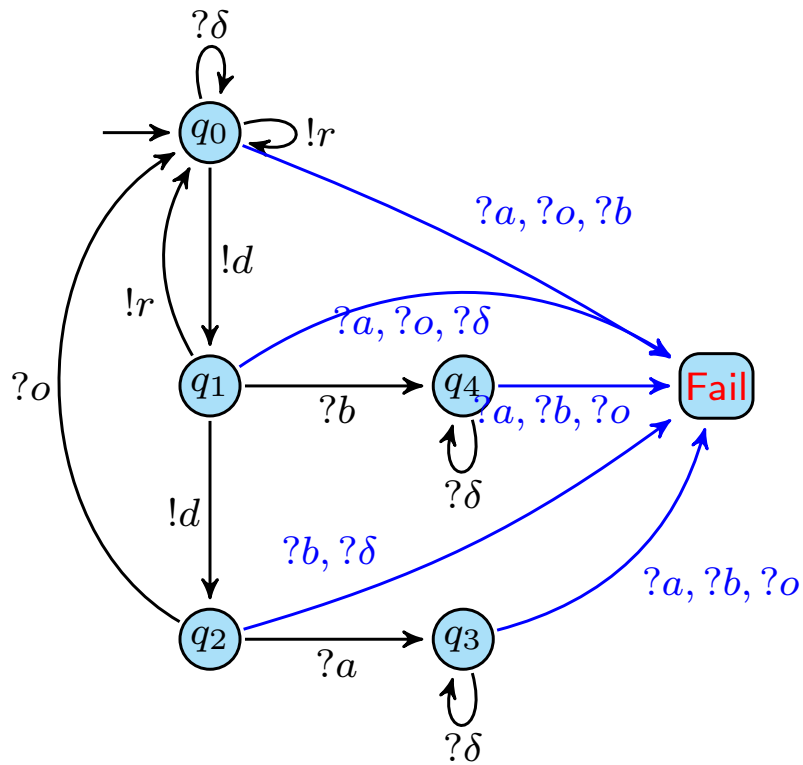


$Can(S)$

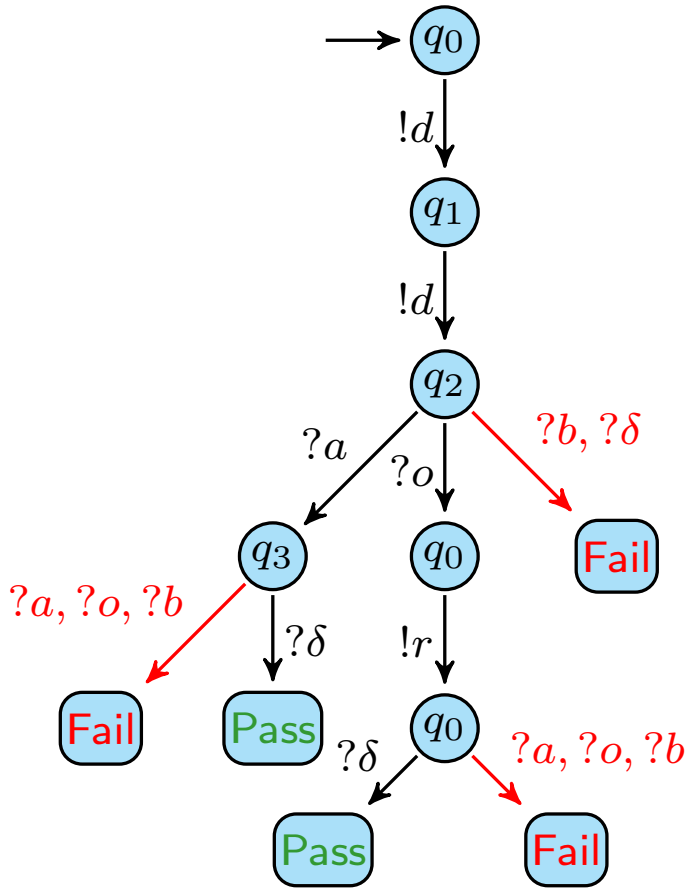


$TC1$

Examples



$Can(S)$



$TC2$

Test Purpose generation

Previous algorithm : maybe quite long if we intend to focus on a specific behavior...

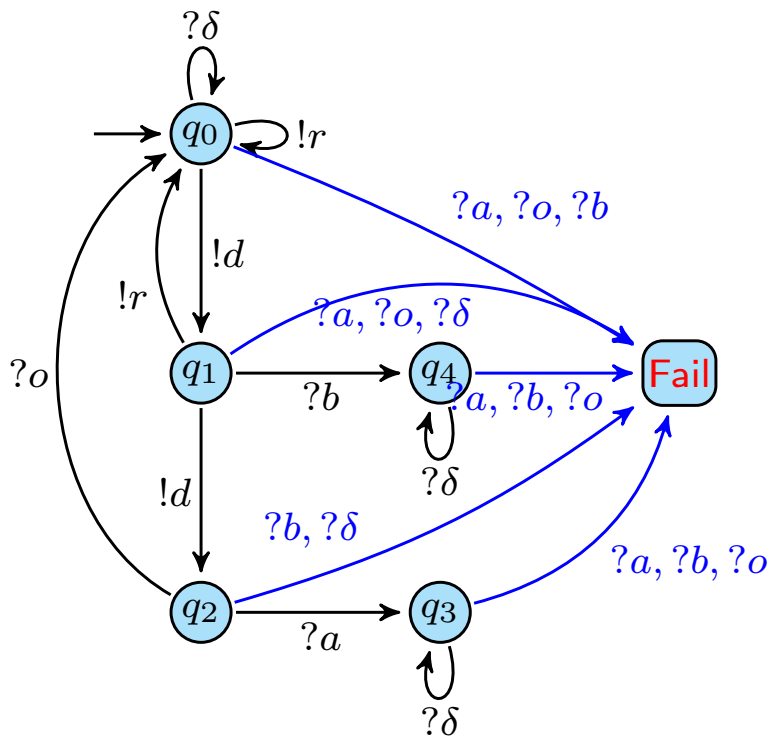
Main characteristics of Test Purpose Generation:

- test selection by test purposes describing a set of behaviors to be tested, targeted by a test case,
- off-line selection, *a posteriori* execution.

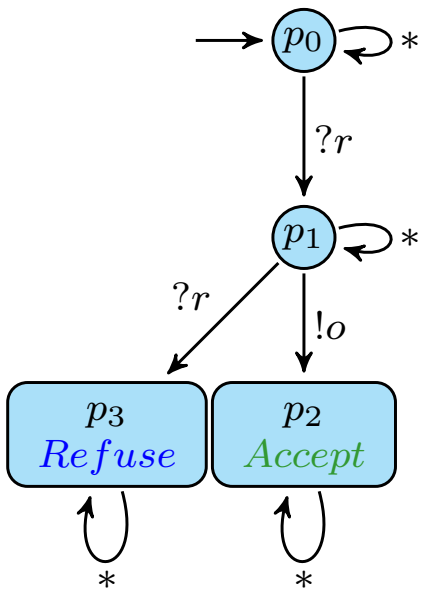
Test Purpose definition

Test Purpose

Deterministic and complete ioLTS $TP = (Q^{\mathsf{TP}}, A^{\mathsf{TP}}, \longrightarrow_{\mathsf{TP}}, q_0^{\mathsf{TP}})$ equipped with two sets $Accept^{\mathsf{TP}}$ and $Refuse^{\mathsf{TP}}$ of trap states, s.t. $A^{TP} = A^S_{VIS} \cup \{\delta\}$

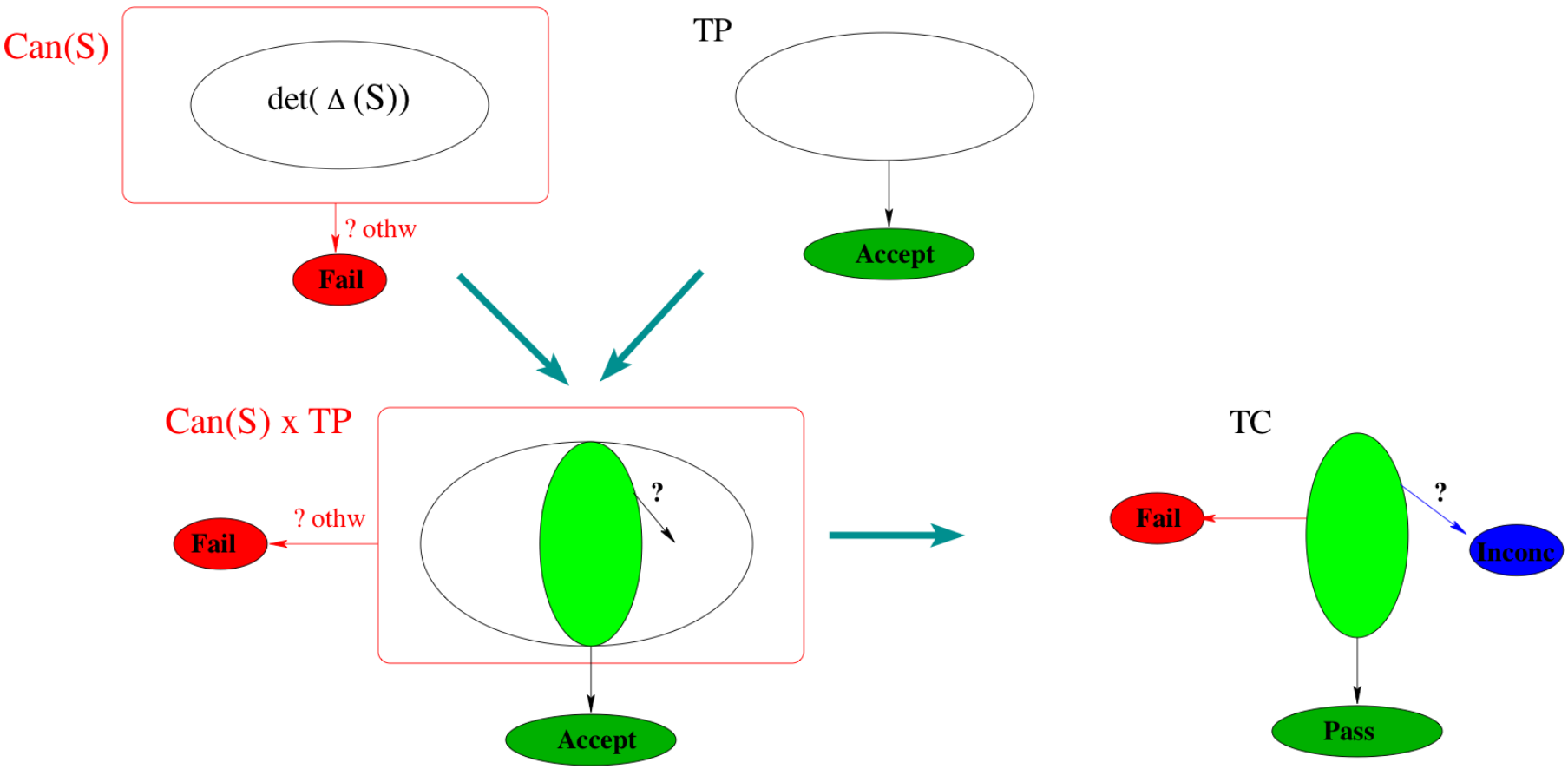


$Can(S)$



TP

Selection principle



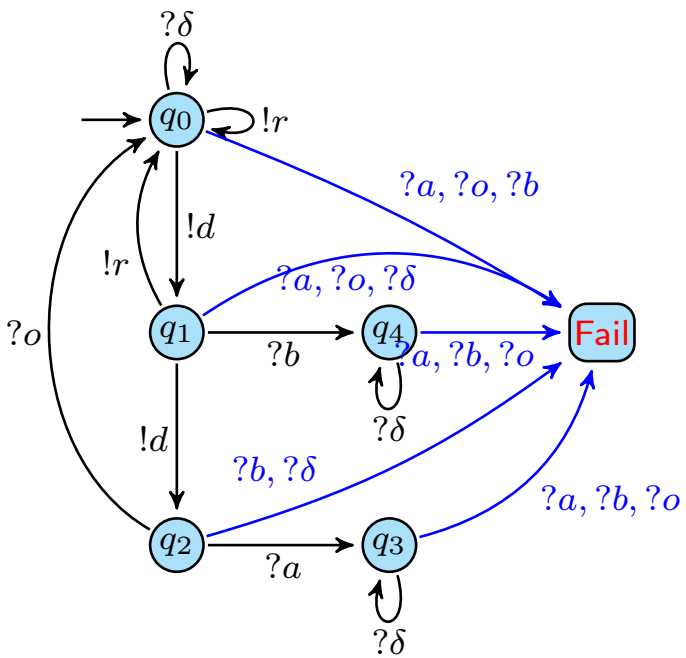
Synchronous Product : definition

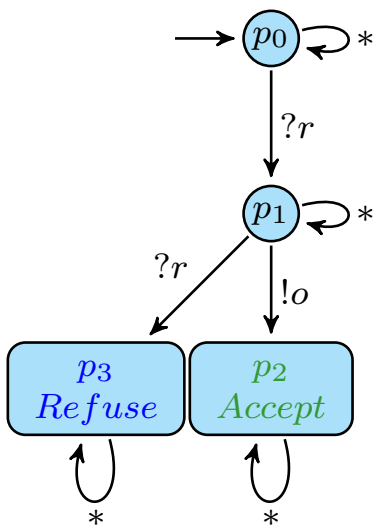
Definition of Synchronous Product

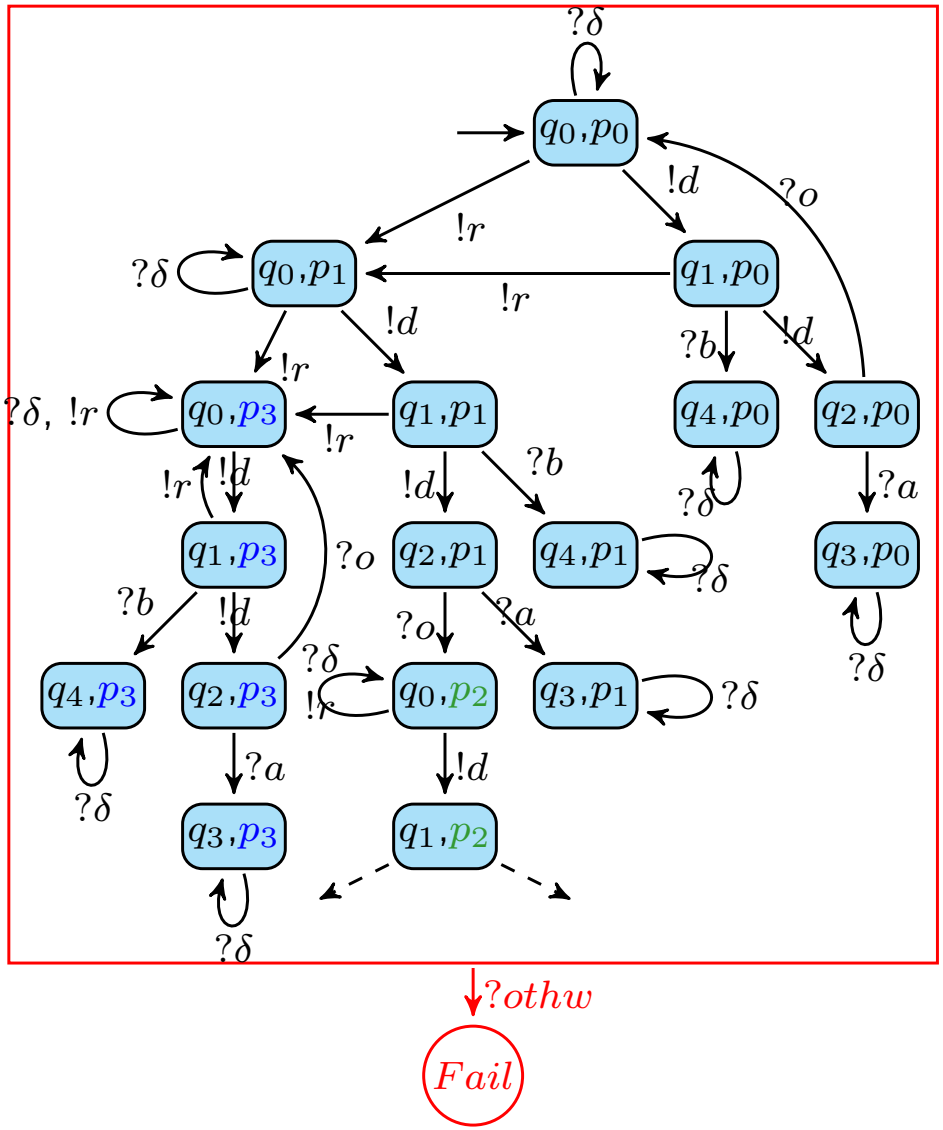
The Synchronous Product of two ioLTS $M_1 = (Q^{M1}, A, \longrightarrow_{M1}, q_0^{M1})$, and $M_2 = (Q^{M2}, A, \longrightarrow_{M2}, q_0^{M2})$ is the ioLTS $M_1 \times M_2 = (Q^{M1} \times Q^{M2}, A, \longrightarrow, q_0^{M1} \times q_0^{M2})$ where $\longrightarrow$ is defined by :

$$(q_{M1}, q_{M2}) \xrightarrow{a} (q'_{M1}, q'_{M2}) \Leftrightarrow (q_{M1} \xrightarrow{a}_{M1} q'_{M1}) \wedge (q_{M2} \xrightarrow{a}_{M2} q'_{M2})$$

The Synchronous Product $Can(S) \times TP$

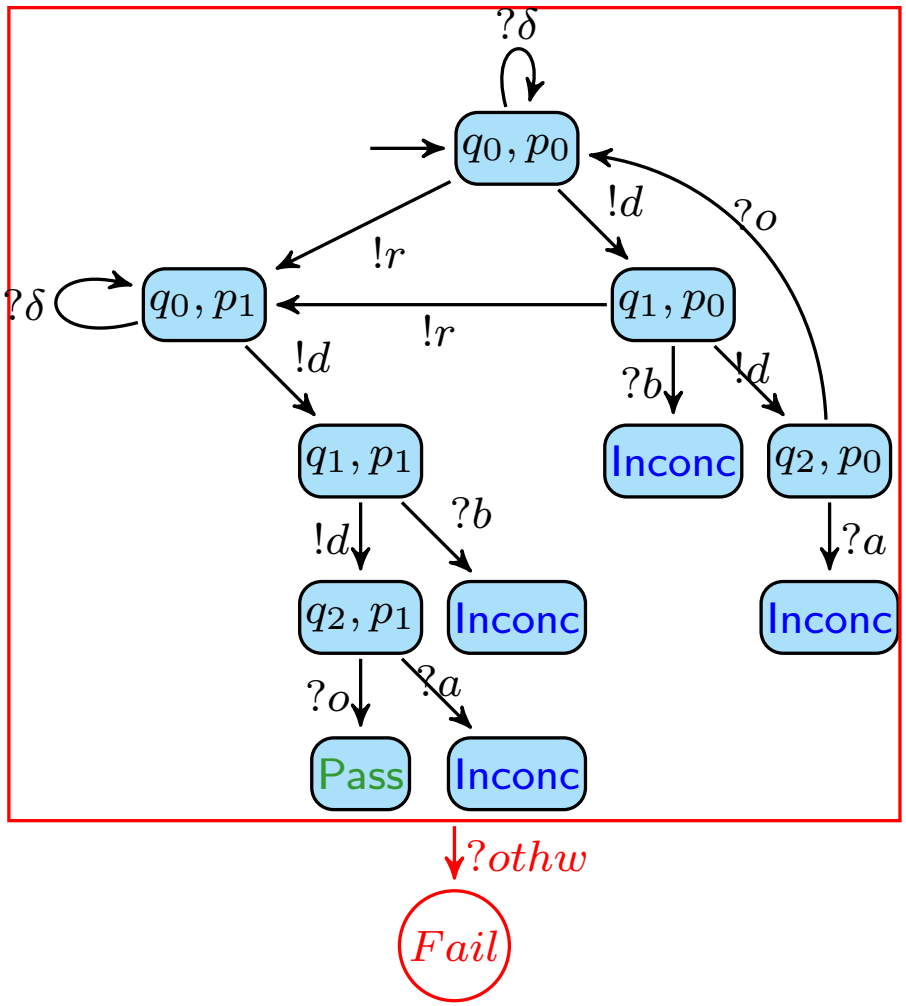




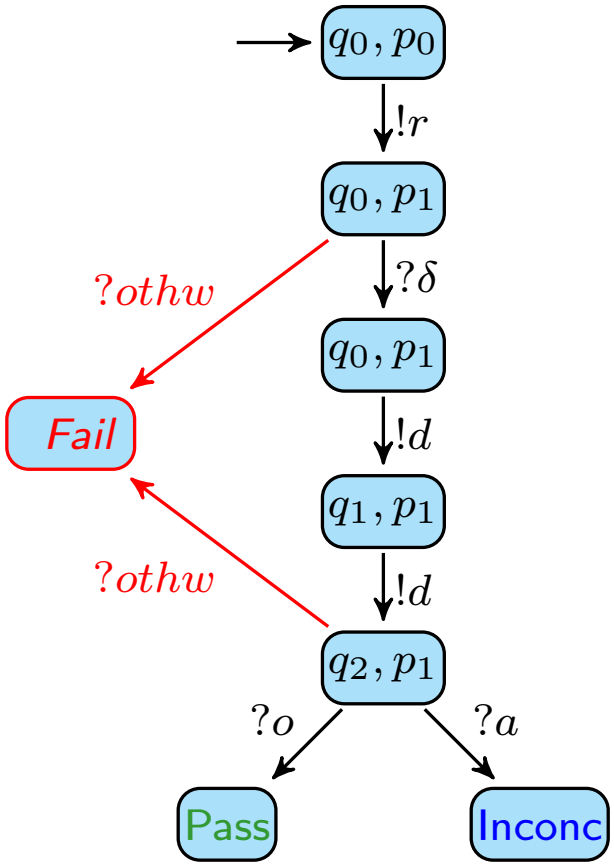


Complete Test Graph (CTG)

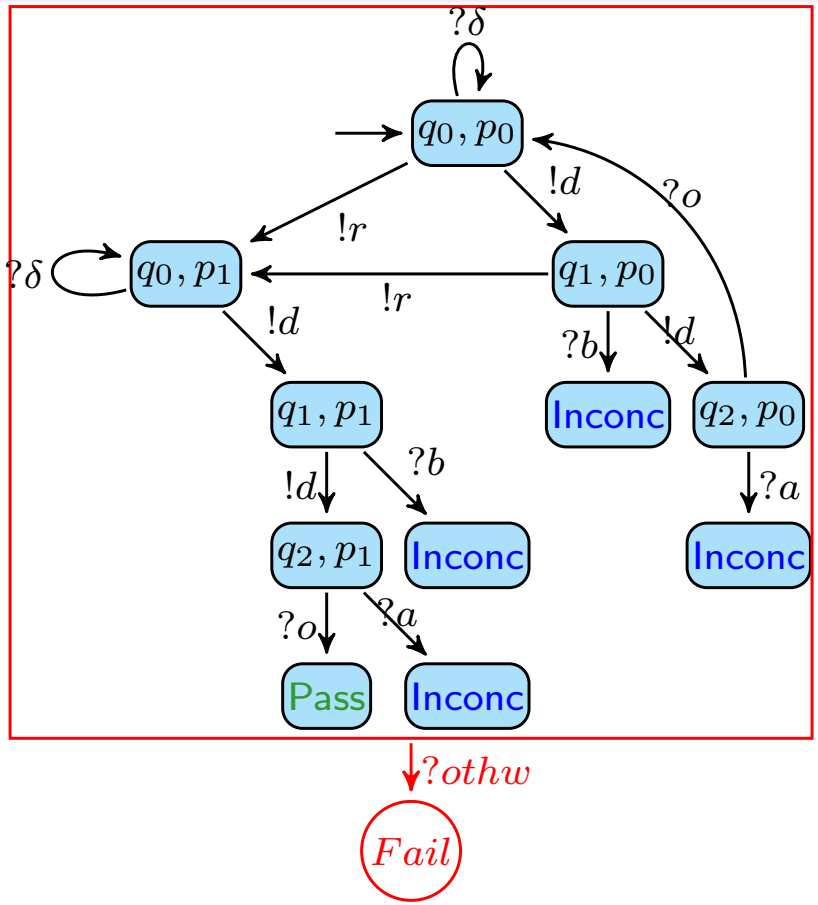
- Keep the first $Accept$ state in a path
- If $q \in coreach(Pass)$ keep q
- If $q \in \{Fail\}$ keep q
- If $q \notin coreach(Pass)$ input (tester point of view) successor of a state $q' \in coreach(Pass)$ then $Inconc$



Ensuring controlabillity of test cases



Example of Test Case



The test suite composed of the set of test cases that the algorithm can produce is sound and limit-exhaustive.

Conclusion

- Testing theory for ioLTS
- Test generation for **finite** ioLTS
  - Non-deterministic selection: unfolding of $Can(S)$
  - Selection by test purpose: for finite ioLTS based on co-reachability analysis.
  - Soundness and exhaustiveness.

Outline

References

Part essentially based on :

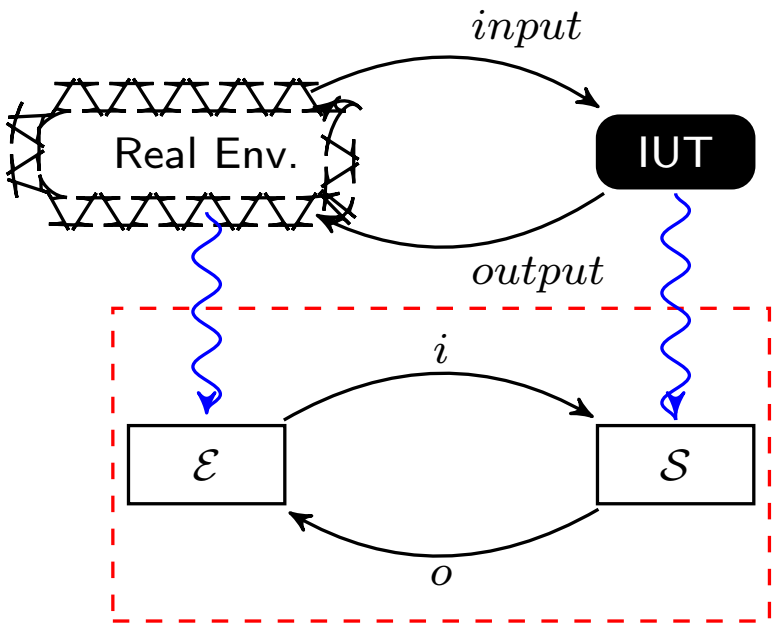
- [HLMNPS08] A. Hessel, K. Larsen, M. Mikucionis, B. Nielsen, P. Pettersson, and A. Skou, "Testing real-time systems using uppaal," in *Formal Methods and Testing*, LNCS, vol. 4949. Springer Berlin / Heidelberg, 2008, pp. 77–117.
- [MLN04] M. Mikucionis, K. G. Larsen, and B. Nielsen, "T-uppaal: Online model-based testing of real-time systems," in *19th IEEE International Conference on Automated Software Engineering (ASE 2004), 20-25 September 2004, Linz, Austria*. IEEE Computer Society, 2004, pp. 396–397.
- [KT04] M. Krichen and S. Tripakis, "Black-box conformance testing for real-time systems," in *Model Checking Software, 11th International SPIN Workshop, Barcelona, Spain, April 1-3, 2004*, LNCS vol. 2989. Springer, 2004, pp. 109–126.

Main lines

- Need a "new" model to describe real-time aspects : Timed Automata with Inputs and Outputs... and semantics.
- Need a "new" conformance relation : **rtioco**
- Non-deterministic online test generation
- Discussion about offline test generation

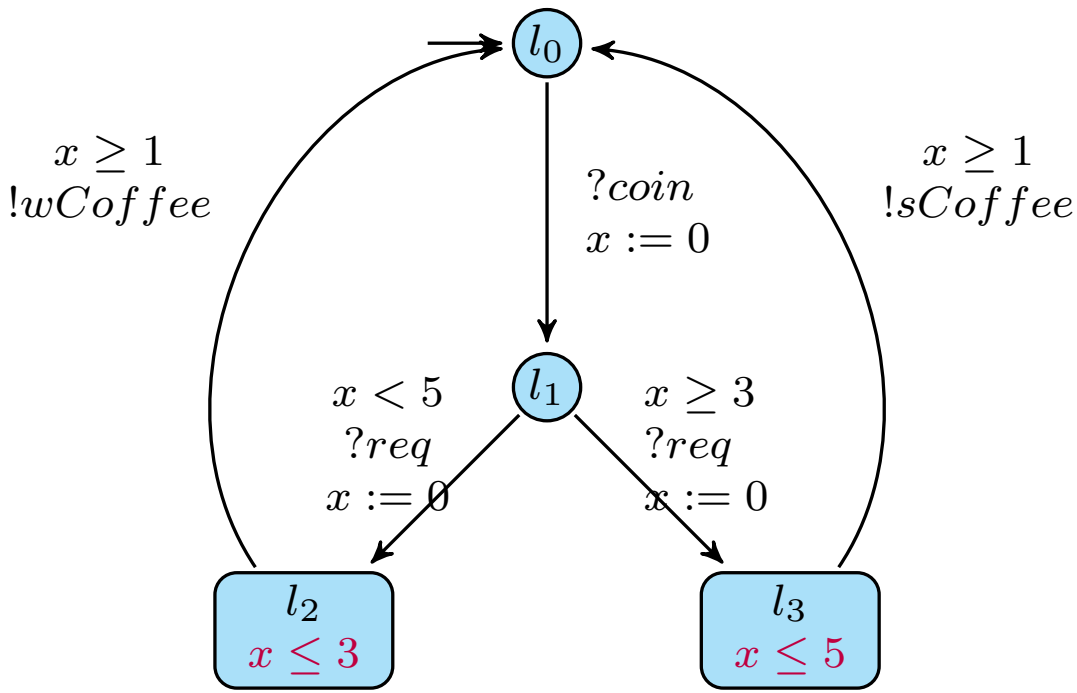
"Uppaal-like" approach

Explicit and separate model of the environment



+ test generation tool can synthesize only relevant scenario
+ designer can lead the test to specific situations

Timed Automaton



Semantics defined in terms of TIOTS.
Possibly non-deterministic

Timed Input Output Transition System (TIOTS)

Given a set of actions A, divided in A_{out} and A_{in}, and $\tau \notin A$. $(A_\tau \triangleq A \cup \{\tau\})$

if no precision is given, in the following $a_{[k]}$ is an action, $d_{[k]}$ is a delay

TIOTS definition

$\mathcal{S} = (S, s_0, A_{in}, A_{out}, \longrightarrow)$ where :

- S set of states, $s_0 \in S$ the initial state
- $\longrightarrow \subseteq S \times (A_\tau \cup \mathbb{R}_{\geq 0}) \times S$ transition relation with
  - time determinism : $(s \xrightarrow{d} s' \wedge s \xrightarrow{d} s'') \Rightarrow s' = s''$
  - time additivity : $(s \xrightarrow{d_1} s' \wedge s' \xrightarrow{d_2} s'') \Rightarrow s \xrightarrow{d_1+d_2} s''$
  - zero-delay : $\forall s, s \xrightarrow{0} s$

Testing point of view : Timed Traces are considered, e.g. $\sigma = ?coin \cdot 1 \cdot ?req \cdot 2 \cdot !wCoffee \cdot 9 \cdot ?coin$

Notations / Definitions

- $s \stackrel{a}{\Rightarrow} s'$ iff $s \xrightarrow{\tau}{}^{*} \xrightarrow{a} \xrightarrow{\tau}{}^{*} s'$
- $s \stackrel{d}{\Rightarrow} s'$ iff $s \xrightarrow{\tau}{}^{*} \xrightarrow{d_1} \xrightarrow{\tau}{}^{*} \xrightarrow{d_2} \xrightarrow{\tau}{}^{*} \ldots \xrightarrow{\tau}{}^{*} \xrightarrow{d_n} \xrightarrow{\tau}{}^{*} s'$ where $d = \sum_{k=1}^{n} d_k$
- usually generalized to sequences

Observable Timed Traces $TTr(s)$

$TTr(s) = \{\sigma \in (A \cup \mathbb{R}_{\geq 0})^* | s \stackrel{\sigma}{\Rightarrow}\}$

Example : $\sigma = ?coin \cdot 1 \cdot ?req \cdot 2 \cdot !wCoffee \cdot 9 \cdot ?coin$

After

s After $\sigma = \{s' | s \stackrel{\sigma}{\Rightarrow} s'\}$, $\quad S'After\sigma = \bigcup_{s \in S'} s$ After σ

Out

$Out(s) = \{a \in A_{out} \cup \mathbb{R}_{\geq 0} | s \stackrel{a}{\Rightarrow}\}$ $\quad Out(S') = \bigcup_{s \in S'} Out(s)$

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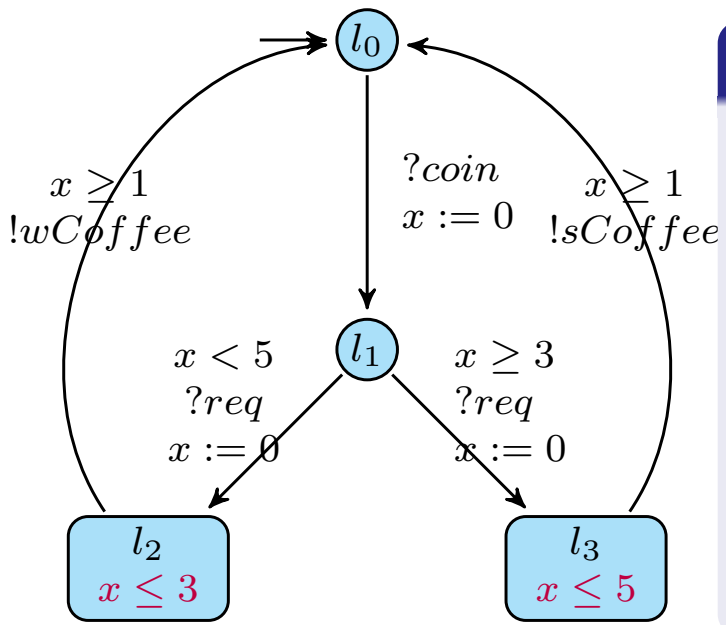
Timed Automata (with Inputs and Outputs) : definition



Given X set of clock variables, $\mathcal{G}(X)$ set of guards, $\mathcal{U}(X)$ set of updates.

Timed Automaton

$TA = (L, l_0, I, E)$ where

- L set of locations, l_0 initial location
- $I : L \to \mathcal{G}(X)$ assigns invariants to locations
- $E \subseteq L \times \mathcal{G}(X) \times A_\tau \times \mathcal{U}(X) \times L$ set of edges (written $l \xrightarrow{g,\alpha,u} l'$)

Observable trace example : $\sigma = ?coin \cdot 6 \cdot ?req \cdot 3 ...$

$Out(?coin \cdot 6 \cdot ?req \cdot 3) = \{sCoffee\} \cup [0, 2]$

Semantics of Timed Automata

Semantics as a TIOTS defined by :

- States of the form $s = (l, \overline{v})$, s.t.
  - l is a location
  - $\overline{v} \in \mathbb{R}^X_{\geq 0}$ clock valuation satisfying invariant of l
- Delay transitions

$$\frac{\forall d' \leq d . I_l(d')}{(l, \overline{v}) \xrightarrow{d} (l, \overline{v} + d)}$$

- Discrete transitions

$$\frac{l \xrightarrow{g,\alpha,u} l' \wedge g(\overline{v}) \wedge I_{l'}(\overline{v'}), \overline{v'} = u(\overline{v})}{(l, \overline{v}) \xrightarrow{\alpha} (l', \overline{v'})}$$

most reasoning done on the semantics

Relativized timed conformance

- $\mathcal{S} = (S^{\mathcal{S}}, s_0^{\mathcal{S}}, A_{in}, A_{out}, \longrightarrow_{\mathcal{S}})$ a weakly input enabled (i.e. $\forall s \in S^{\mathcal{S}}, \forall i \in A_{in}, s \stackrel{i}{\Rightarrow}$) TIOTS
- $\mathcal{IUT} = (S^{\mathcal{IUT}}, s_0^{\mathcal{IUT}}, A_{in}, A_{out}, \longrightarrow_{\mathcal{IUT}})$ a weakly input enabled TIOTS
- $\mathcal{E} = (E^{\mathcal{E}}, e_0^{\mathcal{E}}, A_{out}, A_{in}, \longrightarrow_{\mathcal{E}})$ (input / output inversion) weakly input enabled TIOTS.

rtioco$_e$

Let $s \in S^{\mathcal{S}}$, $e \in E^{\mathcal{E}}$ and $iut \in S^{\mathcal{IUT}}$:

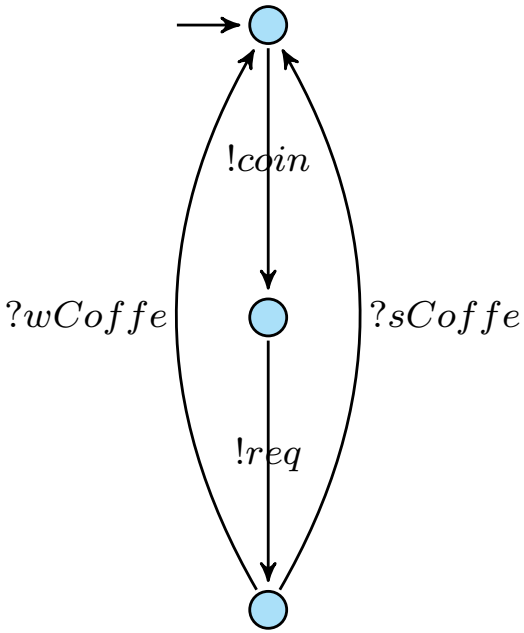
$$iut \textbf{ rtioco}_e \ s$$
iff
$$\forall \sigma \in TTr(e), Out((iut, e) \text{ After } \sigma) \subseteq Out((s, e) \text{ After } \sigma)$$
iff
$$TTr(iut) \cap TTr(e) \subseteq TTr(s) \cap TTr(e)$$

Relativized timed conformance (2)

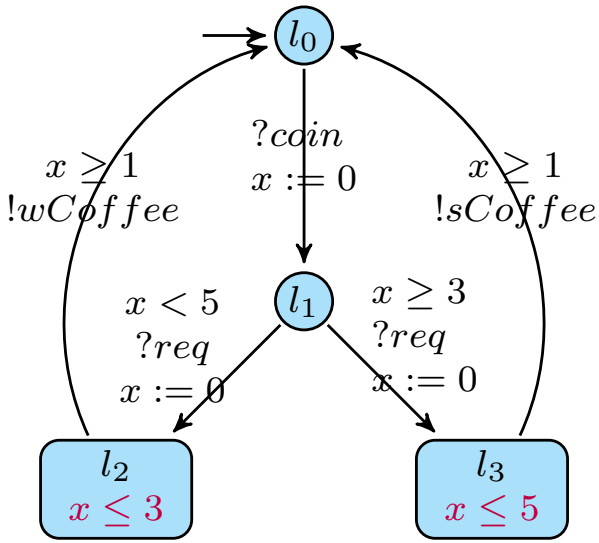
rtioco ensures Implementation has only the behavior allowed by Specification :

- Implementation not allowed to produce an output at a time when not allowed by Specification
- Implementation not allowed to omit producing an output when required by the Specification

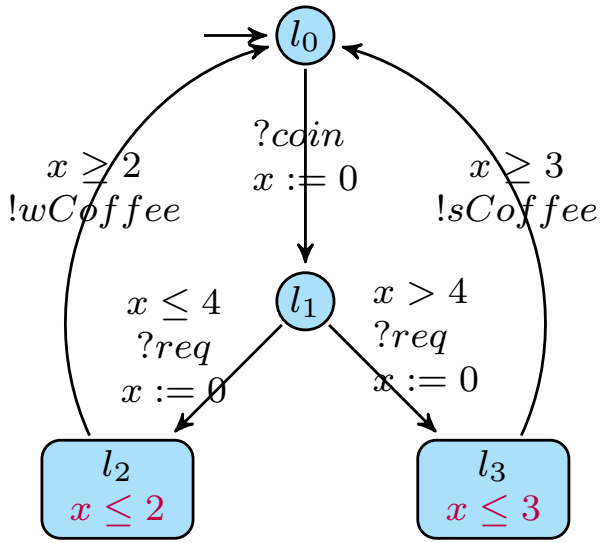
rtioco examples



Environment



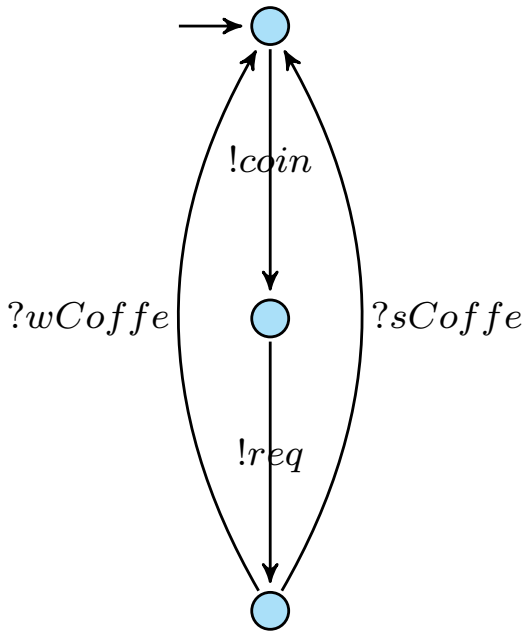
Specification s



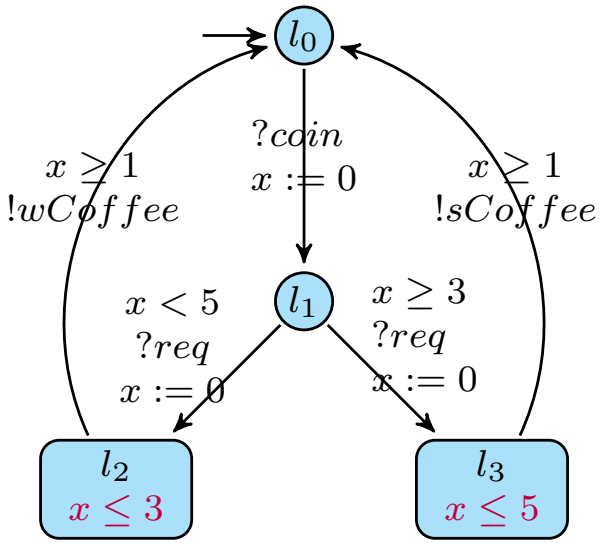
Implementation i_1

Trace σ	$Out(s \text{ After } \sigma)$	$Out(i_1 \text{ After } \sigma)$
$c \cdot 2$	$\mathbb{R}_{\geq 0}$	$\mathbb{R}_{\geq 0}$
$c \cdot 4 \cdot r \cdot 1$	$\{wCoffee, sCoffee\} \cup [0, 4]$	$[0, 1]$
$c \cdot 4 \cdot r \cdot 2$	$\{wCoffee, sCoffee\} \cup [0, 3]$	$\{wCoffee, 0\}$
$c \cdot 5 \cdot r \cdot 3$	$\{sCoffee\} \cup [0, 2]$	$\{sCoffee, 0\}$
$c \cdot 5 \cdot r \cdot 5$	$\{sCoffee, 0\}$	$\emptyset$

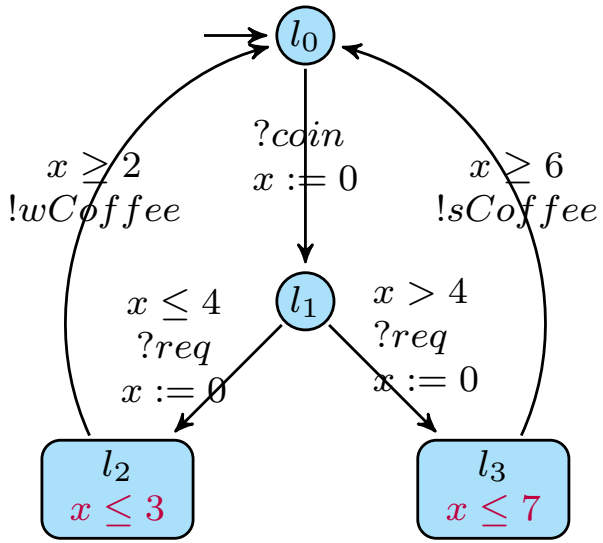
rtioco examples (2)



Environment



Specification s



Implementation i_2

Trace σ	$Out(s \text{ After } \sigma)$	$Out(i_2 \text{ After } \sigma)$
$c \cdot 2$	$\mathbb{R}_{\geq 0}$	$\mathbb{R}_{\geq 0}$
$c \cdot 4 \cdot r \cdot 1$	$\{wCoffee, sCoffee\} \cup [0, 4]$	$[0, 2]$
$c \cdot 4 \cdot r \cdot 2$	$\{wCoffee, sCoffee\} \cup [0, 3]$	$\{wCoffee\} \cup [0, 1]$
$c \cdot 5 \cdot r \cdot 3$	$\{sCoffee\} \cup [0, 2]$	$[0, 4]$
$c \cdot 5 \cdot r \cdot 5$	$\{sCoffee, 0\}$	$[0, 2]$

Online testing (à la TorX)

- On-the-fly testing : combines test generation and execution
- Non-deterministic generation
- Symbolic states
- Weakly input-enabled and non-blocking TIOTS

- Advantages :
  - reduces state space explosion
  - handles non-determinism
- Drawbacks :
  - specification must be analyzed online, in real-time
  - test runs may be long...
  - coverage criteria can not be guaranteed

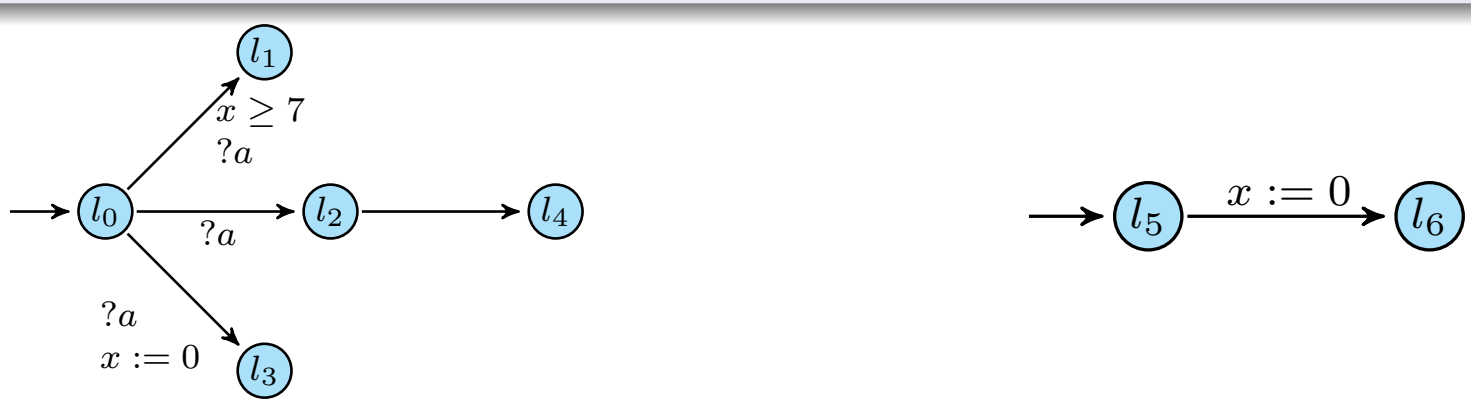
Non-determinism

Often used :

- as means of abstraction
- to model optional behavior, permitted but not required

determinism definition

An TIOTS (S) is deterministic if
$\forall \alpha \in (A_\tau \cup \mathbb{R}_{\geq 0}), \forall s \in S, (s \xrightarrow{\alpha} s' \wedge s \xrightarrow{\alpha} s'') \Rightarrow s' = s''$.

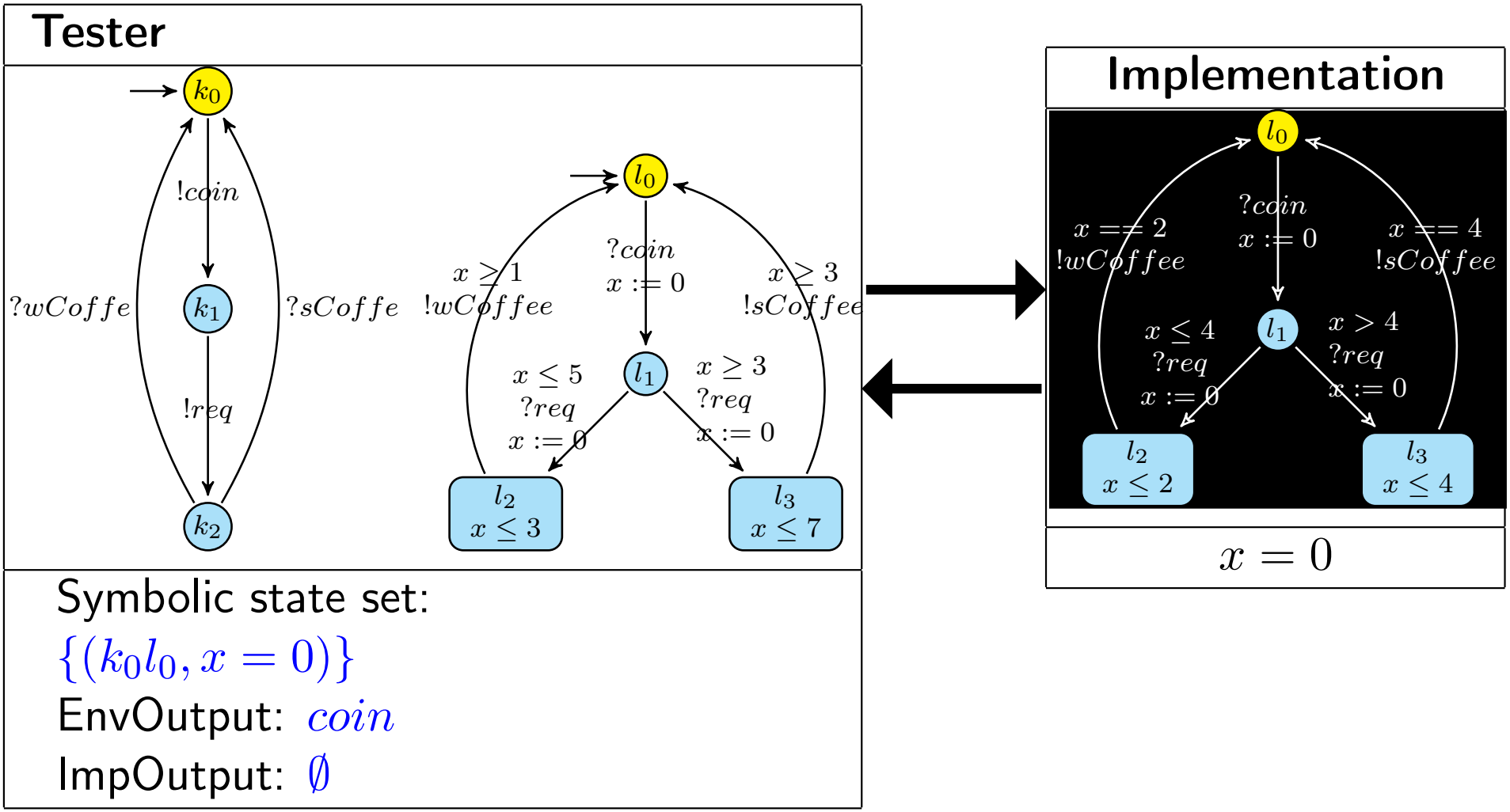


$(l_0, x = 3)$ After $a = \{(l_2, x = 3), (l_4, x = 3), (l3, x = 0)\}$
$(l_5, x = 0)$ After $4 = \{(l_5, x = 4), (l_6, 0 \leq x \leq 4)\}$

Uppaal TRON algorithm $TestGenExe(\mathcal{S}, \mathcal{E}, IUT, T)$

while $\mathcal{Z} \neq \emptyset \wedge \sharp iterations \leq T$ **do**
  switch *randomly choose btw* $action$, $delay$ *and* $restart$ **do**
    case $action$ /* offer an input */
      if $EnvOutput(\mathcal{Z}) \neq \emptyset$ **then**
        randomly choose $i \in EnvOutput(\mathcal{Z})$; send i to IUT ;
        $\mathcal{Z} := \mathcal{Z}$ After i ;
    case $delay$ /* wait for an output */
      randomly choose $d \in Delays(\mathcal{Z})$;
      sleep for d time units or wake up on output o at $d' \leq d$;
      if o *occurs* **then**
        $\mathcal{Z} := \mathcal{Z}$ After d' ;
        if $o \notin ImpOutput(\mathcal{Z})$ **then** **return** *FAIL* **else**
        $\mathcal{Z} := \mathcal{Z}$ After o
      else
        $\mathcal{Z} := \mathcal{Z}$ After d ;
    case $restart$ $\mathcal{Z} := \{(s_0, e_0)\}$, reset IUT /* reset and restart */
if $\mathcal{Z} = \emptyset$ **then** **return** *FAIL* **else** **return** *PASS*

Example of test execution



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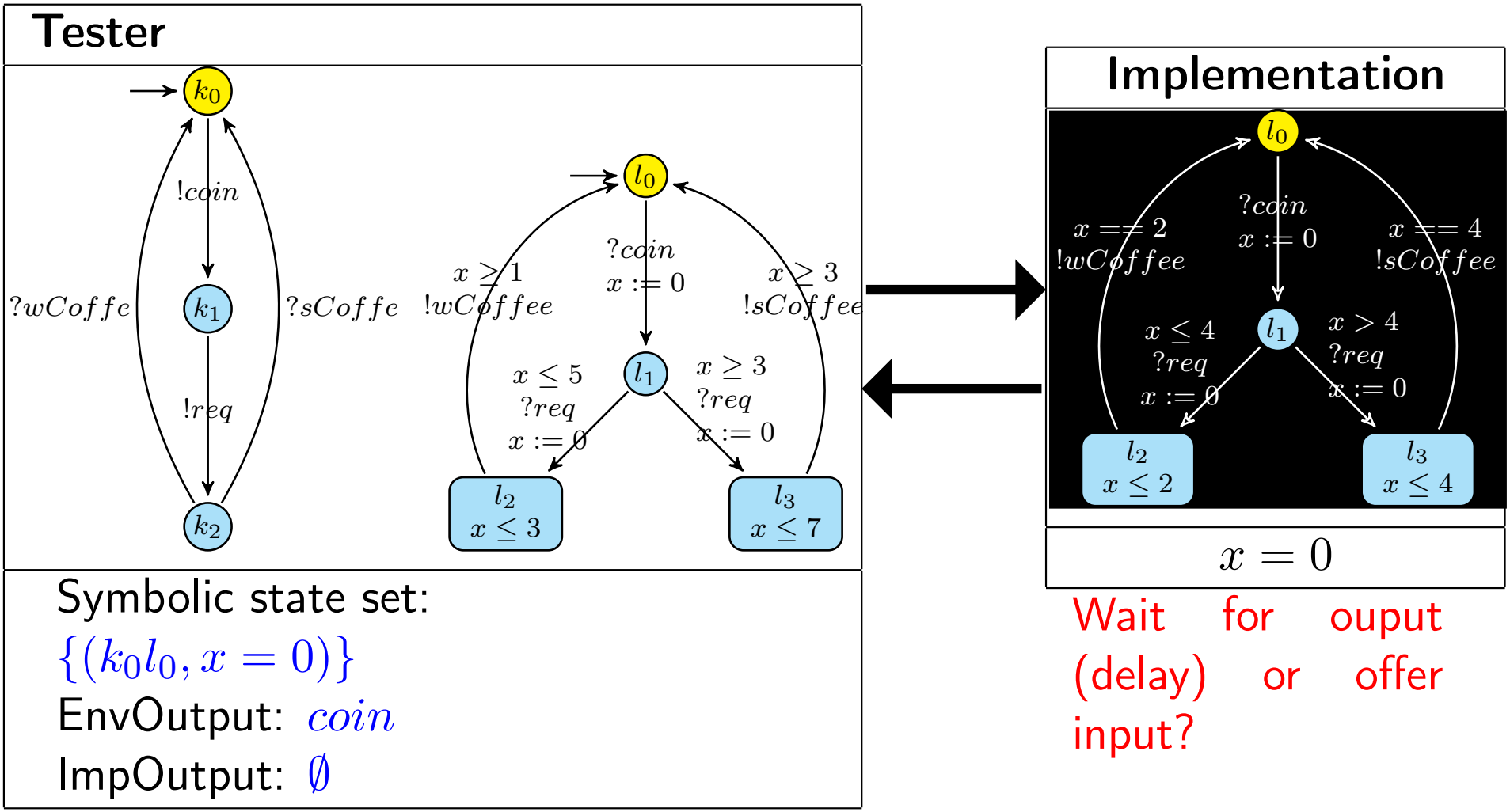

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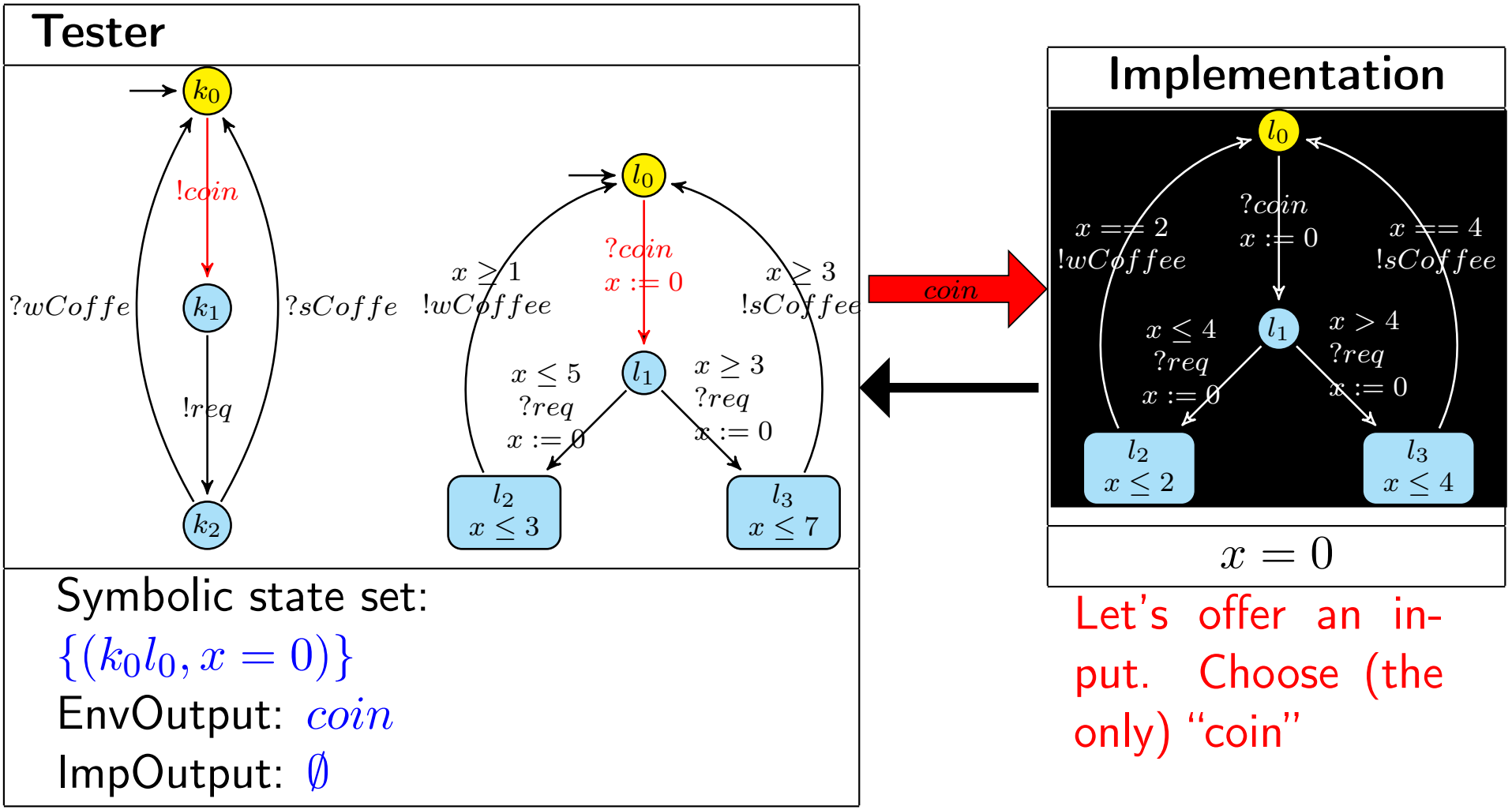

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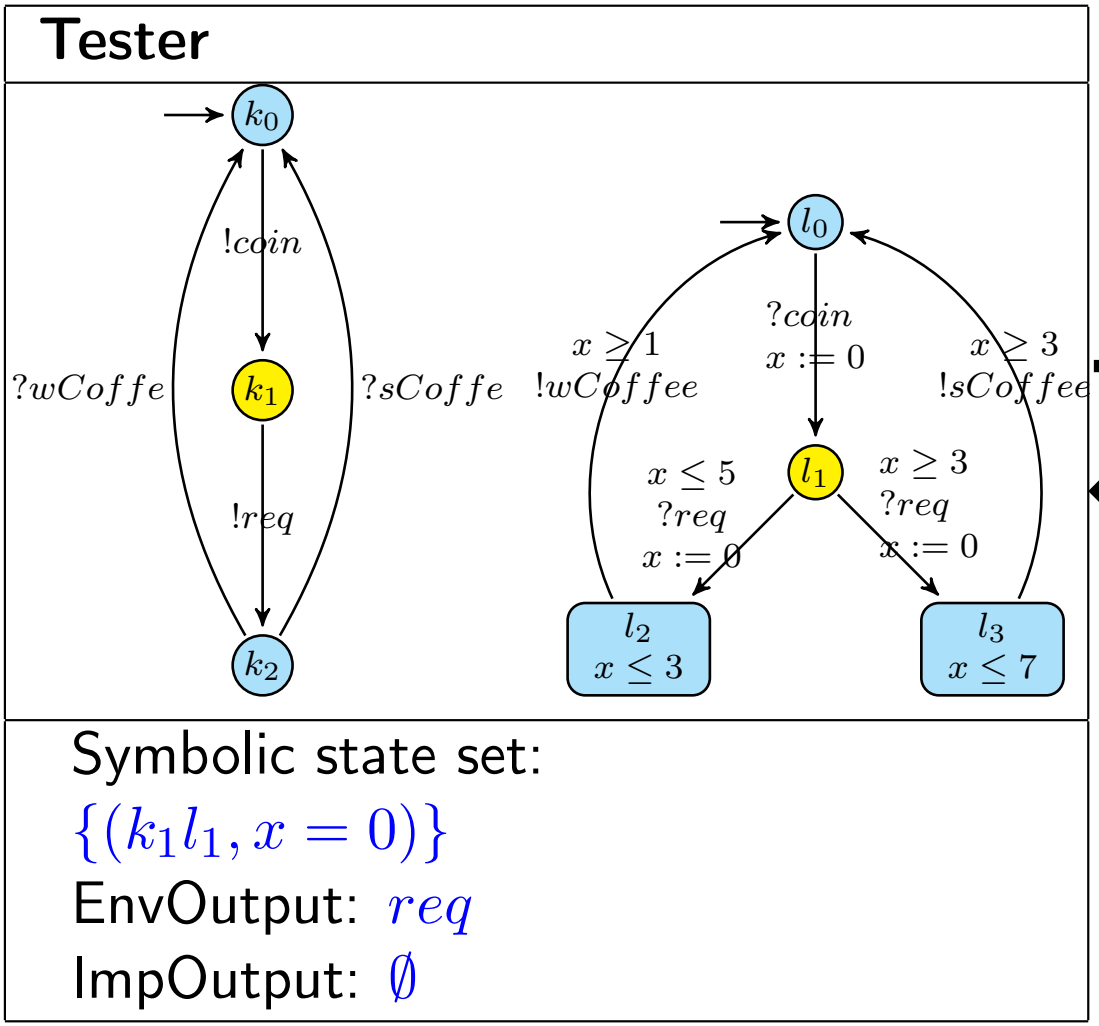
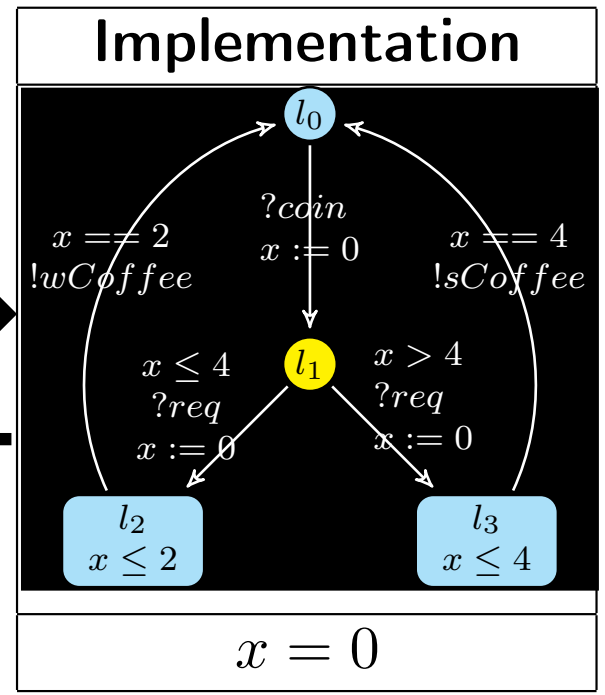
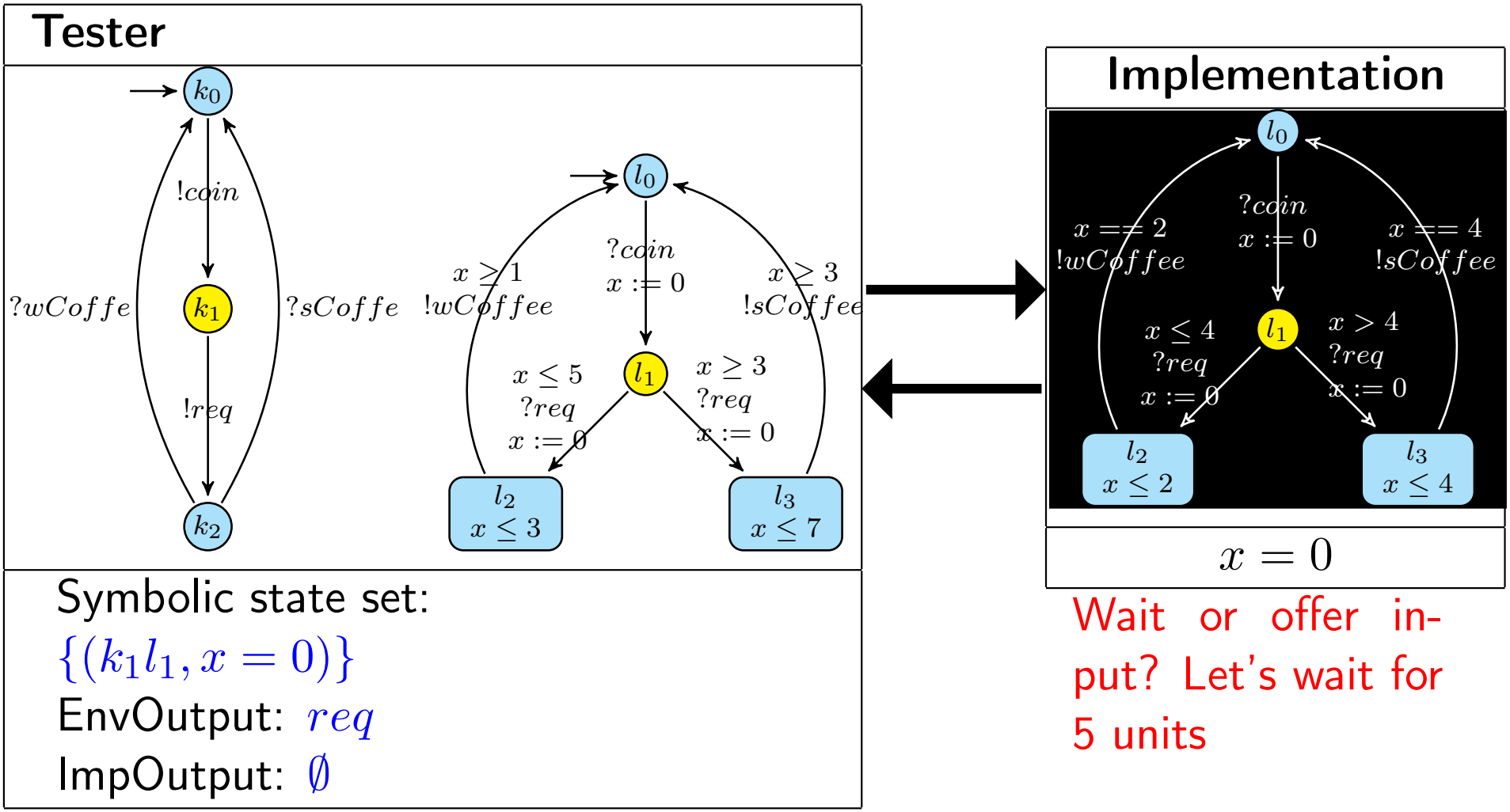




Update the state set and other variables

Example of test execution



Symbolic state set:

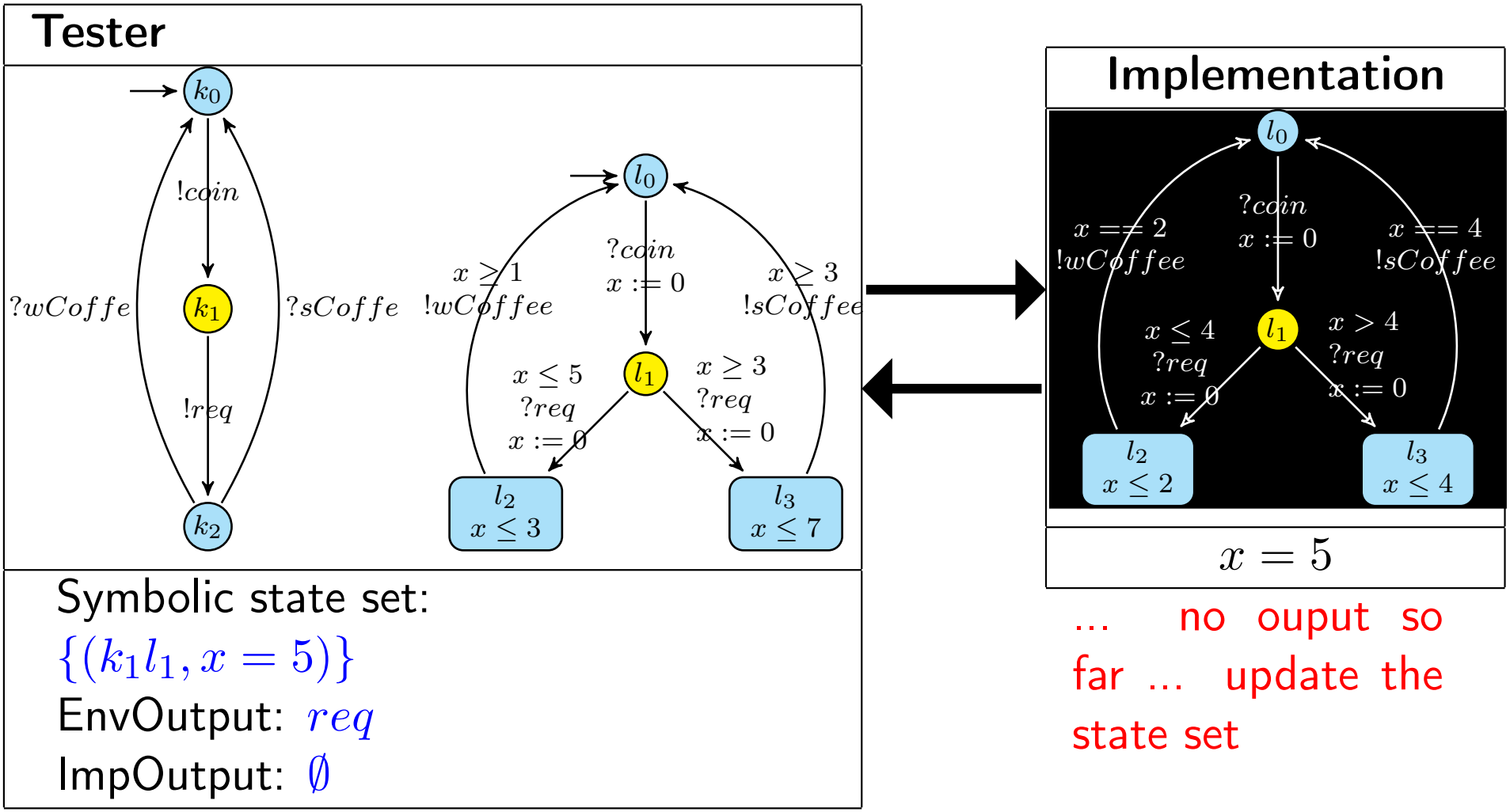
$\{(k_1 l_1, x = 0)\}$

EnvOutput: req

ImpOutput: $\emptyset$

Wait or offer input? Let's wait for 5 units

Example of test execution



Symbolic state set:

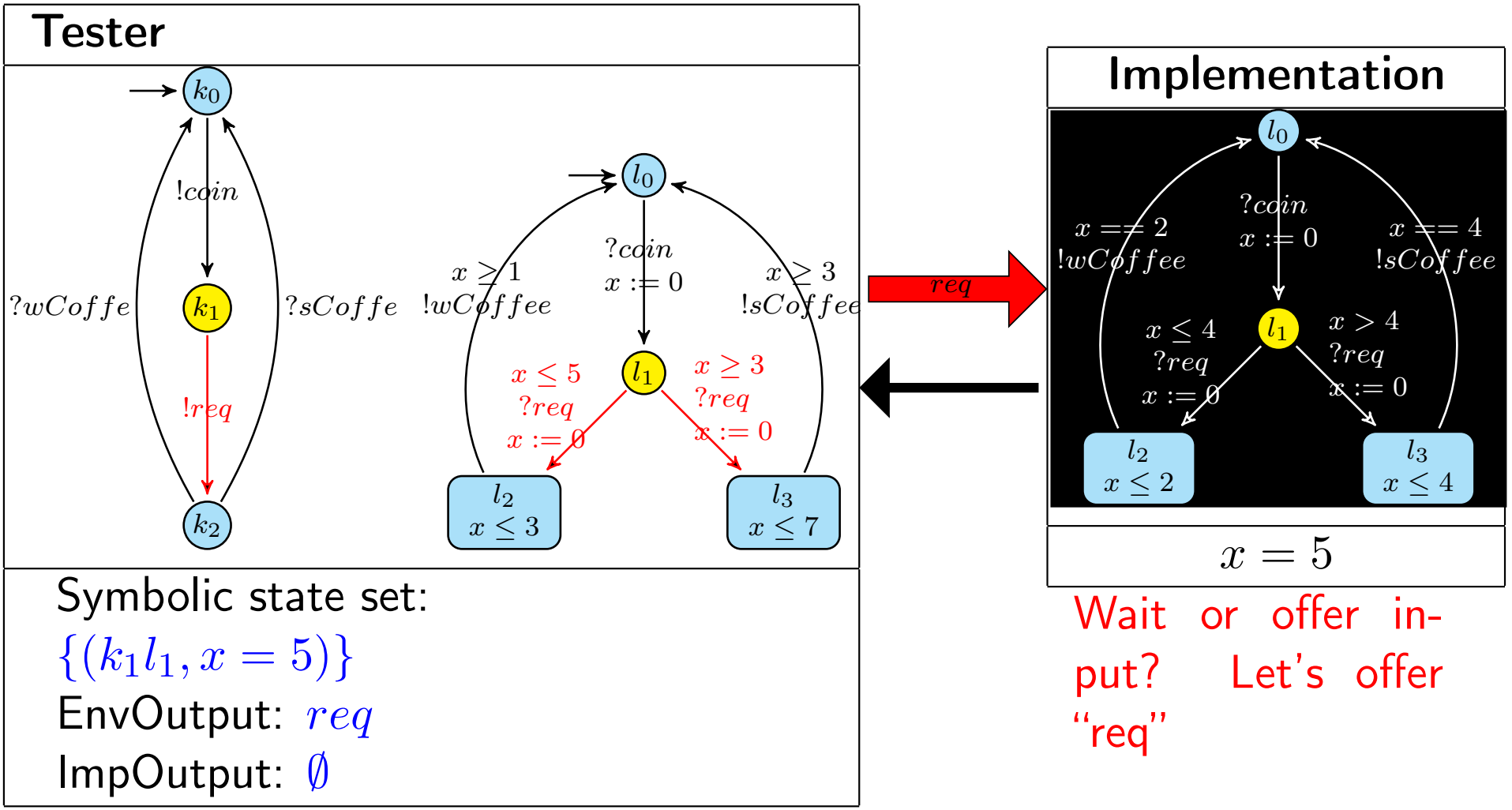
$\{(k_1 l_1, x = 5)\}$

EnvOutput: req

ImpOutput: $\emptyset$

... no ouput so far ... update the state set

Example of test execution



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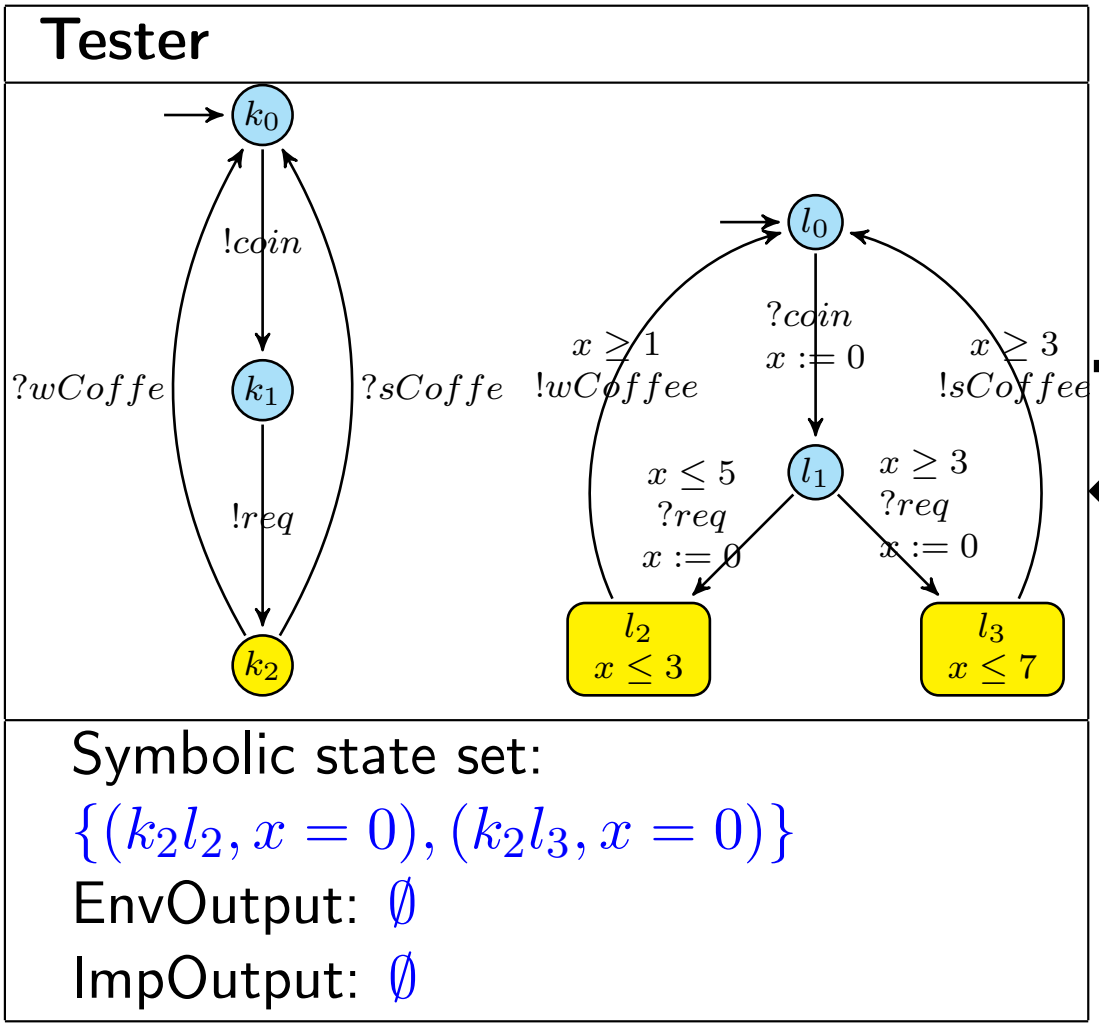

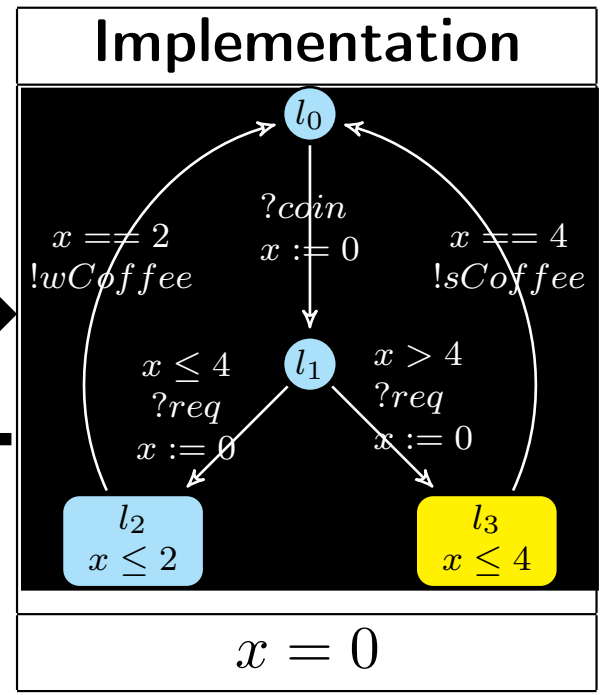

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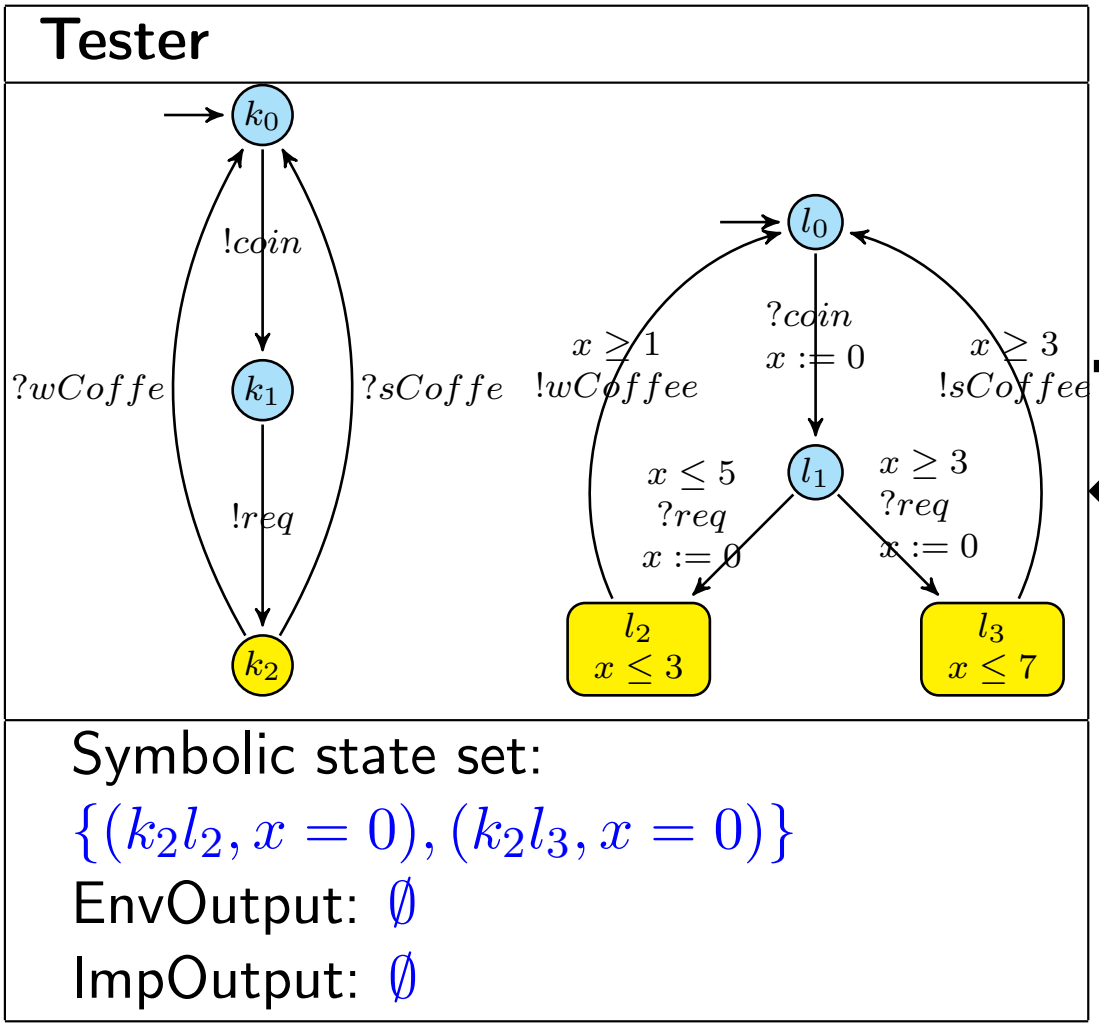
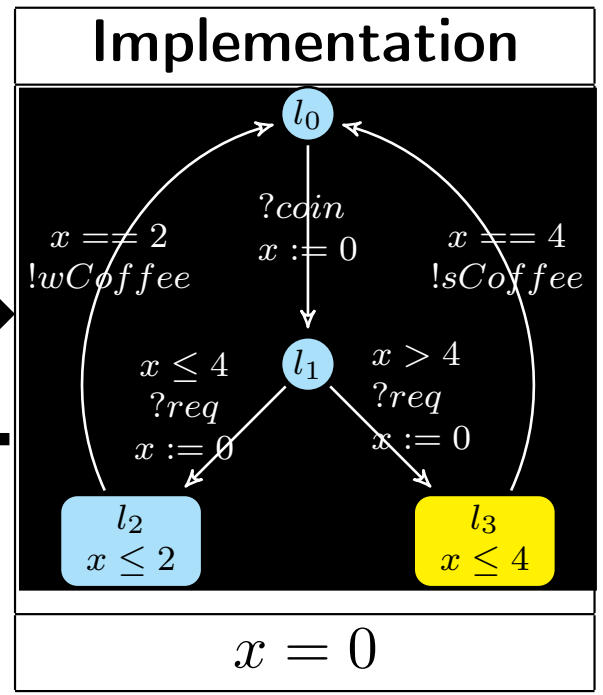
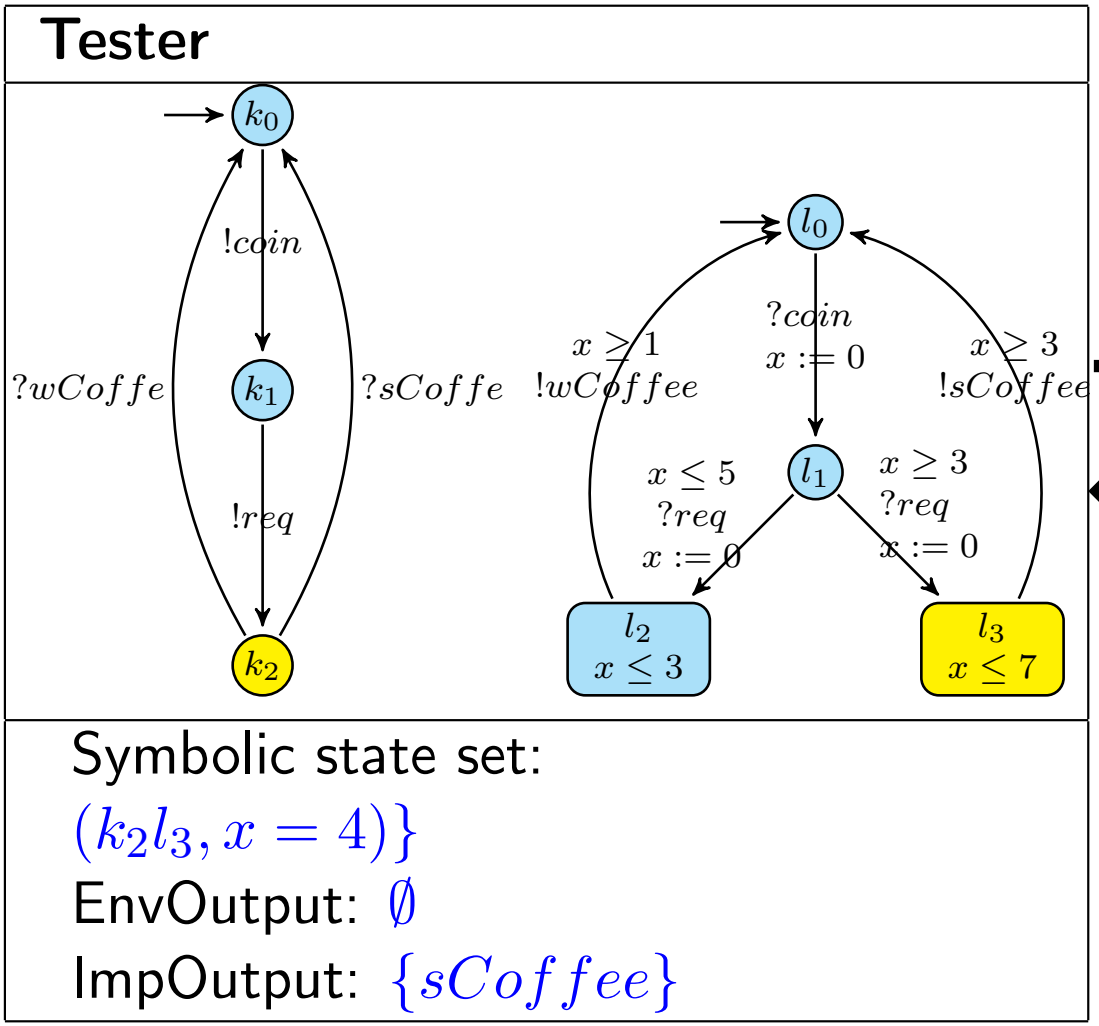
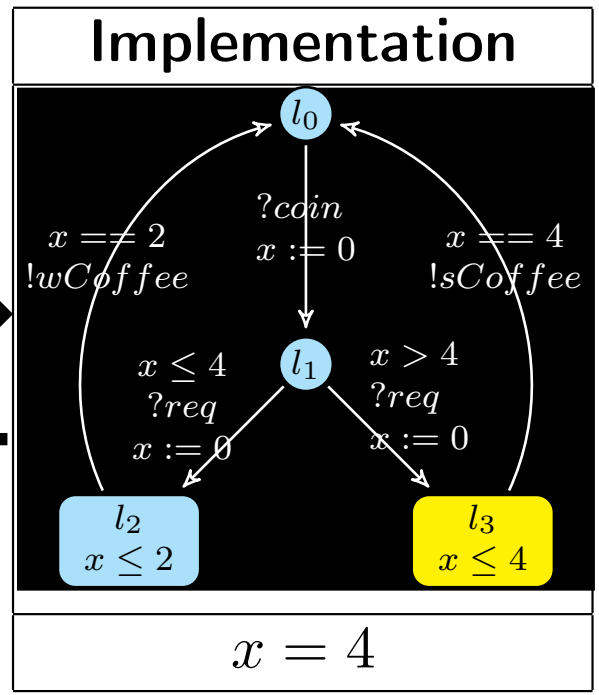




Wait or offer input? Let's wait for 4 units

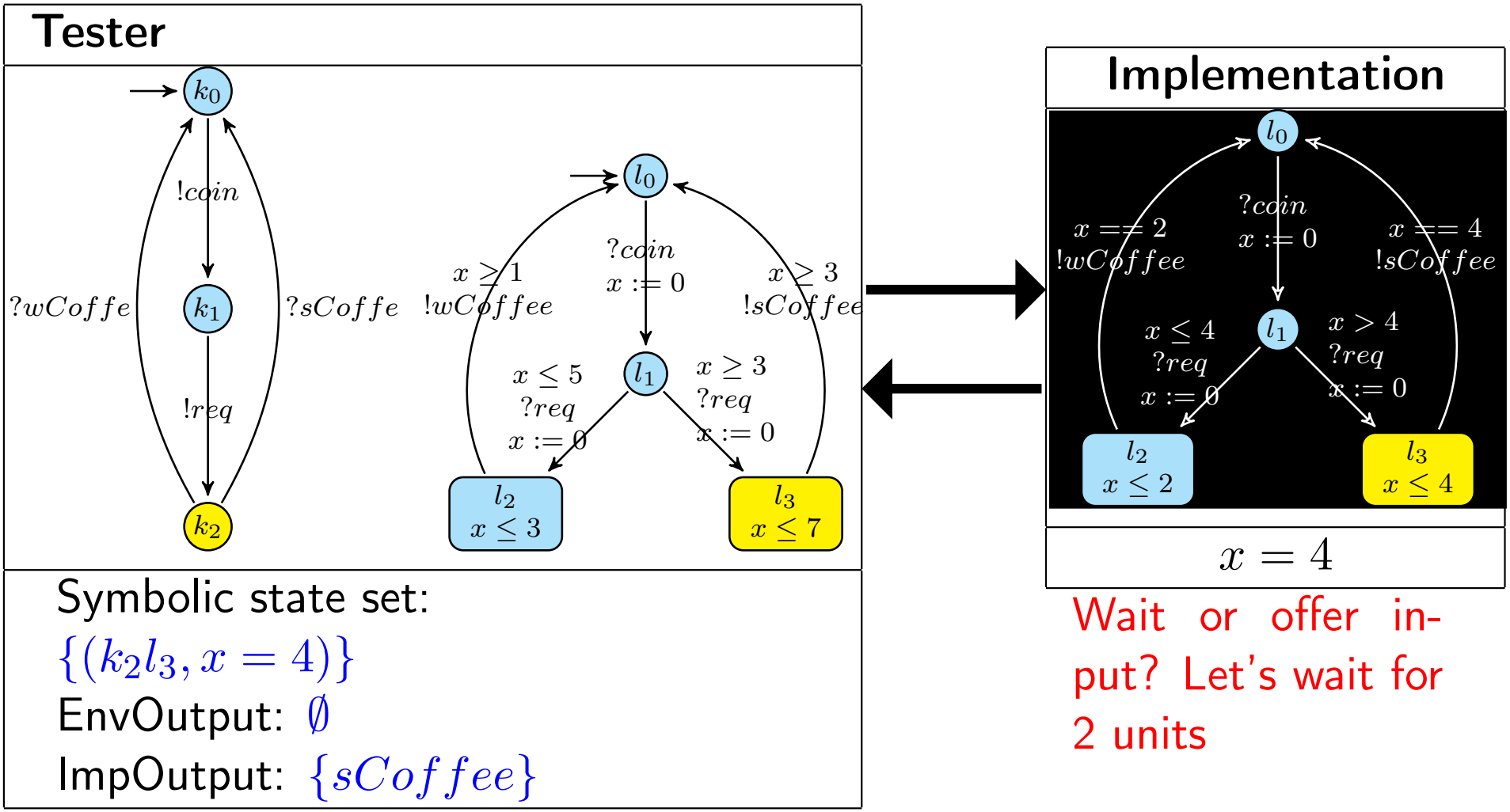
Example of test execution





... no output so far: update the state set

Example of test execution



Symbolic state set:

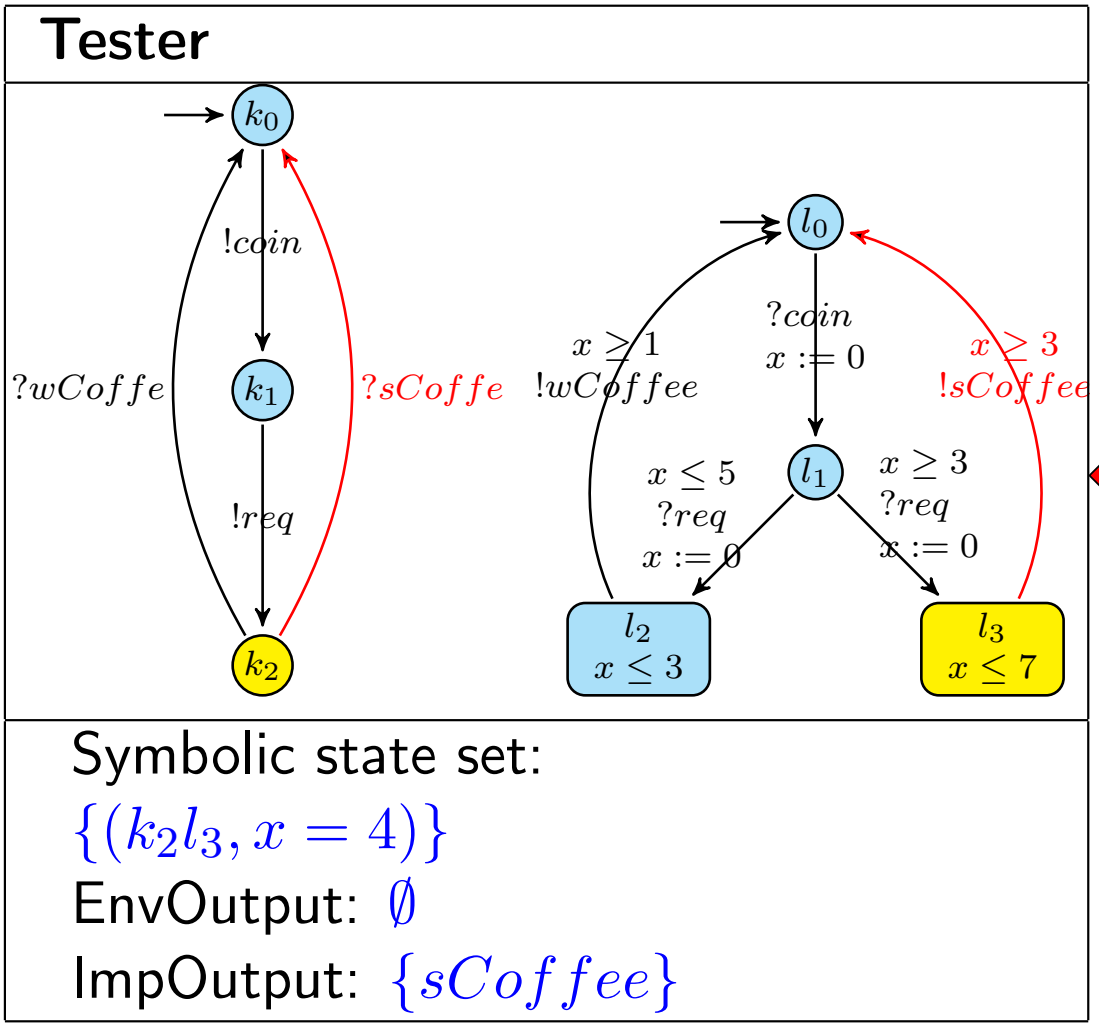
$\{(k_2 l_3, x = 4)\}$

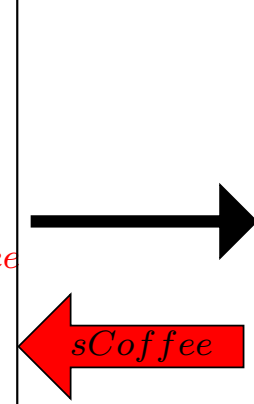
EnvOutput: $\emptyset$

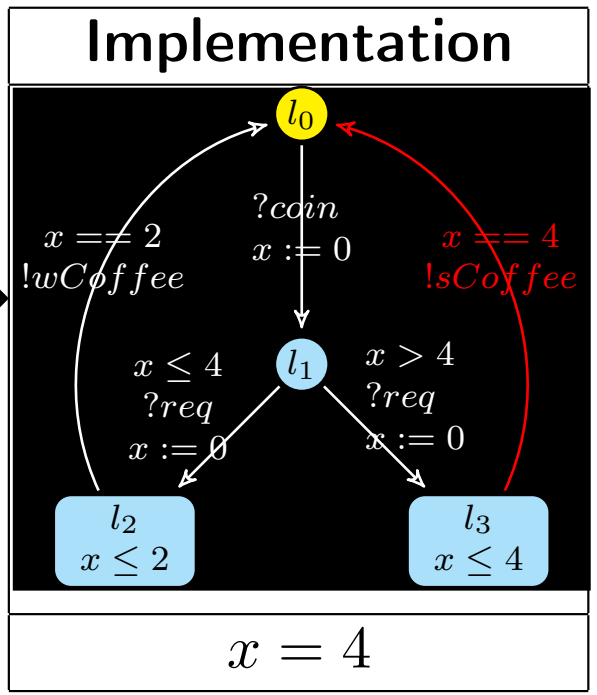
ImpOutput: $\{sCoffee\}$

Wait or offer input? Let's wait for 2 units

Example of test execution

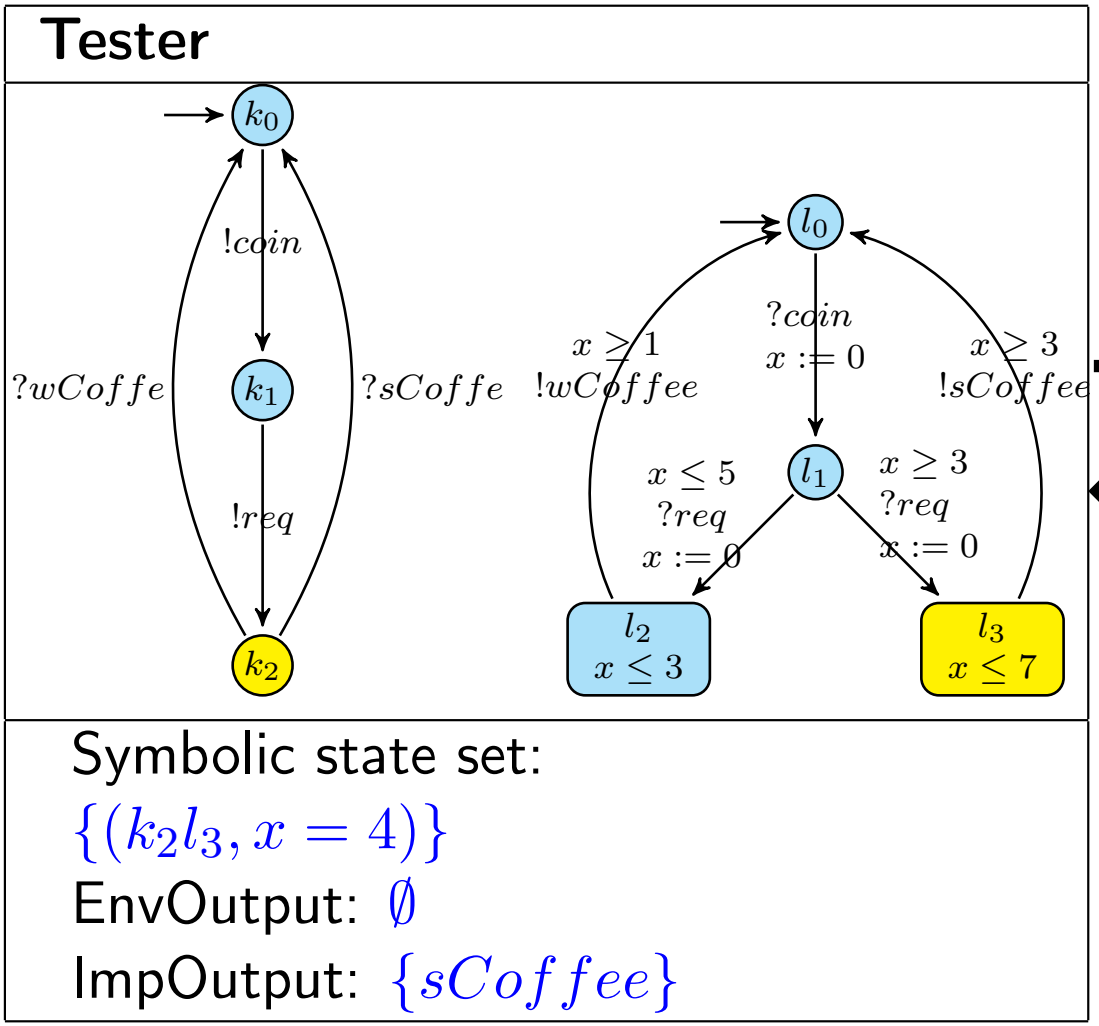


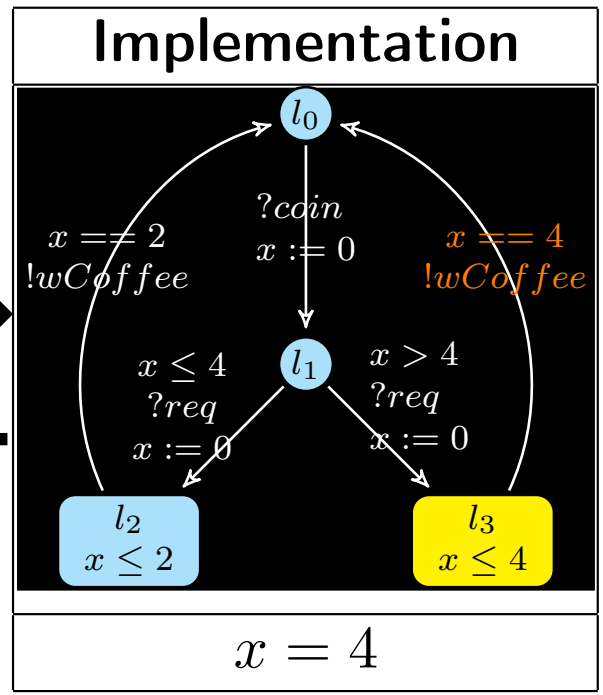




Got output after 0 delay: update the state set

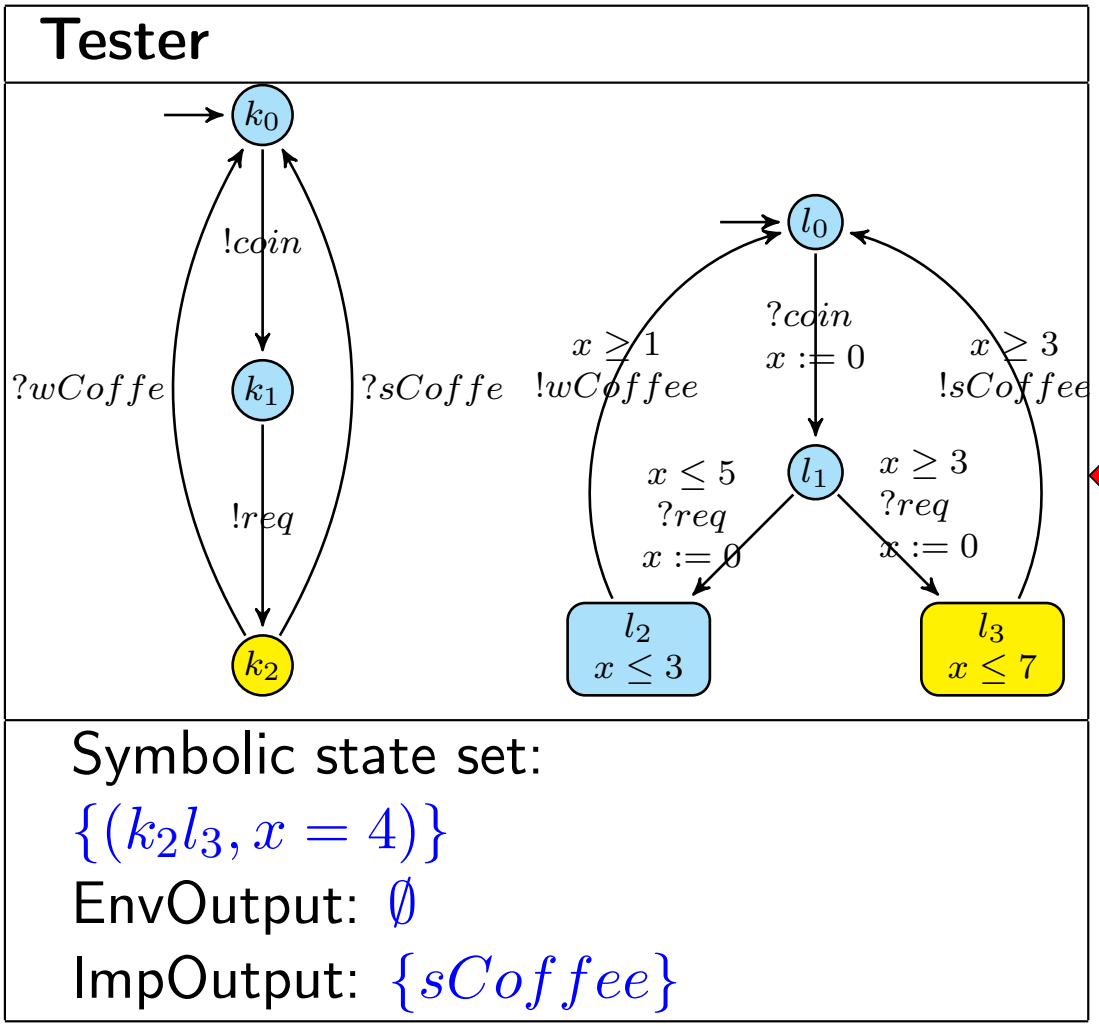
Example of test execution

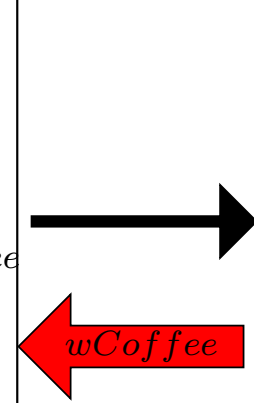


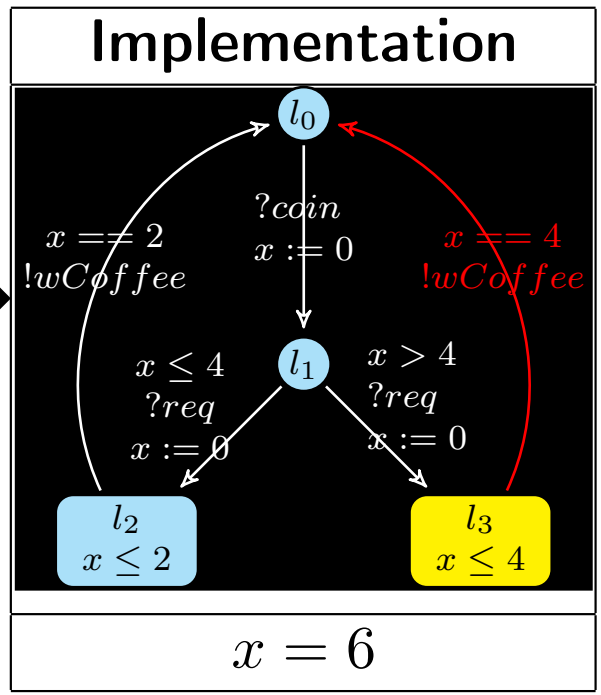


What if there is a bug? Let's wait back for 2 units

Example of test execution







output after 0 delay: $wCoffee \notin \{sCoffee\}$

Properties of test cases

Let a $\mathcal{S}$, $\mathcal{E}$, and $\mathcal{IUT}$ three weakly input enabled TIOTS, with $\mathcal{IUT}$ deterministic.

Soundness, Exhaustiveness

- Soundness :
  $TestGenExe(\mathcal{S}, \mathcal{E}, \mathcal{IUT}, T) = \mathit{Fail} \Rightarrow \neg(\mathcal{IUT}\ \mathbf{rtioco}_{\mathcal{E}}\ \mathcal{S})$
- Exhaustiveness :
  $\neg(\mathcal{IUT}\ \mathbf{rtioco}_{\mathcal{E}}\ \mathcal{S}) \Rightarrow \mathrm{Prob}(TestGenExe(\mathcal{S}, \mathcal{E}, \mathcal{IUT}, T) = \mathit{Fail}) \overset{T \to \infty}{\longrightarrow} 1$

If $\mathcal{IUT}$ is not deterministic, exhaustiveness is not guaranteed

Offline test generation : main ideas

- Advantages :
  - test cases are easier and faster to execute
  - possibility to guarantee a coverage or a test objective
- Drawbacks :
  - specification has to be analyzed entirely $\Rightarrow$ state explosion
  - only deterministic (and impossible to determinize in general case)

Test Generation with Test Purpose

- Synchronous Product btw Spec. and T.P. $\rightarrow$ need a finite symbolic representation of TA (Region Graph, Zones, ...)
- Test Case Generation with Uppaal
- Test Case Generation using Observers

Still immature...

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Test Case generation with Test Purpose using Uppaal

Uppaal Tool :

- Model checker for temporal properties
- Symbolic efficient analysis (using DBM)
- Generates diagnostic traces (shortest or fastest)

Assumptions : TIOTS are deterministic, weakly input enabled and output urgent

Idea

- Formulate the problem as safety property (usually solved by a reachability analysis) $\rightarrow$ obtain a trace of the form $(s_0, e_0) \xrightarrow{\gamma_0} (s_1, e_1) \ldots \xrightarrow{\gamma_{n-1}} (s_n, e_n)$
- Obtain a test sequence by projecting the trace to the $\mathcal{E} - component$ (and summing delays)
- Add Verdicts to the test sequence to obtain a test case

Test sequences are guaranteed to be included in the specification

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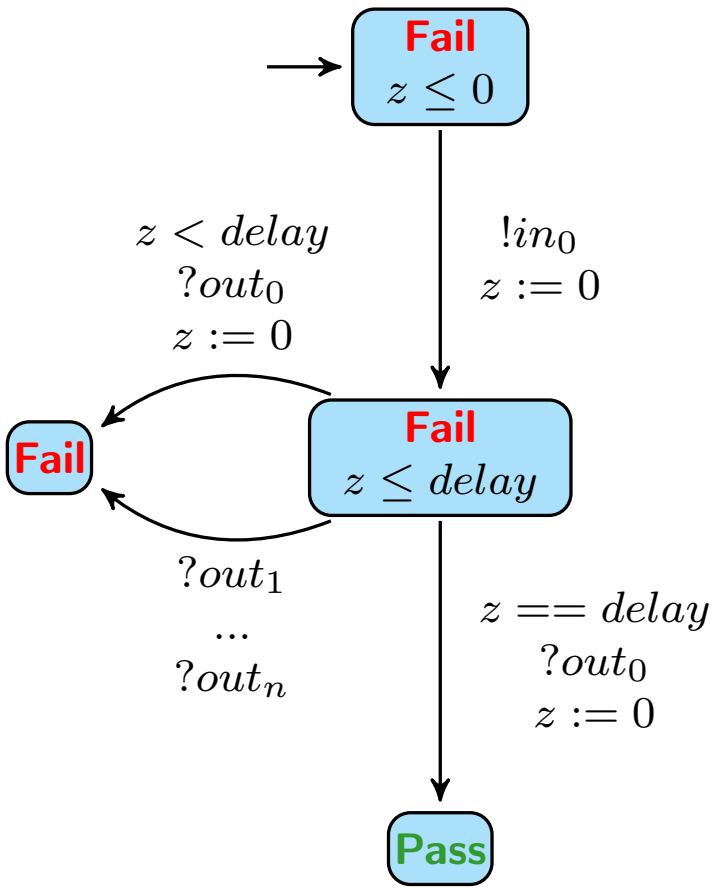
Example of test case

Sequence :
$!in_0 \cdot delay \cdot ?out_0$



Examples of Test Purposes (light controller)

TP1 : Check that the light can become bright :

Simple reachability property : eventually the system specification can enter location **BRIGHT**

TP2 : Check the light switch off after 3 successive touches

reachability property + specific environment :

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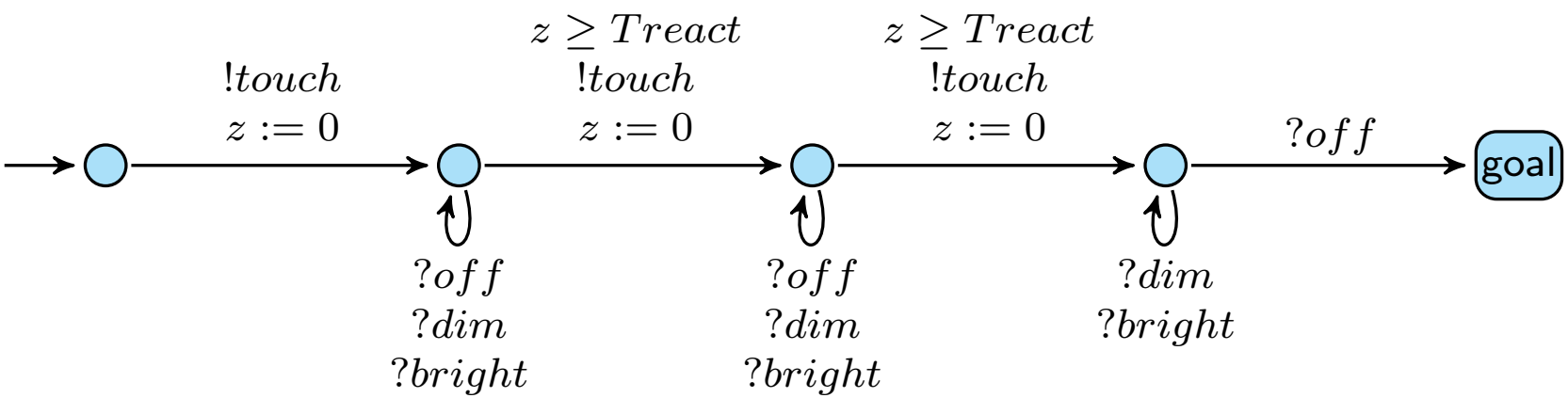

Examples of coverage criteria

Edge Coverage

Reachability property :

- add a boolean variable e_i for each edge to be covered, initially $false$
- add assignment $e_i := true$ for each edge to be covered
- property to reach : $\bigwedge e_i == true$

Location (l_i) Coverage

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Using observers

Weakness of this offline approach :

- time-consuming to find the proper model annotation
- model-checking tools not adapted for test cases generation : may lead to performance problems

$\rightarrow$ Possibility to use a language of observers to describe coverage criteria
$\rightarrow$ Adaptation of model-checking algorithms for test generation based on observers

Outline

Conclusion

- Testing theory and generation algorithms for finite ioLTS
- Extensions for Timed Automata with Inputs and Outputs
- Off-line and on-line algorithms

Perspectives

- Mature tools (scaling)
- "Real-time" coverage criteria
- Testing seen as "Game theory"
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Thank you for your attention

rollet@labri.fr