Model-based Verification and Analysis for Real-Time Systems

Kim G. Larsen
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Timed Aut🕓mata
.. and Prices and Games

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Aalborg

KORT OVER DANMARK
Aalborg
Aarhus
Co

Jomfru Ane Gade

Aalborg University lea
publ

CISS – Center For Embedded Software Systems

Regional ICT Center (2003-)

- 3 research groups
  - Computer Science
  - Control Theory
  - HW/SW- codesign

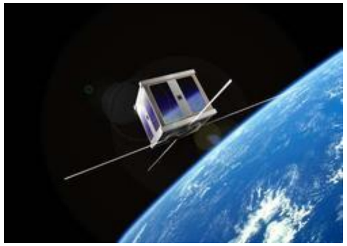
- 20 Employed
- 25 Associated
- 20 PhD Students
- 50 Industrial projects
- 10 Elite-students
- 65 MDKK

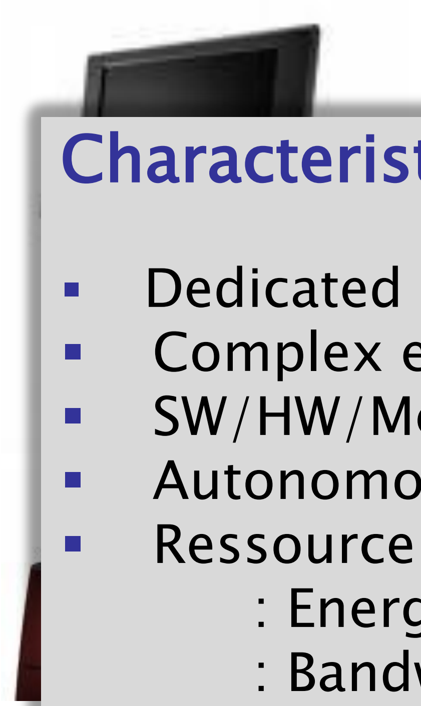
- ARTIST Design
- ARTEMIS

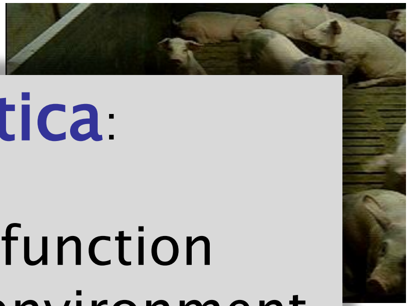
Information Society Technologies

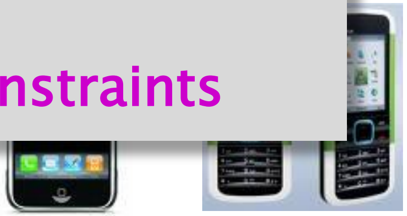
ARTEMIS

ES are Pervasive









Characteristica:

- Dedicated function
- Complex environment
- SW/HW/Mechanics
- Autonomous
- Ressource constrained
  - : Energy
  - : Bandwidth
  - : Memory
  - : ...
- Timing constraints

ES are often Safety Critical

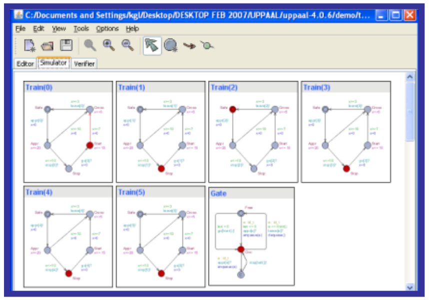
300 horse power
100 processors

How to achieve ES that are:

- correct
- predicable
- dependable
- fault tolerant
- ressource minial
- cheap

Model–Based Development

QUANTITATIVE Model Checking

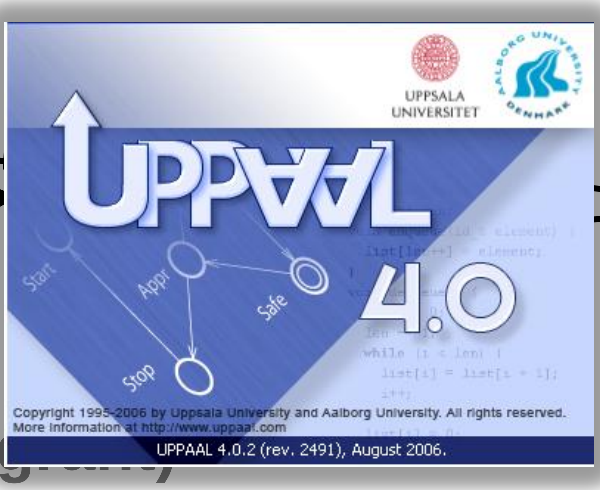

C:/Documents and Settings/kgl/Desktop/DESKTOP FEB 2007/UPPAAL/uppaal-4.0.6/demo/t...
File Edit View Tools Options Help
Editor Simulator Verifier
Train(0)
Train(1)
Train(2)
Train(3)
Train(4)
Train(5)
Gate

System Description

Time

Cost

Probability



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More information at http://www.uppaal.com

UPPAAL 4.0.2 (rev. 2491), August 2006.

Requirement

$A\Box(\text{req} \Rightarrow A\Diamond\ \text{grant})$

$A\Box(\text{req} \Rightarrow A\Diamond_{t<30s}\ \text{grant})$

$A\Box(\text{req} \Rightarrow A\Diamond_{t<30s,c<5\$}\ \text{grant})$

$A\Box(\text{req} \Rightarrow A\Diamond_{t<30s\ ,\ p>0.90}\ \text{grant})$

No!

Debugging Information

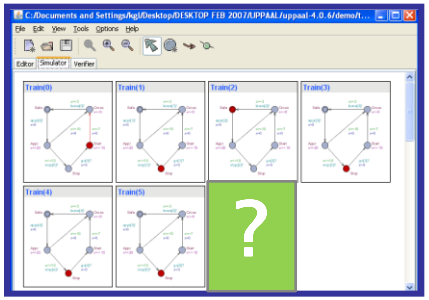
Yes

Prototypes

Executable Code

Test sequences

Synthesis



C:/Documents and Settings/kgl/Desktop/DESKTOP FEB 2007/UPPAAL/uppaal-4.0.6/demo/t...
File Edit View Tools Options Help
Editor Simulator Verifier
Train(0)
Train(1)
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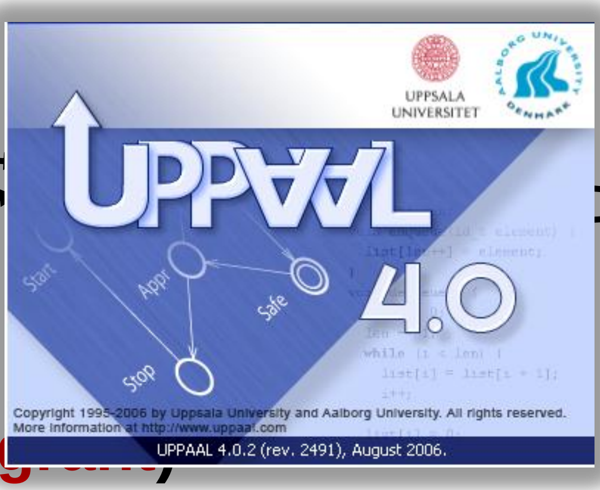
Train(4)
Train(5)
?

System Description

Time

Cost

Probability



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No!
Debugging Information

Yes
Control Strategy

Requirement

$A\square(\ \text{req} \Rightarrow A\Diamond\ \text{grant})$

$A\square(\ \text{req} \Rightarrow A\Diamond_{t<30s}\ \text{grant})$

$A\square(\ \text{req} \Rightarrow A\Diamond_{t<30s,c<5\$}\ \text{grant})$

$A\square(\ \text{req} \Rightarrow A\Diamond_{t<30s\ ,\ p>0.90}\ \text{grant})$

Overview

- Introduction to
  Timed Automata
- Decidability and
  Symbolic verification
- Priced Timed Automata
- Timed Games & Interfaces
- Open Problems

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AALBORG UNIVERSITY DENMARK
UPPAAL
4.0
Start
Appr
Safe
Stop
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CLASSIC

CORA

TIGA

ECDAR

TRON

PRO

Timed Automata

AALBORG UNIVERSITY DENMARK

UPPAAL (1995-)

@AALborg

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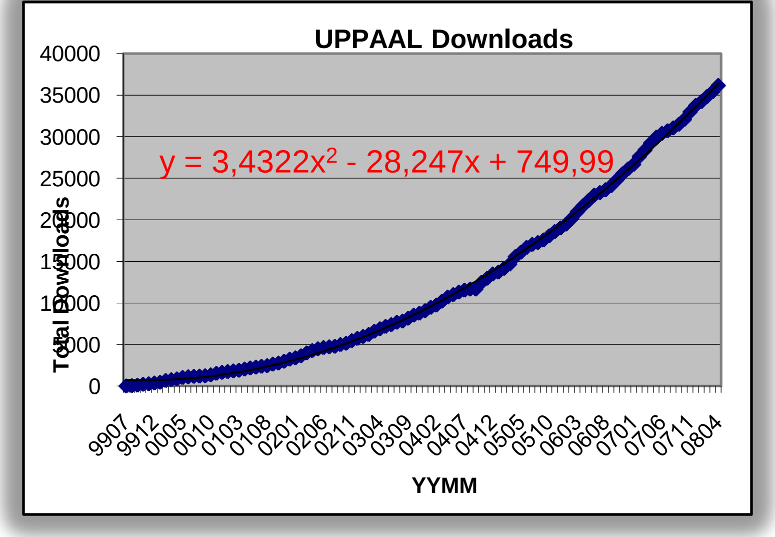
- Alexandre David
- Gerd Behrman
- Marius Mikucionis
- Jacob I. Rasmussen
- Arne Skou
- Brian Nielsen
- Shuhao Li

@UPPsala

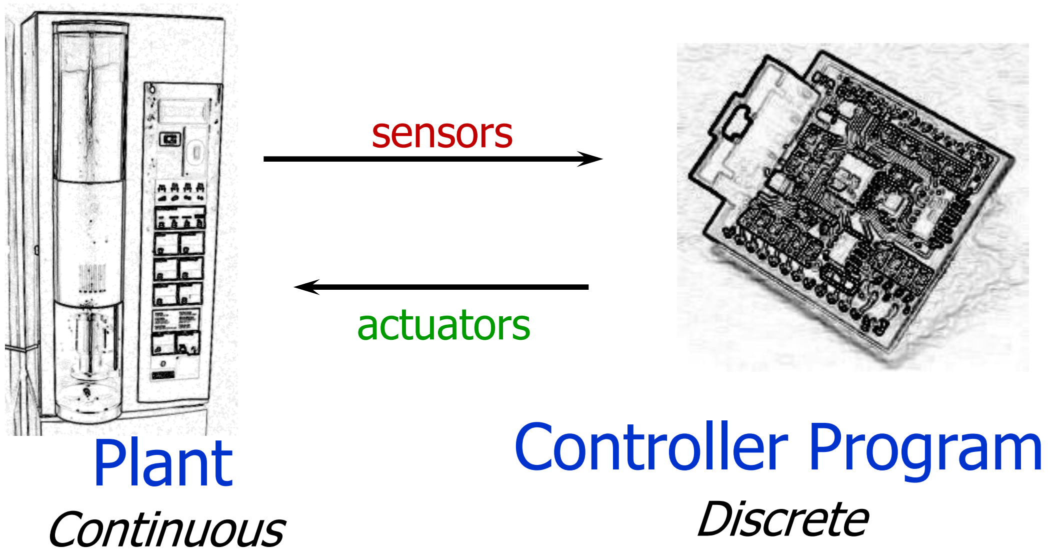
- Wang Yi
- Paul Pettersson
- John Håkansson
- Anders Hessel
- Pavel Krcal
- Leonid Mokrushin
- Shi Xiaochun

@Elsewhere

Emmanuel Fleury, Didier Lime, Johan Bengtsson, Fredrik Larsson, Kåre J Kristoffersen, Tobias Amnell, Thomas Hune, Oliver Möller, Elena Fersman, Carsten Weise, David Griffioen, Ansgar Fehnker, Jan Tretmans, Frits Vandraager, Theo Ruys, Pedro D'Argenio, J-P Katoen,, Judi Romijn, Ed Brinksma, Martijn Hendriks, Klaus Havelund, Franck Cassez, Magnus Lindahl, Francois Laroussinie, Patricia Bouyer, Augusto Burgueno, H. Bowmann, D. Latella, M. Massink, G. Faconti, Kristina Lundqvist, Lars Asplund, Justin Pearson.....



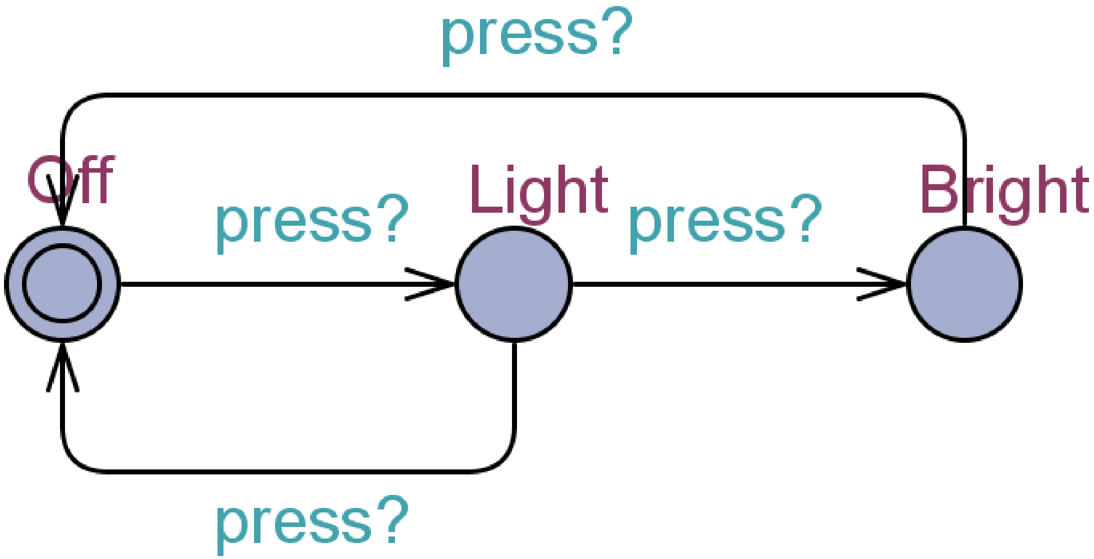
Real Time Systems



Eg.:
- Realtime Protocols
- Pump Control
- Air Bags
- Robots
- Cruise Control
- ABS
- CD Players
- Production Lines

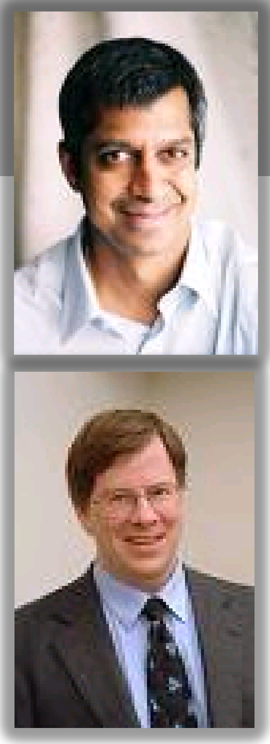
> **Real Time System**
> A system where correctness not only depends on the logical order of events but also on their timing!!

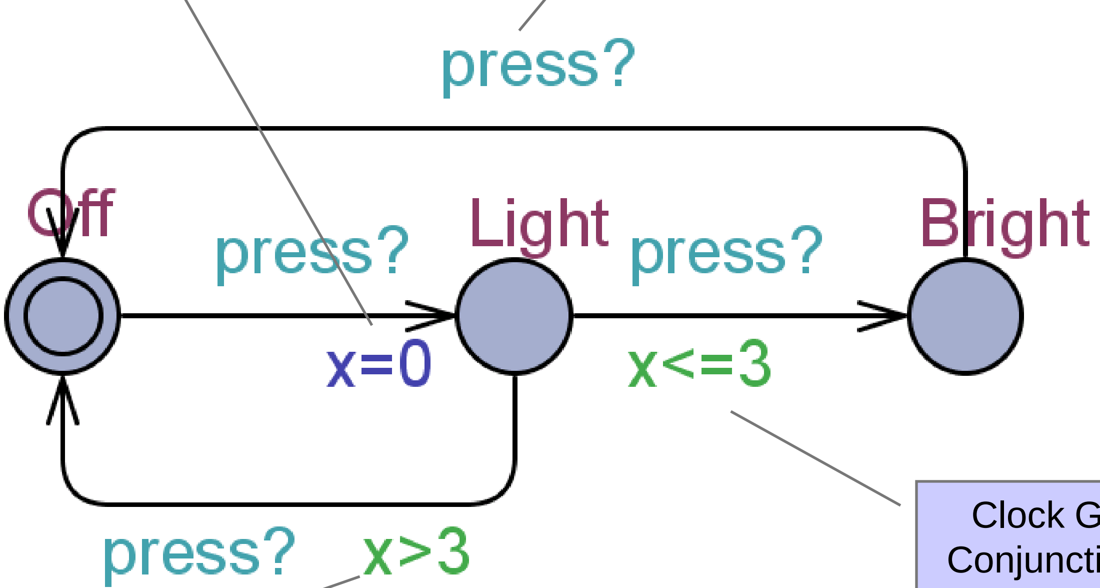
A Dumb Light Controller



Timed Automata

[Alur & Dill'89]





Reset

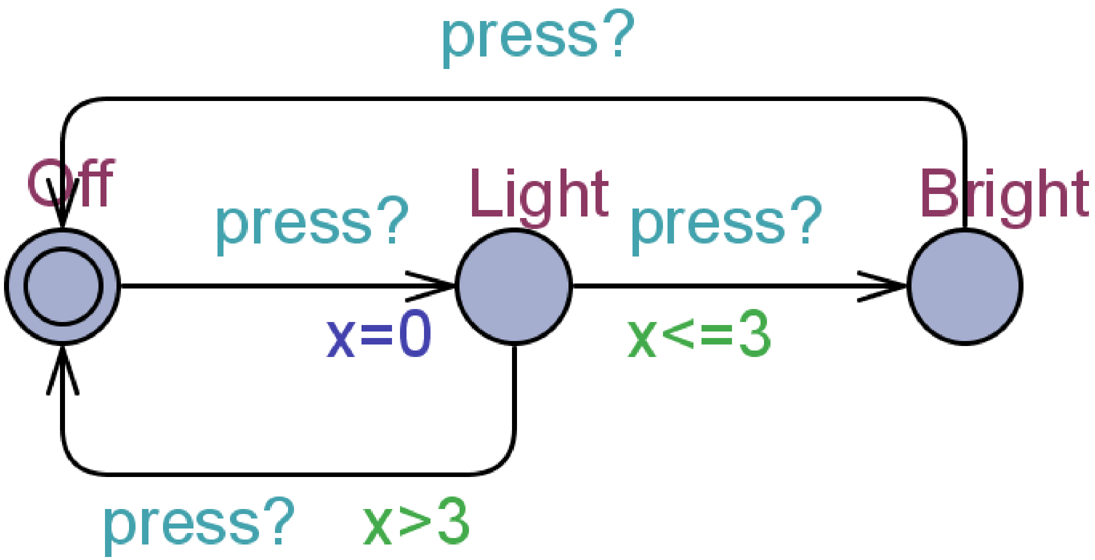
Synchronizing action

Clock Guard Conjunctions of x~n

x: real-valued clock

ADD a clock x

A Timed Automata (Semantics)



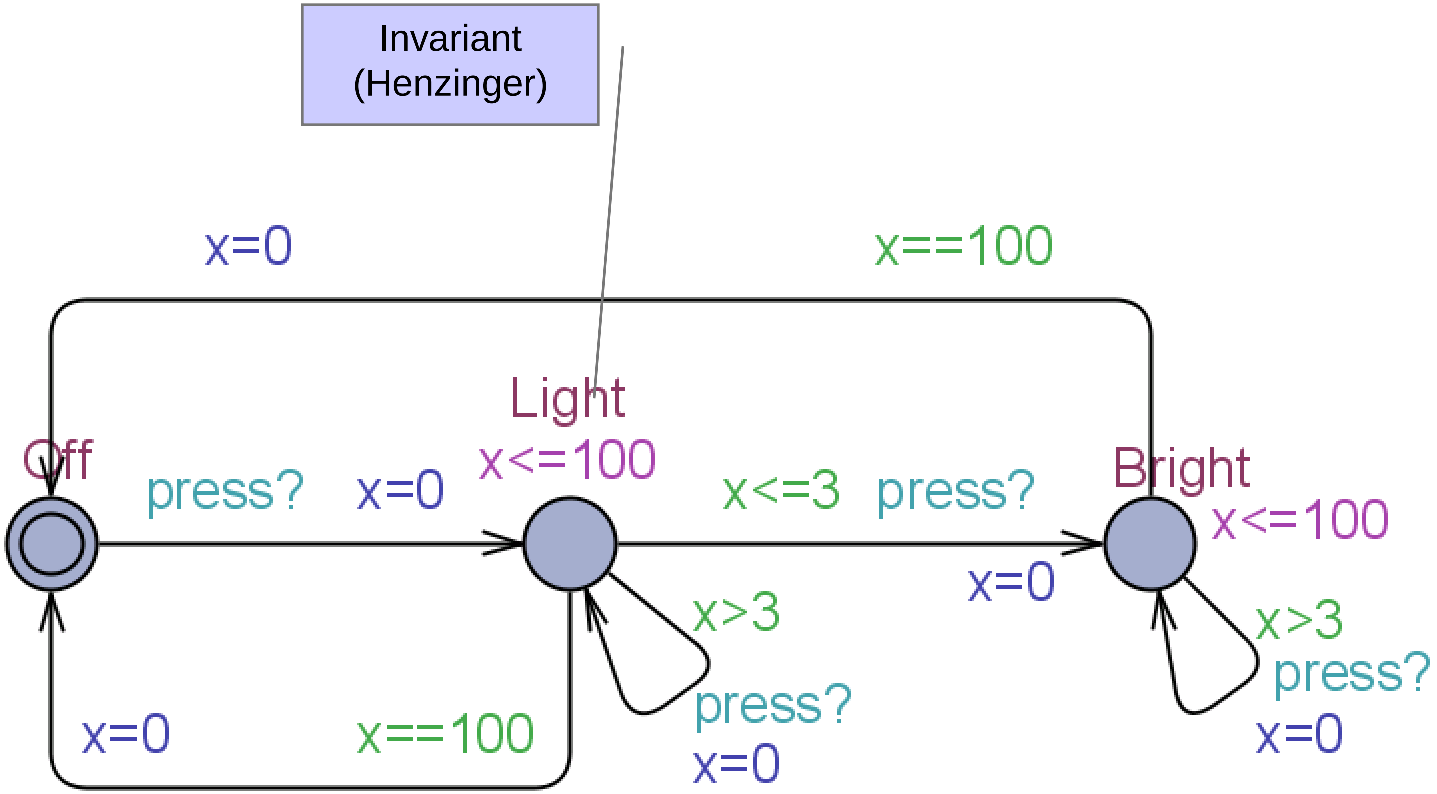
States:

(location , x=v)   where v∈**R**

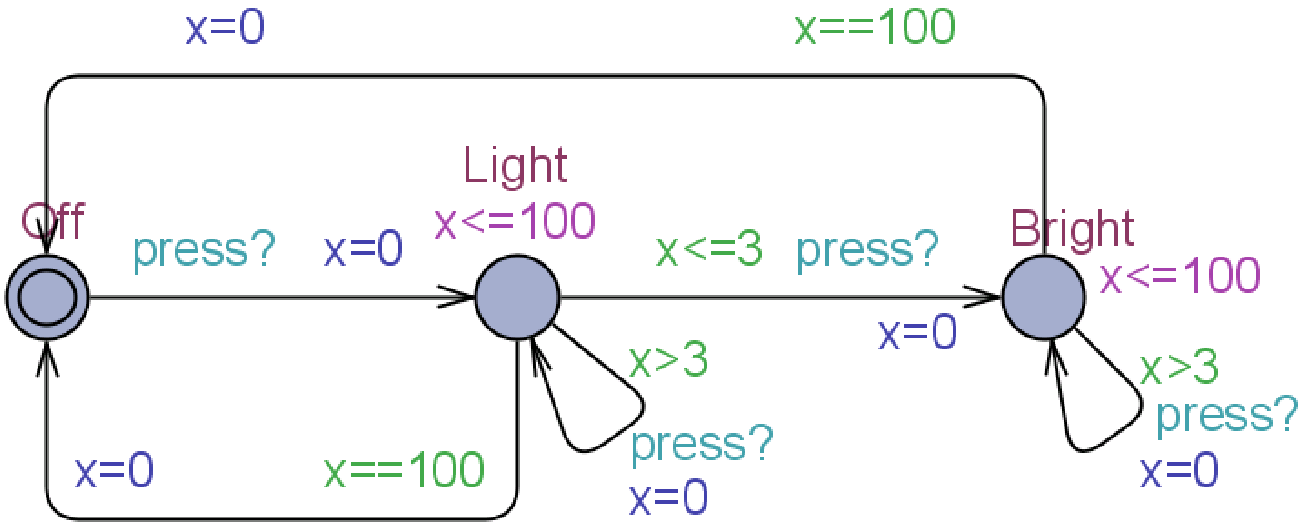
Transitions:

	(Off , x=0)
delay 4.32	→ (Off , x=4.32)
press?	→ (Light , x=0)
delay 2.51	→ (Light , x=2.51)
press?	→ (Bright , x=2.51)

Intelligent Light Controller



Intelligent Light Controller



Transitions:

	(Off , x=0)
delay 4.32	→ (Off , x=4.32)
press?	→ (Light , x=0)
delay 4.51	→ (Light , x=4.51)
press?	→ (Light , x=0)
delay 100	→ (Light , x=100)
τ	→ (Off , x=0)

Note: X

(Light , x=0) delay 103 →

Invariants ensures progress

Timed Automata (formally)

Constraints

Definition

Let X be a set of clock variables. The set $\mathcal{B}(X)$ of *clock constraints* ϕ is given by the grammar:

$$\phi \ ::= \ x \leq c \mid c \leq x \mid x < c \mid c < x \mid \phi_1 \wedge \phi_2$$

where $c \in \mathbb{N}$ (or $\mathbb{Q}$).

Timed Automata (formally)

Clock Valuations and Notation

Definition

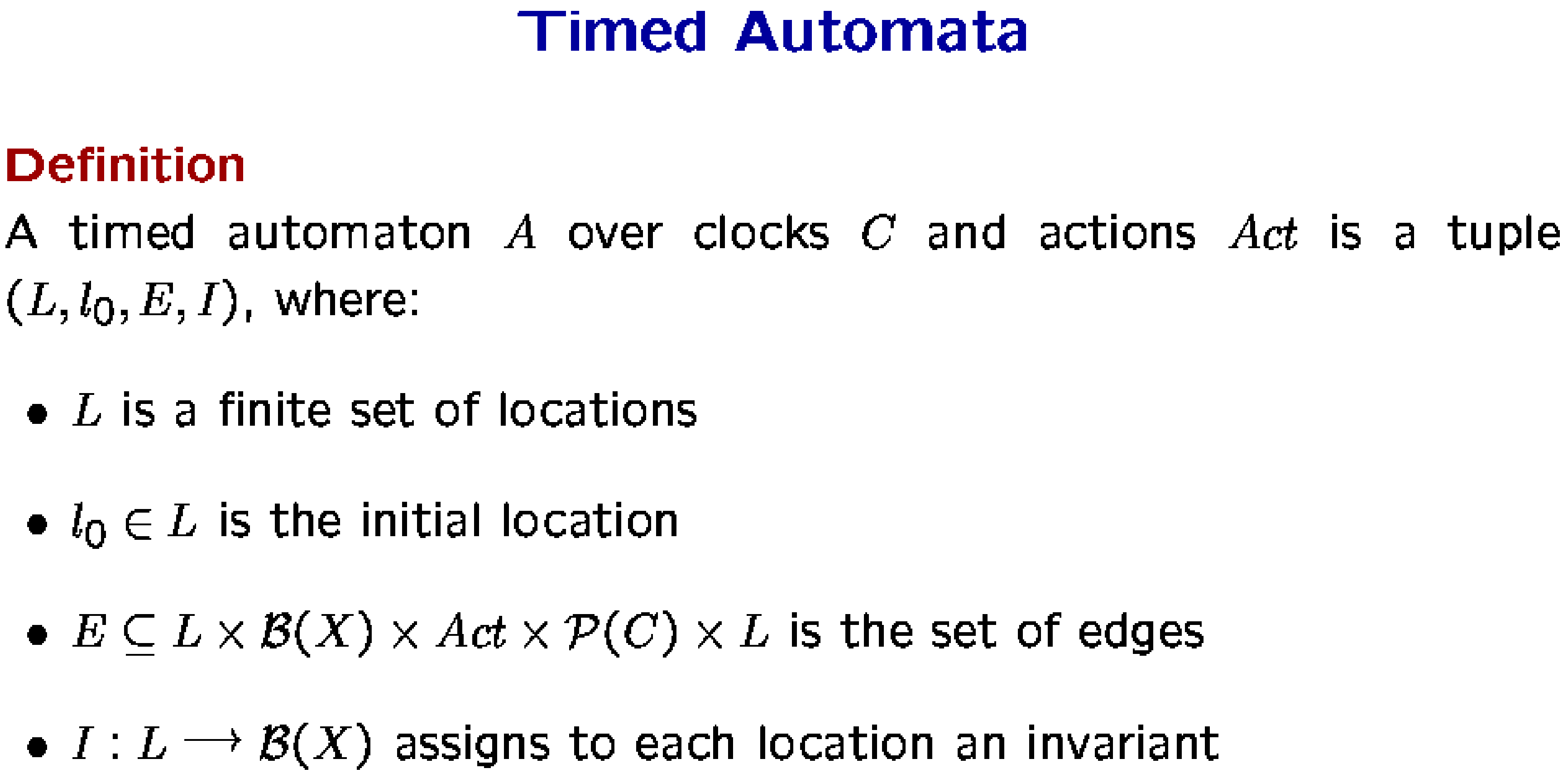
The set of *clock valuations*, $\mathbb{R}^C$ is the set of functions $C \longrightarrow \mathbb{R}_{\geq 0}$ ranged over by $u, v, w, \ldots$.

Notation

Let $u \in \mathbb{R}^C$, $r \subseteq C$, $d \in \mathbb{R}_{\geq 0}$, and $g \in \mathcal{B}(X)$ then:

- $u + d \in \mathbb{R}^C$ is defined by $(u + d)(x) = u(x) + d$ for any clock x
- $u[r] \in \mathbb{R}^C$ is defined by $u[r](x) = 0$ when $x \in r$ and $u[r](x) = u(x)$ for $x \notin r$.
- $u \models g$ denotes that g is satisfied by u.

Timed Automata (formally)



Timed Automata

Definition

A timed automaton A over clocks C and actions Act is a tuple (L, l_0, E, I), where:

- L is a finite set of locations
- $l_0 \in L$ is the initial location
- $E \subseteq L \times \mathcal{B}(X) \times Act \times \mathcal{P}(C) \times L$ is the set of edges
- $I : L \longrightarrow \mathcal{B}(X)$ assigns to each location an invariant

Timed Automata (formally)

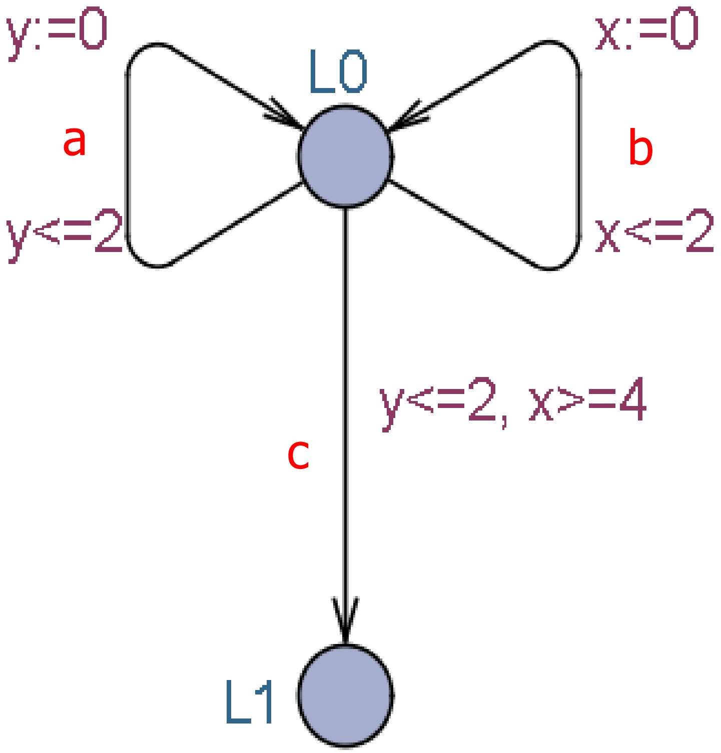
Semantics

Definition
The semantics of a timed automaton A is a labelled transition system with state space $L \times \mathbb{R}^C$ with initial state (l_0, u_0)* and with the following transitions:

- $(l, u) \xrightarrow{\epsilon(d)} (l, u + d)$ iff $u \in I(l)$ and $u + d \in I(l)$,
- $(l, u) \xrightarrow{a} (l', u')$ iff there exists $(l, g, a, r, l') \in E$ such that
  - $u \models g$,
  - $u' = u[r]$, and
  - $u' \in I(l')$

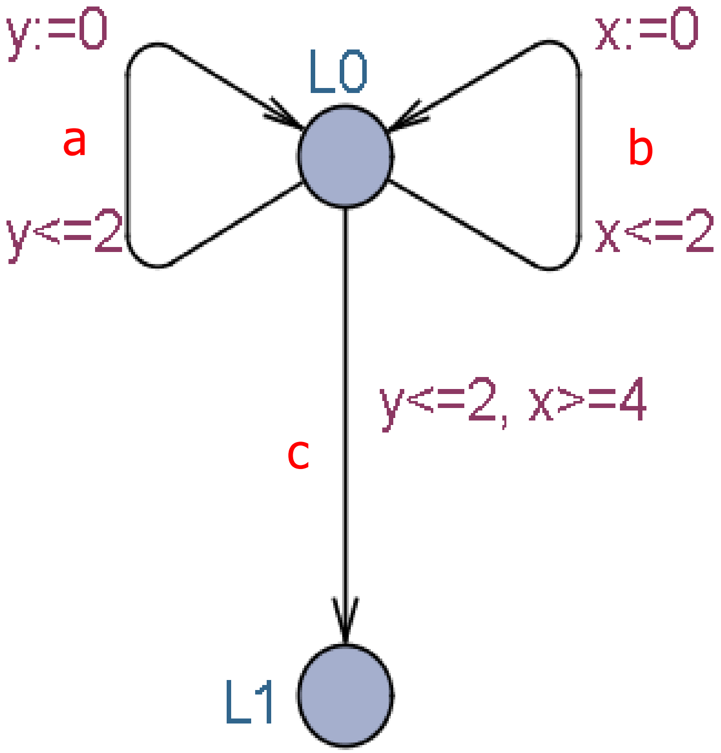
*$u_0(x) = 0$ for all $x \in C$

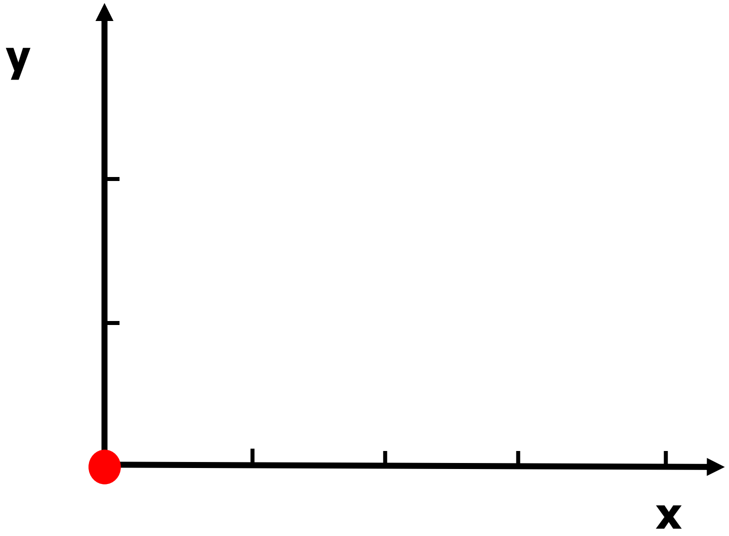
Example



Is L1 reachable ?

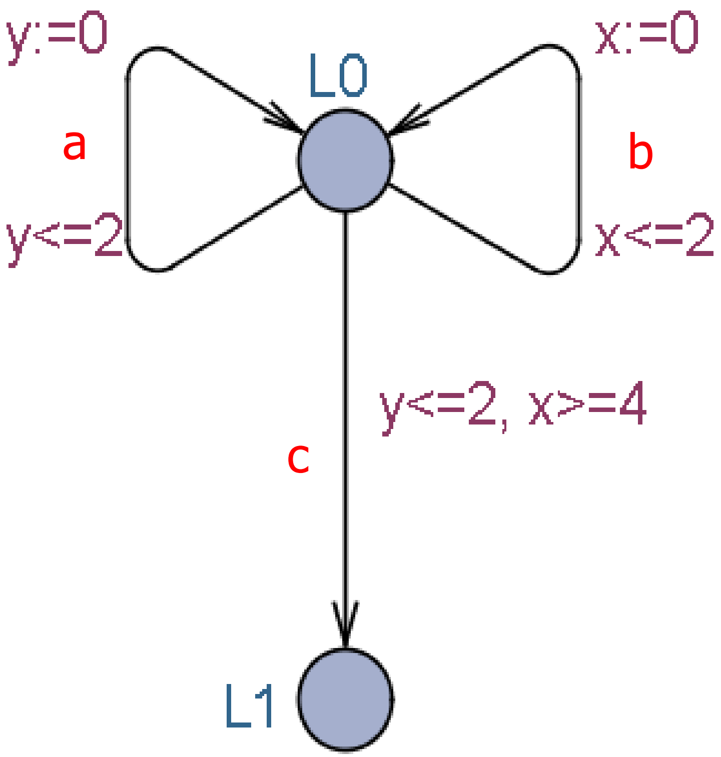
Example

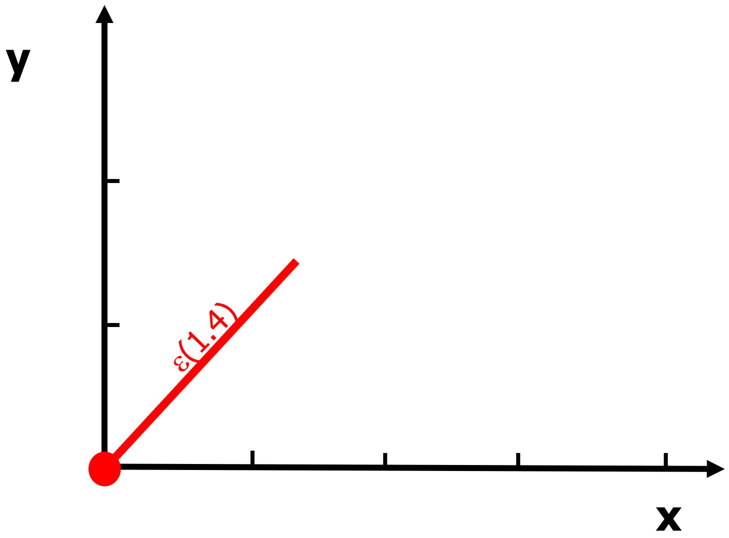




$(\ell_0, x = 0, y = 0)$

Example

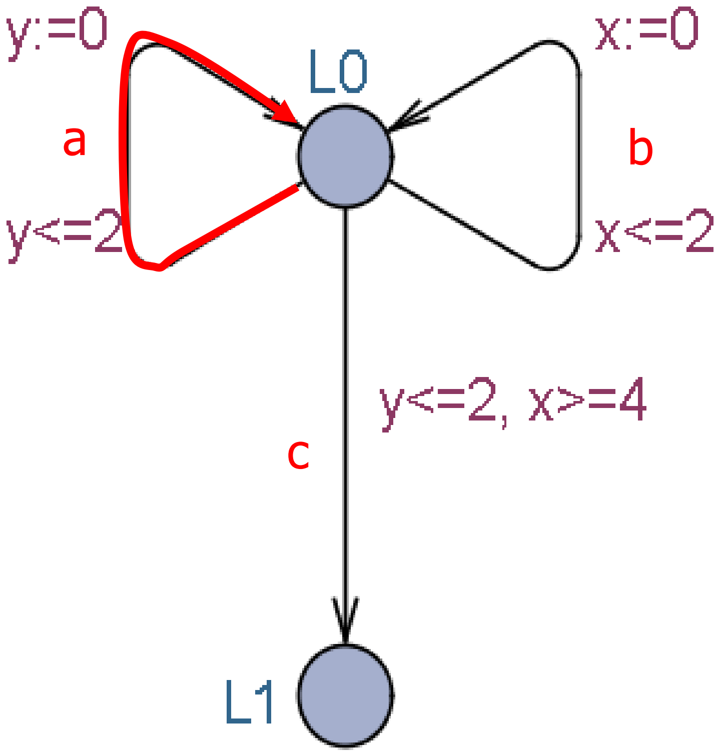


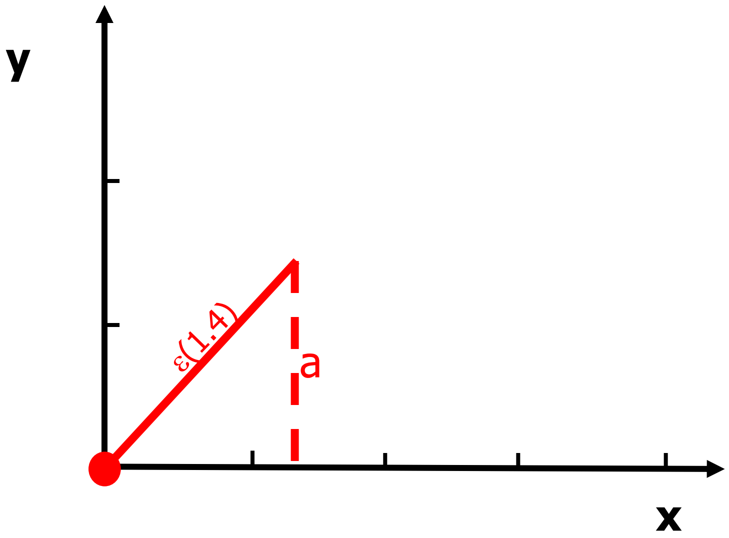


$$(\ell_0, x = 0, y = 0)$$

$$\xrightarrow{1.4} (\ell_0, x = 1.4, y = 1.4)$$

Example



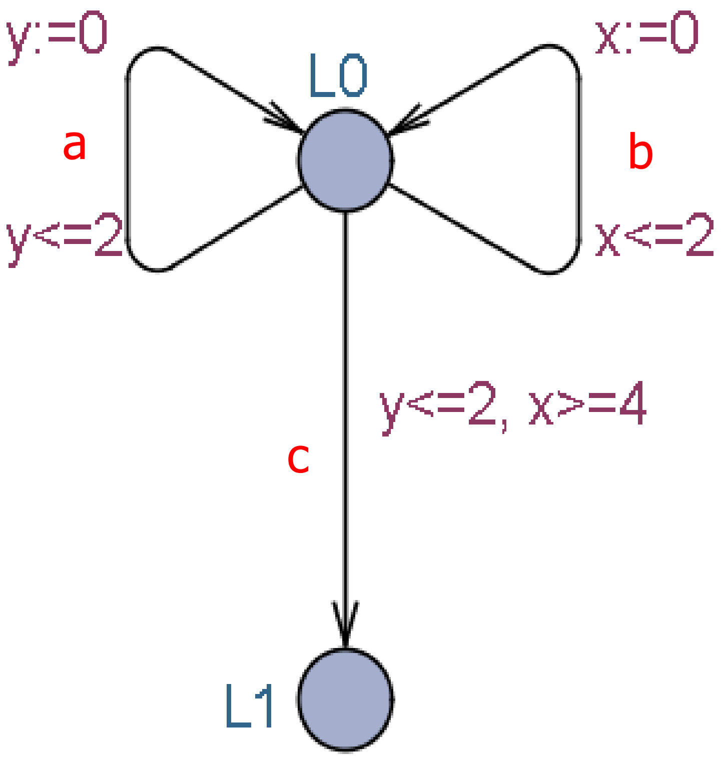


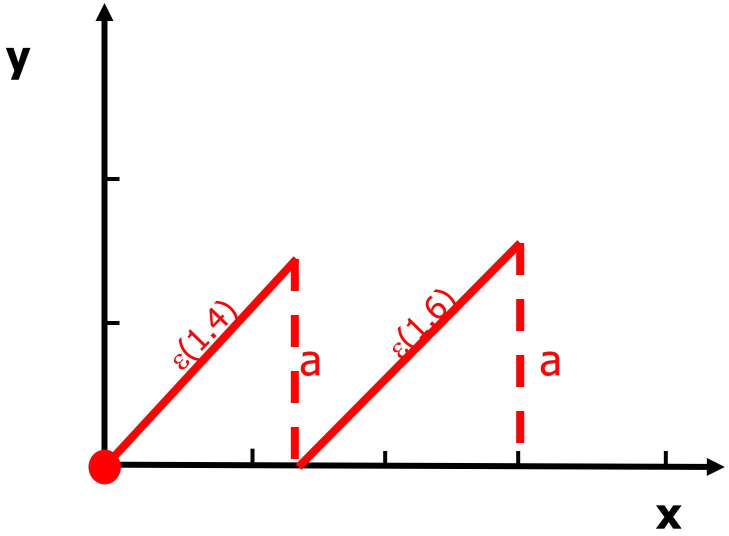
$(\ell_0, x = 0, y = 0)$

$\xrightarrow{1.4} (\ell_0, x = 1.4, y = 1.4)$

$\xrightarrow{a} (\ell_0, x = 1.4, y = 0)$

Example





$$(\ell_0, x=0, y=0)$$

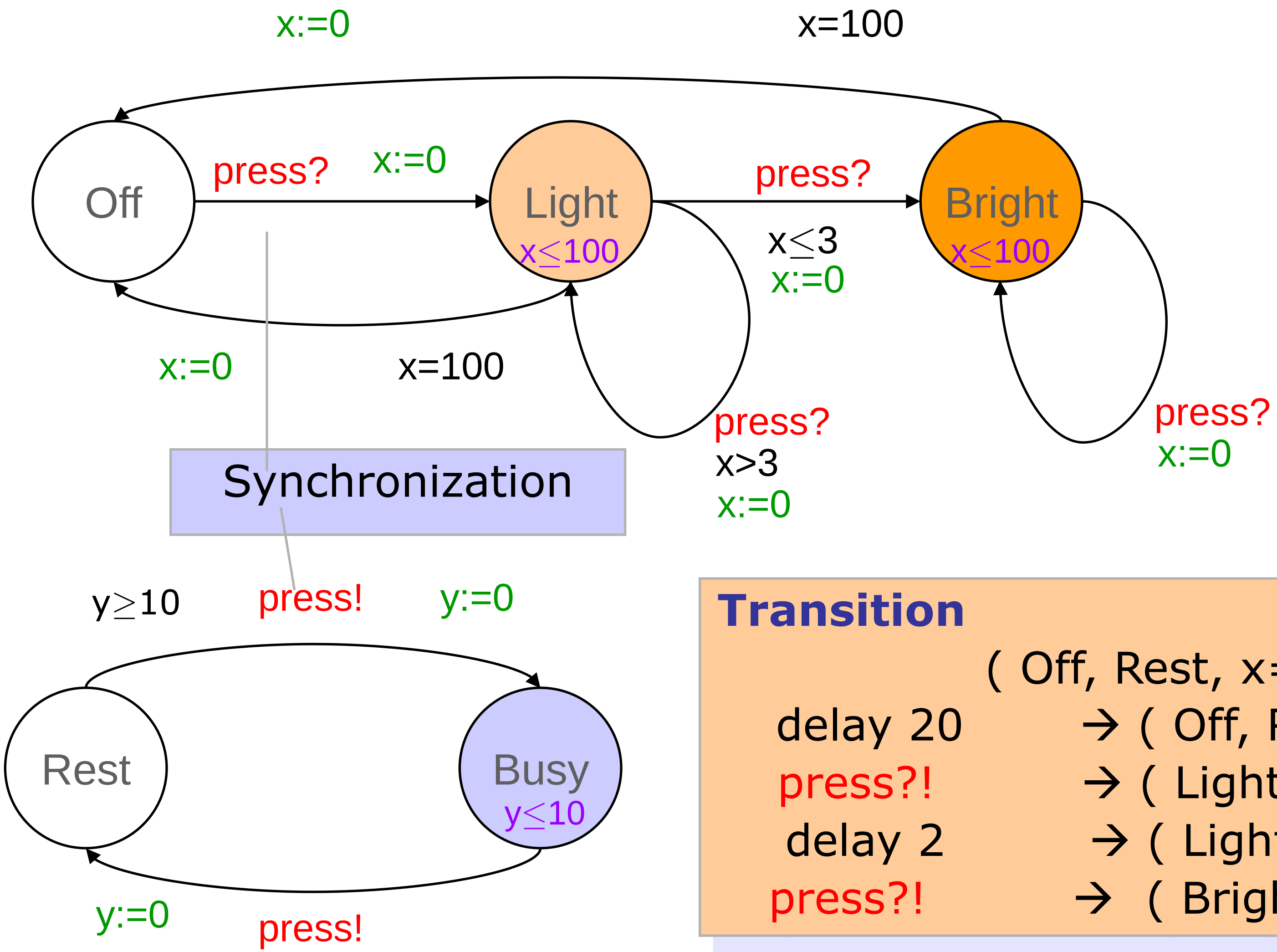
$$\xrightarrow{1.4} (\ell_0, x=1.4, y=1.4)$$

$$\xrightarrow{a} (\ell_0, x=1.4, y=0)$$

$$\xrightarrow{1.6} (\ell_0, x=3.0, y=1.6)$$

$$\xrightarrow{a} (\ell_0, x=3.0, y=0)$$

Networks Light Controller & User



Transition

	(Off, Rest, x=0, y=0)
delay 20	→ (Off, Rest, x=20, y=20)
press?!	→ (Light, Busy, x=0, y=0)
delay 2	→ (Light, Busy, x=2, y=2)
press?!	→ (Bright, Rest, x=0, y=0)

Network Semantics

$T_1 \|_X T_2 = (S_1 \times S_2, \rightarrow, s_0^1 \|_X s_0^2)$ where

$$\frac{s_1 \xrightarrow{\mu}_1 s_1'}{s_1 \|_X s_2 \xrightarrow{\mu} s_1' \|_X s_2} \qquad \frac{s_2 \xrightarrow{\mu}_2 s_2'}{s_1 \|_X s_2 \xrightarrow{\mu} s_1 \|_X s_2'}$$

$$\frac{s_1 \xrightarrow{a!}_1 s_1' \qquad s_2 \xrightarrow{a?}_2 s_2'}{s_1 \|_X s_2 \xrightarrow{\tau} s_1' \|_X s_2'}$$

$$\frac{s_1 \xrightarrow{e(d)}_1 s_1' \qquad s_2 \xrightarrow{e(d)}_2 s_2'}{s_1 \|_X s_2 \xrightarrow{e(d)} s_1' \|_X s_2'}$$

Network Semantics

(URGENT synchronization)

+ Urgent synchronization

$$T_1 \|_X T_2 = (S_1 \times S_2, \rightarrow, s_0^1 \|_X s_0^2)$$ where

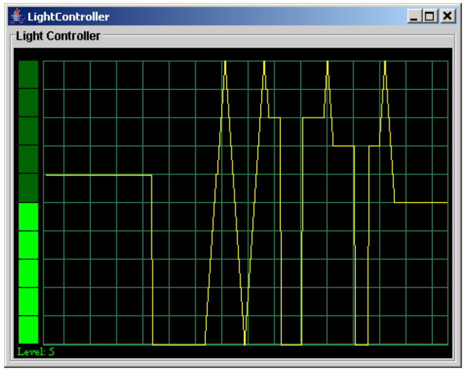
$$\frac{s_1 \xrightarrow{\mu}_1 s_1'}{s_1 \|_X s_2 \xrightarrow{\mu} s_1' \|_X s_2} \qquad \frac{s_2 \xrightarrow{\mu}_2 s_2'}{s_1 \|_X s_2 \xrightarrow{\mu} s_1 \|_X s_2'}$$

$$\frac{s_1 \xrightarrow{a!}_1 s_1' \qquad s_2 \xrightarrow{a?}_2 s_2'}{s_1 \|_X s_2 \xrightarrow{\tau} s_1' \|_X s_2'}$$

$\forall d' < d, \forall u \in \mathrm{UAct}:$

$\neg (s_1 \xrightarrow{e(d')} \xrightarrow{u?} \wedge s_2 \xrightarrow{e(d')} \xrightarrow{u!})$

$$\frac{s_1 \xrightarrow{e(d)}_1 s_1' \qquad s_2 \xrightarrow{e(d)}_2 s_2'}{s_1 \|_X s_2 \xrightarrow{e(d)} s_1' \|_X s_2'}$$

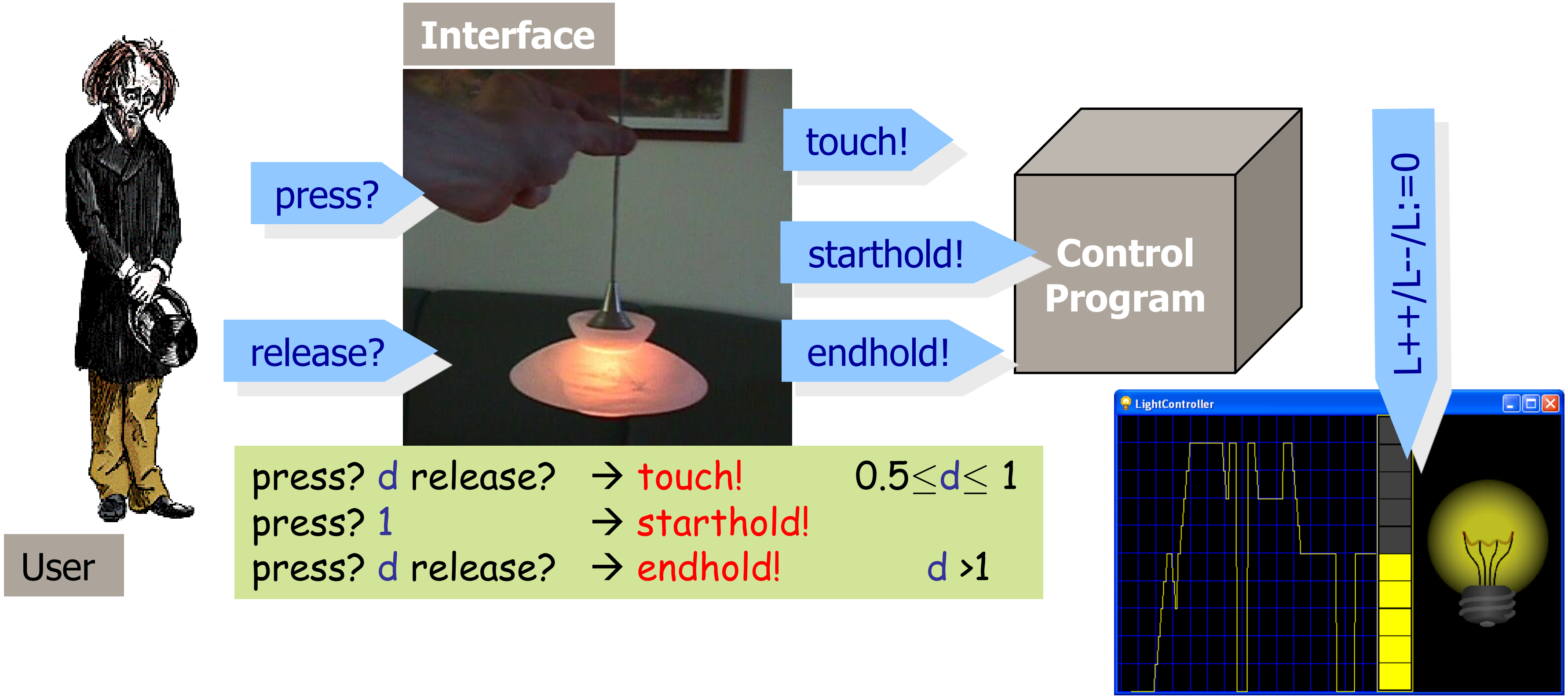


Light Control Interface

Light Control Interface

press? 0.2 release? ... press? 0.7 release? ... press? 1.0 2.4 release? ...

∅ touch! starthold! endhold!

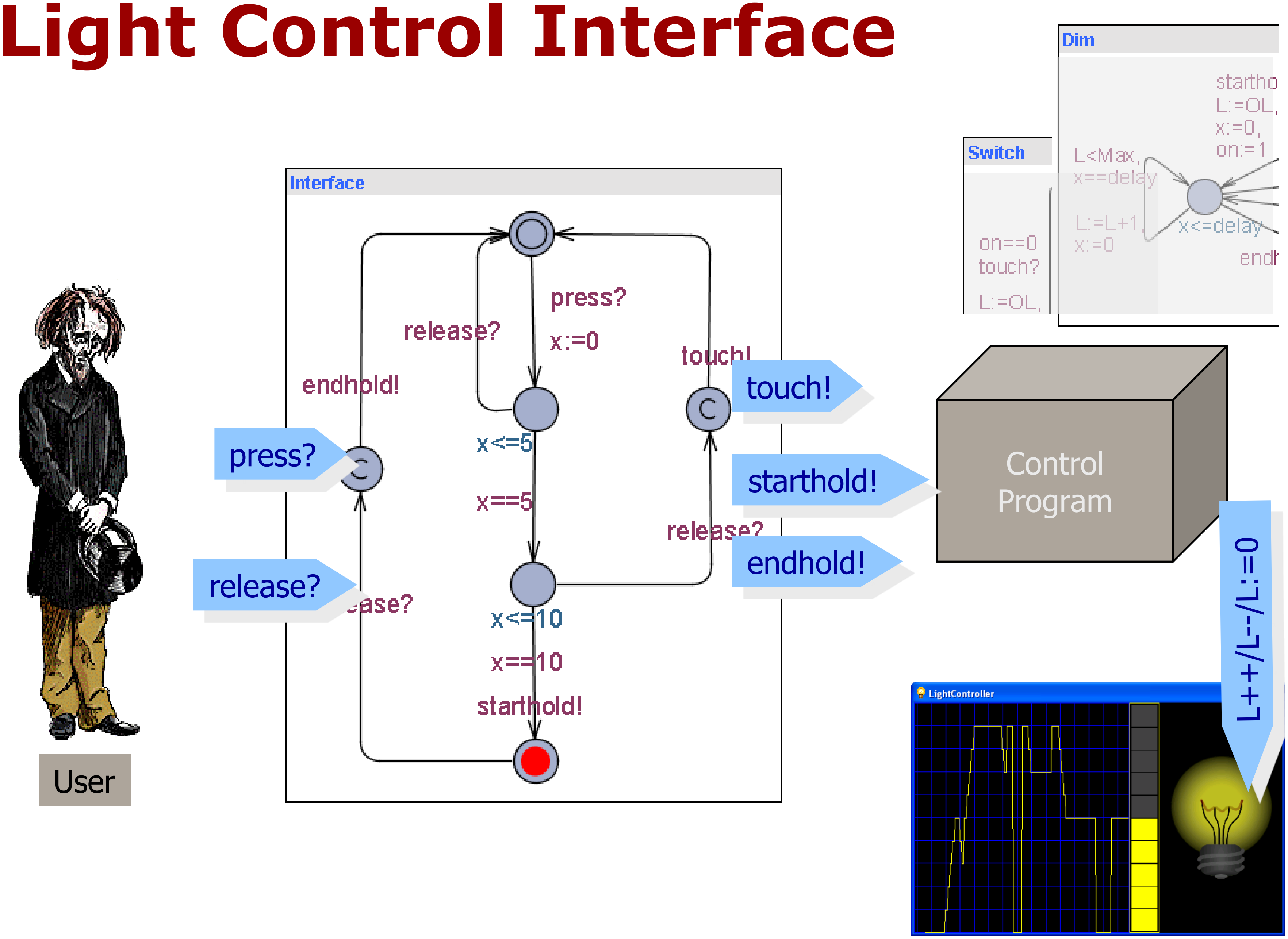


press? d release? → touch! 0.5≤d≤ 1

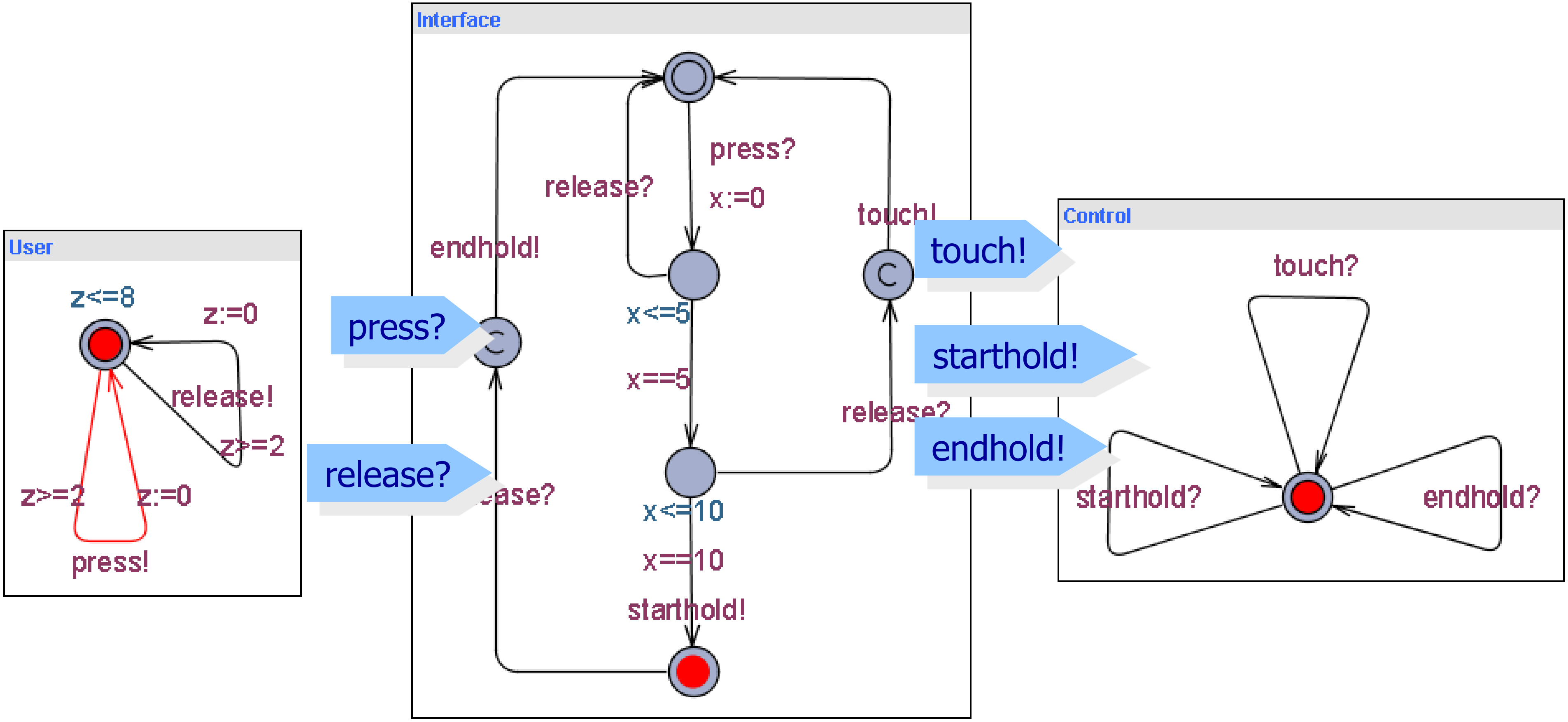
press? 1 → starthold!

press? d release? → endhold! d >1

Light Control Interface



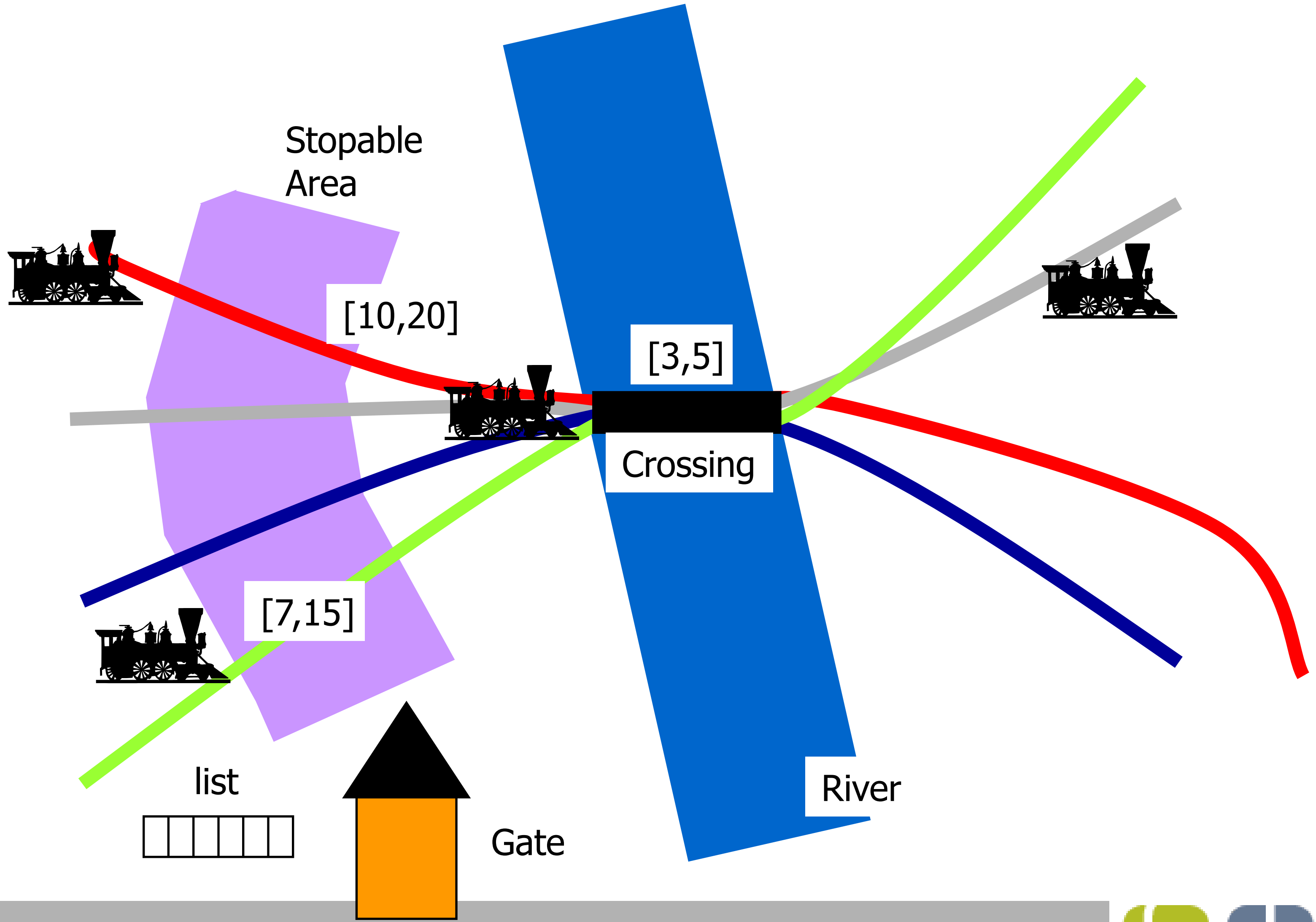
Light Control Network



UPPAAL

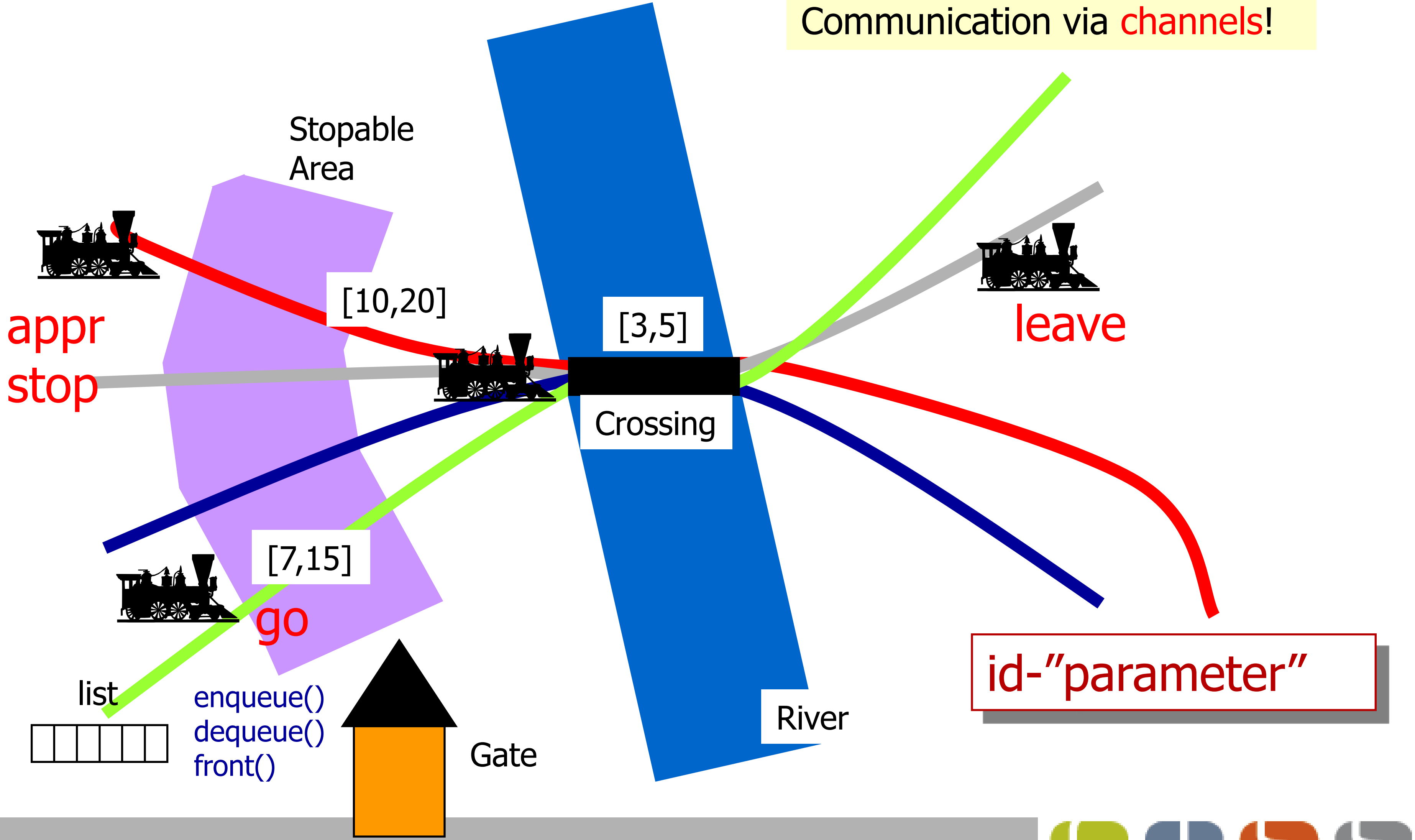
Modeling & Specification

Train Crossing

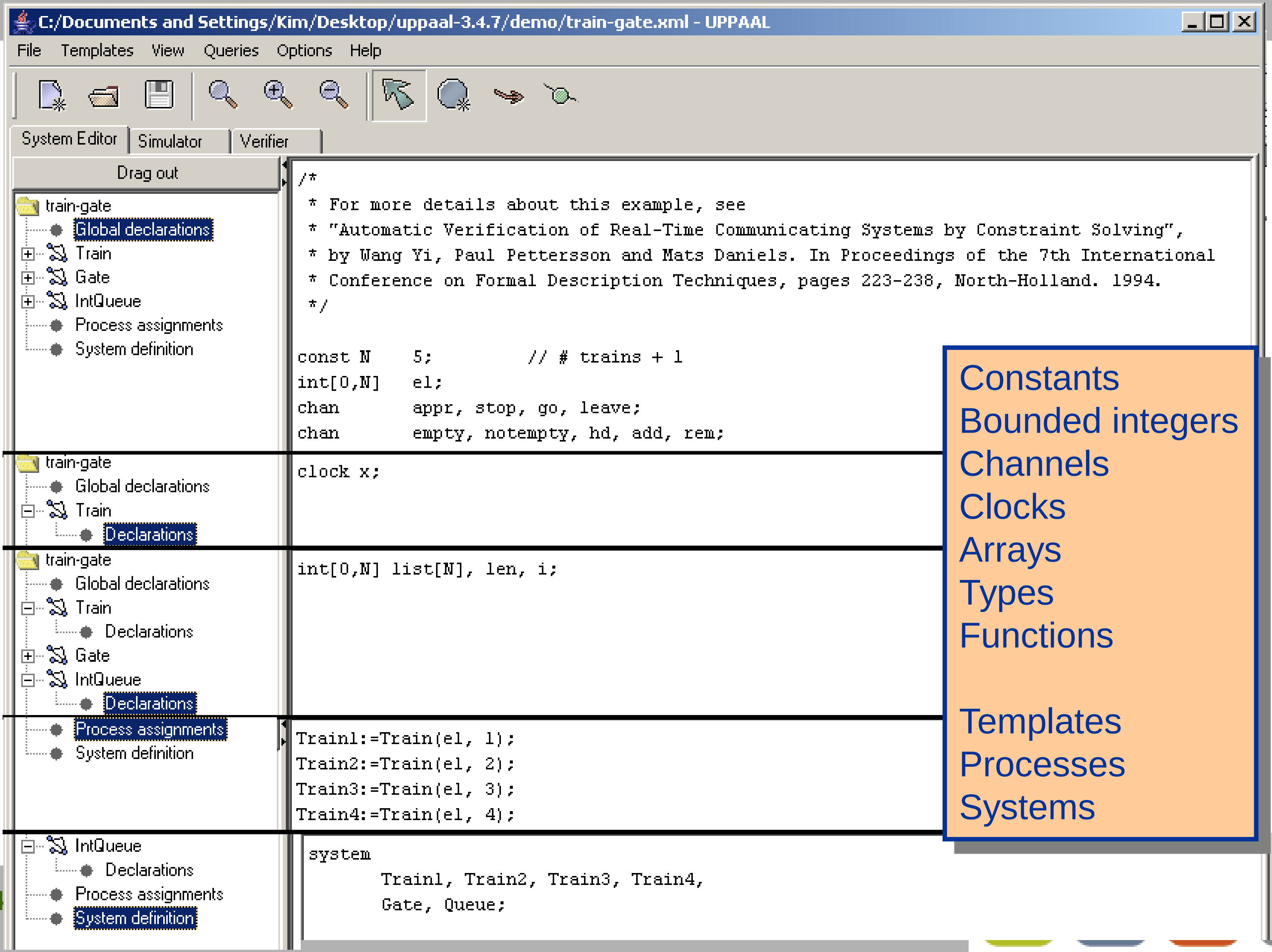


Train Crossing

Communication via channels!



Declarations



```
/*
 * For more details about this example, see
 * "Automatic Verification of Real-Time Communicating Systems by Constraint Solving",
 * by Wang Yi, Paul Pettersson and Mats Daniels. In Proceedings of the 7th International
 * Conference on Formal Description Techniques, pages 223-238, North-Holland. 1994.
 */

const N    5;         // # trains + 1
int[0,N]   el;
chan       appr, stop, go, leave;
chan       empty, notempty, hd, add, rem;
```

```
clock x;
```

```
int[0,N] list[N], len, i;
```

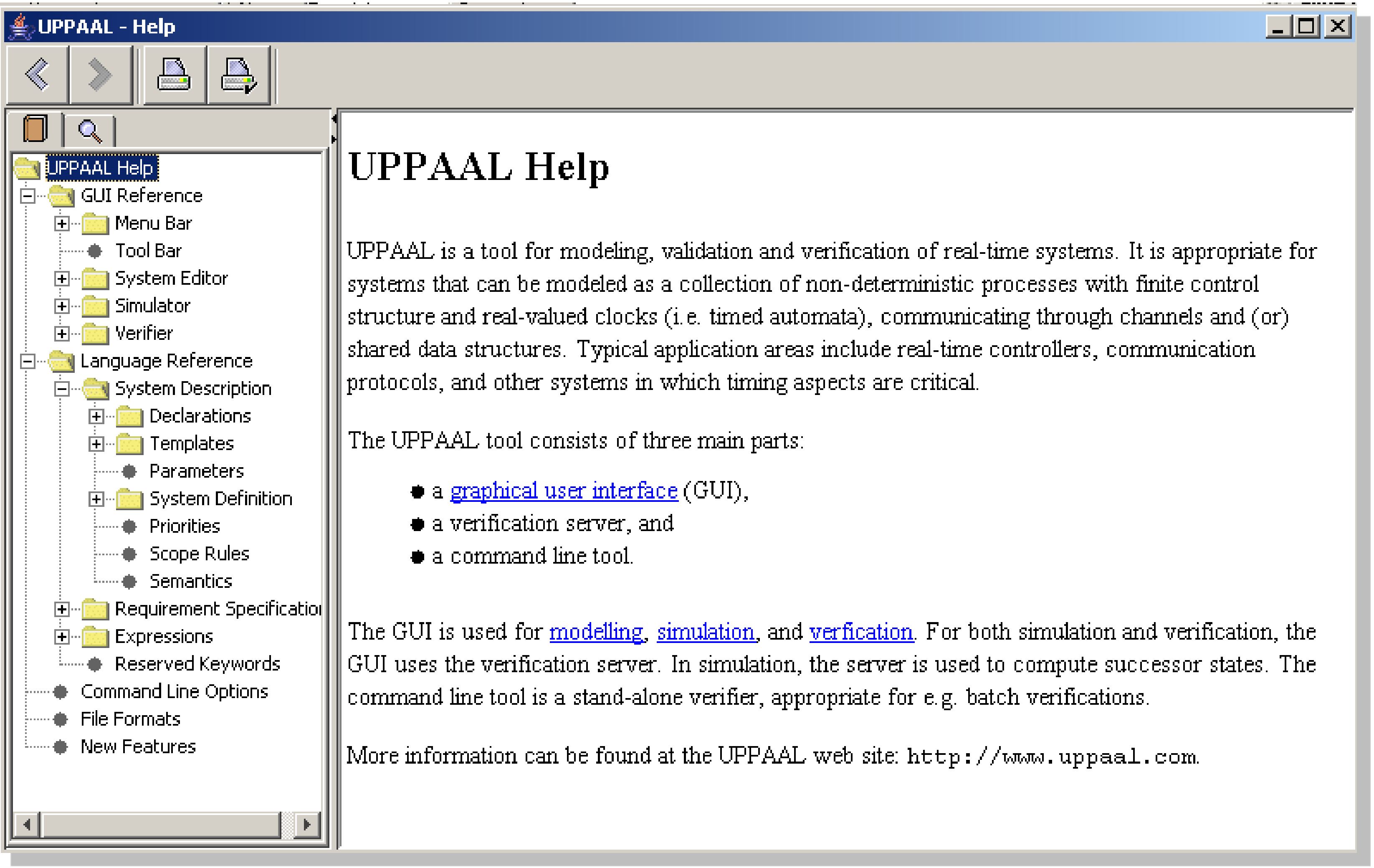
```
Train1:=Train(el, 1);
Train2:=Train(el, 2);
Train3:=Train(el, 3);
Train4:=Train(el, 4);
```

```
system
       Train1, Train2, Train3, Train4,
       Gate, Queue;
```

Constants
Bounded integers
Channels
Clocks
Arrays
Types
Functions

Templates
Processes
Systems

UPPAAL Help



UPPAAL Help

UPPAAL is a tool for modeling, validation and verification of real-time systems. It is appropriate for systems that can be modeled as a collection of non-deterministic processes with finite control structure and real-valued clocks (i.e. timed automata), communicating through channels and (or) shared data structures. Typical application areas include real-time controllers, communication protocols, and other systems in which timing aspects are critical.

The UPPAAL tool consists of three main parts:

- a graphical user interface (GUI),
- a verification server, and
- a command line tool.

The GUI is used for modelling, simulation, and verfication. For both simulation and verification, the GUI uses the verification server. In simulation, the server is used to compute successor states. The command line tool is a stand-alone verifier, appropriate for e.g. batch verifications.

More information can be found at the UPPAAL web site: `http://www.uppaal.com`.

Logical Specifications

- Validation Properties
  - Possibly: E<> P
- Safety Properties
  - Invariant: A[] P
  - Pos. Inv.: E[] P
- Liveness Properties
  - Eventually: A<> P
  - Leadsto: $\mathrm{P} \rightarrow Q$
- Bounded Liveness
  - Leads to within: $P \rightarrow_{\leq \mathrm{t}} Q$

The expressions P and Q must be type safe, side effect free, and evaluate to a boolean.

Only references to integer variables, constants, clocks, and locations are allowed (and arrays of these).

Case Studies: Controllers

- Gearbox Controller [TACAS'98]
- Bang & Olufsen Power Controller [RTPS'99,FTRTFT'2k]
- SIDMAR Steel Production Plant [RTCSA'99, DSVV'2k]
- Real-Time RCX Control-Programs [ECRTS'2k]
- Terma, Verification of Memory Management for Radar (2001)
- Scheduling Lacquer Production (2005)
- Memory Arbiter Synthesis and Verification for a Radar Memory Interface Card [NJC'05]

- Adapting the UPPAAL Model of a Distributed Lift System, 2007
- Analyzing a χ model of a turntable system using Spin, CADP and Uppaal, 2006
- **Designing, Modelling and Verifying a Container Terminal System Using UPPAAL, 2008**
- Model-based system analysis using Chi and Uppaal: An industrial case study, 2008
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- Bang & Olufsen Audio/Video Protocol [RTSS'97]
- TDMA Protocol [PRFTS'97]
- Lip-Synchronization Protocol [FMICS'97]
- ATM ABR Protocol [CAV'99]
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- Analysis of a protocol for dynamic configuration of IPv4 link local addresses using Uppaal, 2006
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Using UPPAAL as Back-end

- Vooduu: verification of object-oriented designs using Uppaal, 2004
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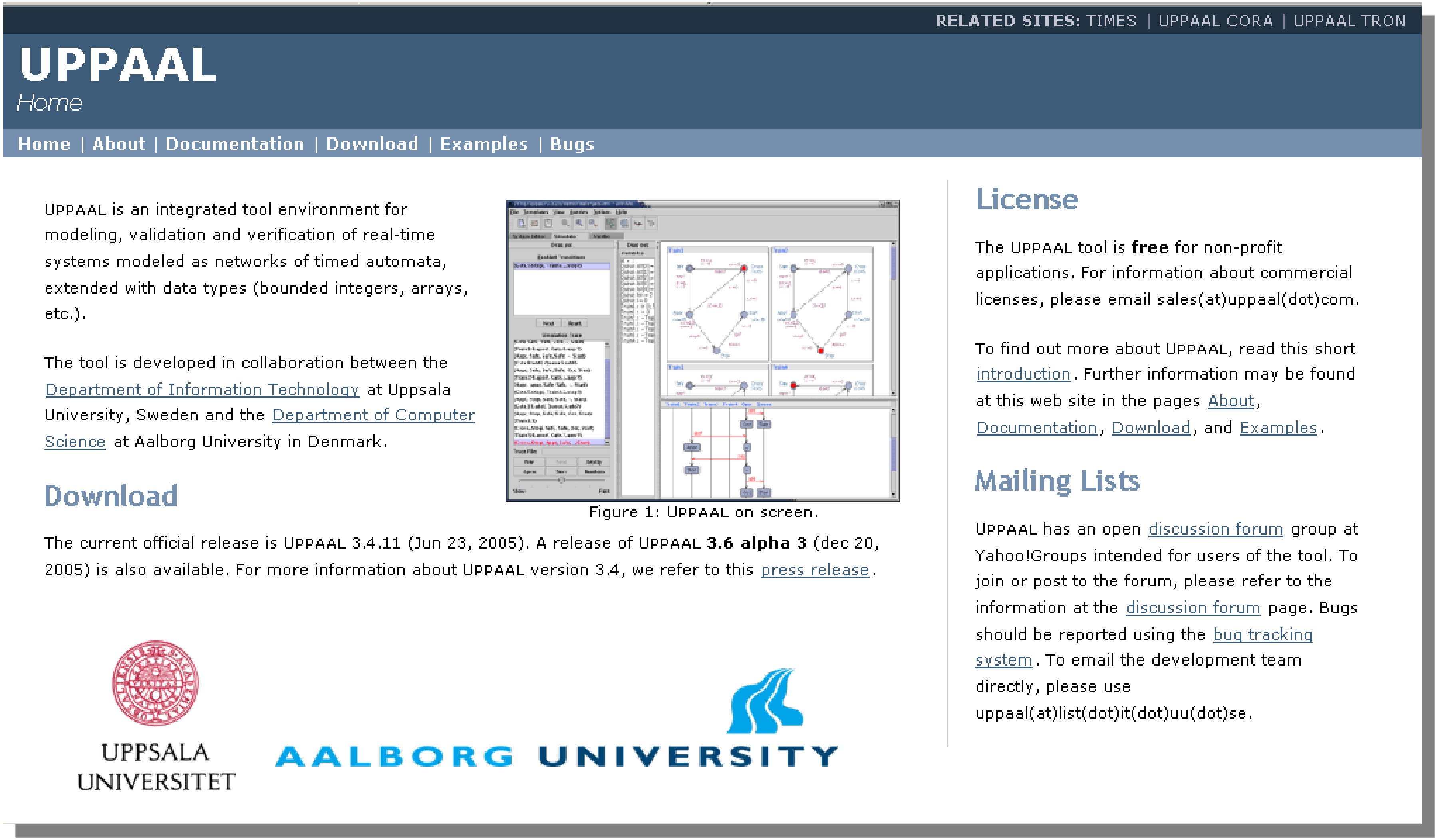

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UPPAAL is an integrated tool environment for modeling, validation and verification of real-time systems modeled as networks of timed automata, extended with data types (bounded integers, arrays, etc.).

The tool is developed in collaboration between the Department of Information Technology at Uppsala University, Sweden and the Department of Computer Science at Aalborg University in Denmark.

Figure 1: UPPAAL on screen.

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The current official release is UPPAAL 3.4.11 (Jun 23, 2005). A release of UPPAAL **3.6 alpha 3** (dec 20, 2005) is also available. For more information about UPPAAL version 3.4, we refer to this press release.

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The UPPAAL tool is **free** for non-profit applications. For information about commercial licenses, please email sales(at)uppaal(dot)com.

To find out more about UPPAAL, read this short introduction. Further information may be found at this web site in the pages About, Documentation, Download, and Examples.

Mailing Lists

UPPAAL has an open discussion forum group at Yahoo!Groups intended for users of the tool. To join or post to the forum, please refer to the information at the discussion forum page. Bugs should be reported using the bug tracking system. To email the development team directly, please use uppaal(at)list(dot)it(dot)uu(dot)se.

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