

5. Real-time models: Timed Automata

José Proença

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CISTER – U.Porto, Porto, Portugal

<https://fm-dcc.github.io/sv2425>



CISTER - Research Centre in
Real-Time & Embedded
Computing Systems

Motivation

Specifying an airbag saying that **in a car crash the airbag eventually inflates** maybe not enough, but:

in a car crash the airbag eventually inflates **within 20ms**

*Correctness in time-critical systems not only depends on the logical result of the computation, but also **on the time at which the results are produced***

[Baier & Katoen, 2008]

Lip-synchronization protocol

Synchronizes the separate video and audio sources bounding on the amount of time mediating the presentation of a video frame and the corresponding audio frame. Humans tolerate less than 160 ms.

Bounded retransmission protocol

Controls communication of large files over infrared channel between a remote control unit and a video/audio equipment. Correctness depends crucially on

- transmission and synchronization delays
- time-out values for times at sender and receiver

And many others...

- medical instruments
- hybrid systems (eg for controlling industrial plants)

- Introduction to model-checking
- CCS: a simple language for concurrency
 - Syntax
 - Semantics
 - Equivalence
 - mCRL2: modelling
- Dynamic logic
 - Syntax
 - Semantics
 - Relation with equivalence
 - mCRL2: verification
- Timed Automata
 - Syntax
 - Semantics (composition, Zeno)
 - Equivalence
 - UPPAAL: modelling
- Temporal logics (LTL/CTL)
 - Syntax
 - Semantics
 - UPPAAL: verification
- Probabilistic and stochastic systems
 - Going probabilistic
 - UPPAAL: monte-carlo

1. Motivation
2. Timed Automata
3. Semantics
4. Modelling in UPPAAL

- **timed transition systems**, **timed Petri nets**, **timed IO automata**, **timed process algebras** and other formalisms associate lower and upper bounds to transitions, but no **time constraints** to transverse the automaton.
- Expressive power is often somehow limited and **infinite-state LTS** (introduced to express **dense** time models) are difficult to handle in practice

Example

Typical process algebra tools are unable to express a system which has one action a which can only occur at time point 5 with the effect of moving the system to its initial state.

This example has, however, a simple description in terms of time measured by a stopwatch:

1. Set the stopwatch to 0
2. When the stopwatch measures 5, action a can occur. If a occurs go to 1., if not idle forever.

This suggests resorting to an **automaton-based formalism** with an explicit notion of **clock** (stopwatch) to control availability of transitions.

Timed Automata [Alur & Dill, 90]

- emphasis on decidability of the **reachability** problem and corresponding practically efficient algorithms
- infinite underlying timed transition systems are converted to **finitely large** symbolic transition systems where **reachability** becomes decidable (**region** or **zone** graphs)

Associated tools

- UPPAAL [Behrmann, David, Larsen, 04]
- IMITATOR [André, 09]
- PRISM [Parker, Kwiatkowska, 00]
- KRONOS [Bozga, 98]

UPPAAL = (Uppsala University + Aalborg University) [1995]

- A toolbox for modeling, simulation and verification of real-time systems
- where systems are modeled as networks of timed automata enriched with integer variables, structured data types, channel synchronisations and urgency annotations
- Properties are specified in a subset of CTL

www.uppaal.org

Timed Automata

Finite-state machine equipped with a finite set of real-valued clock variables (**clocks**)

Clocks

- **dense-time** model
- clocks can only be **inspected** or
- **reset to zero**, after which they start increasing their value implicitly as time progresses
- the value of a clock corresponds to time elapsed since its last reset
- all clocks proceed synchronously (at the same rate)

$$\langle L, L_0, \text{Act}, C, \text{Tr}, \text{Inv} \rangle$$

where

- L is a set of **locations**, and $L_0 \subseteq L$ the set of **initial** locations
- Act is a set of **actions** and C a set of **clocks**
- $\text{Tr} \subseteq L \times \mathcal{C}(C) \times \text{Act} \times \mathcal{P}(C) \times L$ is the **transition relation**

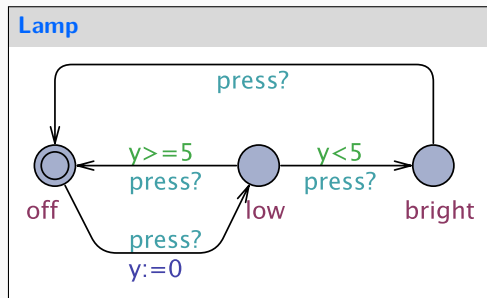
$$\ell_1 \xrightarrow{g, a, U} \ell_2$$

denotes a transition from location ℓ_1 to ℓ_2 , **labelled** by a , enabled if **guard** g is valid, which, when performed, **resets** the set U of **clocks**

- $\text{Inv} : L \longrightarrow \mathcal{C}(C)$ is the assignment of **invariants** to locations

where $\mathcal{C}(C)$ denotes the set of clock constraints over a set C of clock variables

(extracted from UPPAAL)



Ex. 5.1: Define $\langle L, L_0, Act, C, Tr, Inv \rangle$.

$\mathcal{C}(C)$ denotes the set of clock constraints over a set C of clock variables. Each constraint is formed according to

$$g ::= x \square n \mid x - y \square n \mid g \wedge g \mid \text{true}$$

where $x, y \in C, n \in \mathbb{N}$ and $\square \in \{<, \leq, >, \geq, =\}$

used in

- **transitions** as **guards** (enabling conditions)

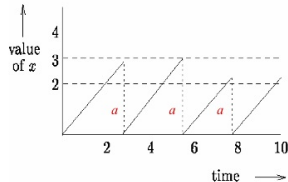
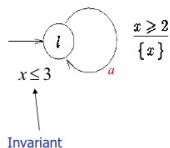
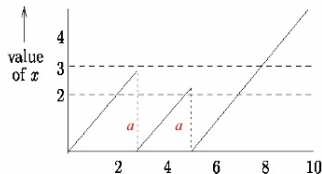
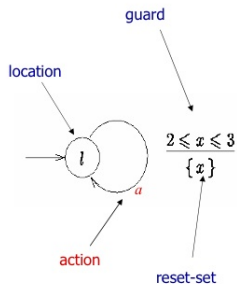
a transition cannot occur if its guard is invalid

- **locations** as **invariants** (safety specifications)

a location must be left before its invariant becomes invalid

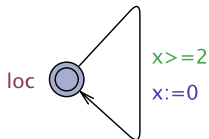
Note

Invariants are the **only** way to force transitions to occur

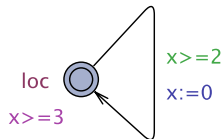


Demo (in Uppaal)

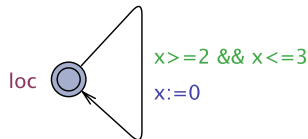
Process 1



Process 2



Process 3



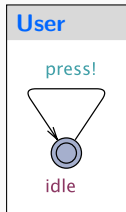
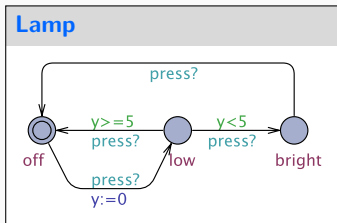
- Action labels as **channel** identifiers
- Communication by **forced handshaking** over a subset of common actions
- Is defined as an automaton construction over a finite set of timed automata originating a so-called **network** of timed automata

Let $H \subseteq (Act_1 \cap Act_2) - \{\tau\}$. The parallel composition of ta_1 and ta_2 synchronizing on H is the timed automata

$$ta_1 \parallel_H ta_2 := \langle L_1 \times L_2, L_{0,1} \times L_{0,2}, Act_{\parallel_H}, C_1 \cup C_2, Tr_{\parallel_H}, Inv_{\parallel_H} \rangle$$

where

- $Act_{\parallel_H} = ((Act_1 \cup Act_2) - H) \cup \{\tau\}$
- $Inv_{\parallel_H} \langle \ell_1, \ell_2 \rangle = Inv_1(\ell_1) \wedge Inv_2(\ell_2)$
- Tr_{\parallel_H} is given by:
 - $\langle \ell_1, \ell_2 \rangle \xrightarrow{g,a,U} \langle \ell'_1, \ell_2 \rangle$ if $a \notin H \wedge \ell_1 \xrightarrow{g,a,U} \ell'_1$
 - $\langle \ell_1, \ell_2 \rangle \xrightarrow{g,a,U} \langle \ell_1, \ell'_2 \rangle$ if $a \notin H \wedge \ell_2 \xrightarrow{g,a,U} \ell'_2$
 - $\langle \ell_1, \ell_2 \rangle \xrightarrow{g,\tau,U} \langle \ell'_1, \ell'_2 \rangle$ if $a \in H \wedge \ell_1 \xrightarrow{g_1,a,U_1} \ell'_1 \wedge \ell_2 \xrightarrow{g_2,a,U_2} \ell'_2$
with $g = g_1 \wedge g_2$ and $U = U_1 \cup U_2$

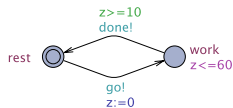


Uppaal:

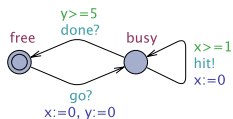
- takes $H = Act_1 \cap Act_2$ (actually as **complementary** actions denoted by the ? and ! annotations)
- only deals with **closed** systems

Ex. 5.2: Define the TA of the composition.

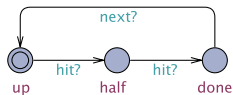
Worker



Hammer



Nail



Ex. 5.3: Define the TA of the composition.

Semantics

Syntax <i>(How to write)</i>	Semantics <i>(How to execute)</i>
Process Languages	LTS (Labelled Transition Systems)
Timed Automaton	TLTS (Timed LTS)

Syntax (How to write)	Semantics (How to execute)
Process Languages Timed Automaton	LTS (Labelled Transition Systems) TLTS (Timed LTS)

Timed LTS

Introduce **delay transitions** to capture the passage of time within a LTS:

$s \xrightarrow{a} s'$ for $a \in Act$, are ordinary transitions due to action occurrence

$s \xrightarrow{d} s'$ for $d \in R_0^+$, are **delay** transitions

subject to a number of constraints, eg,

Timed LTS

- time additivity

$$(s \xrightarrow{d} s' \wedge 0 \leq d' \leq d) \Rightarrow s \xrightarrow{d'} s'' \xrightarrow{d-d'} s' \text{ for some state } s''$$

- delay transitions are deterministic

$$(s \xrightarrow{d} s' \wedge s \xrightarrow{d} s'') \Rightarrow s' = s''$$

Semantics of TA:

Every TA ta defines a TLTS

$$\mathcal{T}(ta)$$

whose states are pairs

$\langle \text{location}, \text{clock valuation} \rangle$

with **infinitely**, even **uncountably** many states, and infinite branching

Definition

A **clock valuation** η for a set of clocks C is a function

$$\eta : C \longrightarrow \mathcal{R}_0^+$$

assigning to each clock $x \in C$ its current value ηx .

Satisfaction of clock constraints

$$\eta \models x \sqcap n \Leftrightarrow \eta x \sqcap n$$

$$\eta \models x - y \sqcap n \Leftrightarrow (\eta x - \eta y) \sqcap n$$

$$\eta \models g_1 \wedge g_2 \Leftrightarrow \eta \models g_1 \wedge \eta \models g_2$$

Delay

For each $d \in \mathcal{R}_0^+$, valuation $\eta + d$ is given by

$$(\eta + d)x = \eta x + d$$

Reset

For each $R \subseteq C$, valuation $\eta[R]$ is given by

$$\begin{cases} \eta[R]x = \eta x & \Leftarrow x \notin R \\ \eta[R]x = 0 & \Leftarrow x \in R \end{cases}$$

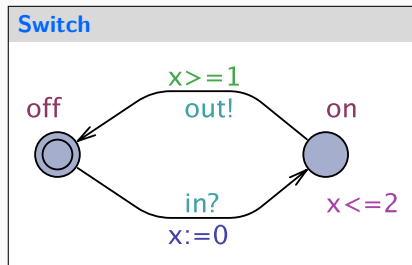
Let $ta = \langle L, L_0, Act, C, Tr, Inv \rangle$

$$\mathcal{T}(ta) = \langle S, S_0 \subseteq S, N, T \rangle$$

where

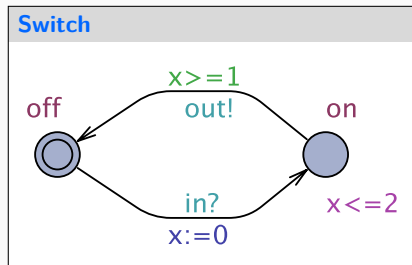
- $S = \{ \langle l, \eta \rangle \in L \times (\mathcal{R}_0^+)^C \mid \eta \models Inv(l) \}$
- $S_0 = \{ \langle \ell_0, \eta \rangle \mid \ell_0 \in L_0 \wedge \eta x = 0 \text{ for all } x \in C \}$
- $N = Act \cup \mathcal{R}_0^+$ (ie, transitions can be labelled by actions or delays)
- $T \subseteq S \times N \times S$ is given by:

$$\begin{aligned} \langle l, \eta \rangle \xrightarrow{a} \langle l', \eta' \rangle &\Leftarrow \exists_{l \xrightarrow{g, a, U} l' \in Tr} \eta \models g \wedge \eta' = \eta[U] \wedge \eta' \models Inv(l') \\ \langle l, \eta \rangle \xrightarrow{d} \langle l, \eta + d \rangle &\Leftarrow \exists_{d \in \mathcal{R}_0^+} \eta + d \models Inv(l) \end{aligned}$$



Ex. 5.4: Define $\mathcal{T}(\text{SwitchA})$

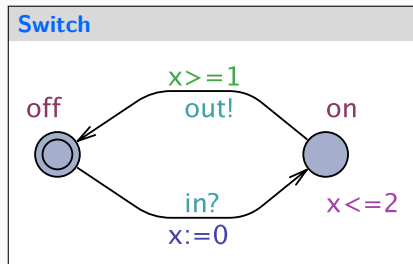
$S =$



Ex. 5.4: Define $\mathcal{T}(\text{SwitchA})$

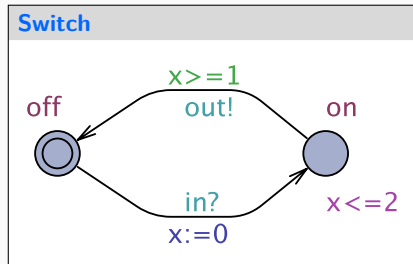
$$S = \{\langle \text{off}, \bar{t} \rangle \mid t \in \mathcal{R}_0^+\} \cup \{\langle \text{on}, \bar{t} \rangle \mid 0 \leq t \leq 2\}$$

where \bar{t} is a shorthand for η such that $\eta x = t$



Ex. 5.4: Define $\mathcal{T}(\text{SwitchA})$

$T = \dots$



Ex. 5.4: Define $\mathcal{T}(\text{SwitchA})$

$$\langle \text{off}, \bar{t} \rangle \xrightarrow{d} \langle \text{off}, \bar{t} + d \rangle \text{ for all } t, d \geq 0$$

$$\langle \text{off}, \bar{t} \rangle \xrightarrow{\text{in}} \langle \text{on}, \bar{0} \rangle \text{ for all } t \geq 0$$

$$\langle \text{on}, \bar{t} \rangle \xrightarrow{d} \langle \text{on}, \bar{t} + d \rangle \text{ for all } t, d \geq 0 \text{ and } t + d \leq 2$$

$$\langle \text{on}, \bar{t} \rangle \xrightarrow{\text{out}} \langle \text{off}, \bar{t} \rangle \text{ for all } 1 \leq t \leq 2$$

- The elapse of time in timed automata **only** takes place in locations:
- ... actions take place instantaneously
- Thus, several actions may take place at a single time unit

- Paths in $\mathcal{T}(ta)$ are discrete representations of continuous-time behaviours in ta
- ... at least they indicate the states immediately before and after the execution of an action
- However, as interval delays may be realised in uncountably many different ways, different paths may represent the same behaviour

- Paths in $\mathcal{T}(ta)$ are **discrete representations of continuous-time behaviours** in ta
- ... at least they indicate the states immediately before and after the execution of an action
- However, as interval delays may be realised in **uncountably** many different ways, different paths may represent the same behaviour
- ... but not all paths correspond to valid (**realistic**) behaviours:

undesirable paths:

- **time-convergent** paths
- **timelock** paths
- **zeno** paths

$$\langle l, \eta \rangle \xrightarrow{d_1} \langle l, \eta + d_1 \rangle \xrightarrow{d_2} \langle l, \eta + d_1 + d_2 \rangle \xrightarrow{d_3} \langle l, \eta + d_1 + d_2 + d_3 \rangle \xrightarrow{d_4} \dots$$

such that

$$\forall i \in \mathbb{N}. d_i > 0 \wedge \sum_{i \in \mathbb{N}} d_i = d$$

ie, the infinite sequence of delays converges toward d

- Time-convergent paths are **counterintuitive**; as their existence cannot be avoided, they are simply **ignored** in the semantics of Timed Automata
- Time-**divergent** paths are the ones in which time always progresses

Definition

An infinite path fragment $\rho = s_0 \xrightarrow{\delta_0} s_1 \xrightarrow{\delta_1} \dots$ is **time-divergent** if $\text{ExecTime}(\rho) = \infty$
Otherwise is **time-convergent**.

where

$$\text{ExecTime}(\rho) = \sum_{i=0.. \infty} \text{ExecTime}(\delta_i)$$

$$\text{ExecTime}(\delta) = \begin{cases} 0 & \Leftarrow \delta \in Act \\ \delta & \Leftarrow \delta \in \mathcal{R}_0^+ \end{cases}$$

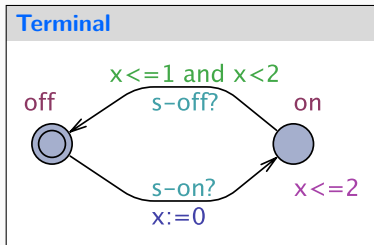
for ρ a path and δ a label in $\mathcal{T}(ta)$

Definition

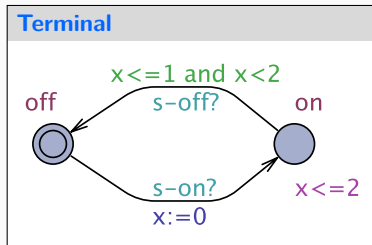
A path is **timelock** if it contains a state with a timelock, ie, a **state from which there is not any time-divergent path**

A **timelock** represents a situation that causes time progress to halt (e.g. when it is impossible to leave a location before its invariant becomes invalid)

- any **terminal state** (\neq terminal location) in $\mathcal{T}(ta)$ contains a timelock
- ... but not all timelocks arise as terminal states in $\mathcal{T}(ta)$



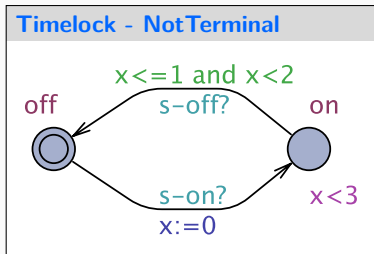
State $\langle on, 2 \rangle \dots$



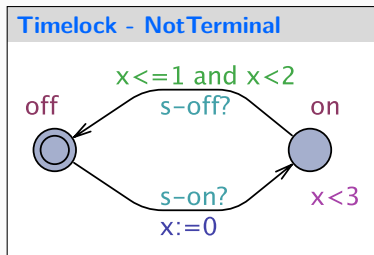
State $\langle on, 2 \rangle$ is reachable through path

$$\langle off, 0 \rangle \xrightarrow{s-on} \langle on, 0 \rangle \xrightarrow{2} \langle on, 2 \rangle$$

and is terminal



State $\langle on, 2 \rangle \dots$



State $\langle on, 2 \rangle$ is not terminal but has a **convergent** path:

$\langle on, 2 \rangle \langle on, 2.9 \rangle \langle on, 2.99 \rangle \langle on, 2.999 \rangle \dots$

In a Timed Automaton

- The elapse of time only takes place at **locations**
- Actions occur **instantaneously**: at a single time instant several actions may take place

... it may perform **infinitely** many actions in a **finite** time interval
(non realizable because it would require infinitely fast processors)

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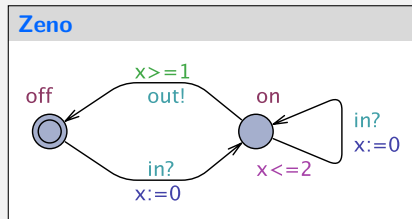
Definition

An infinite path fragment ρ is **zeno** if it is **time-convergent** and **infinitely many actions occur along it**

A timed automaton ta is **non-zeno** if there is not an initial zeno path in $\mathcal{T}(ta)$

Example

Suppose the user can press the *in* button when the light is *on* in



In doing so clock x is reset to 0 and light stays *on* for more 2 time units (unless the button is pushed again ...)

Example

Typical paths: The user presses *in* infinitely fast:

$$\langle \text{off}, 0 \rangle \xrightarrow{\text{in}} \langle \text{on}, 0 \rangle \xrightarrow{\text{in}} \langle \text{on}, 0 \rangle \xrightarrow{\text{in}} \langle \text{on}, 0 \rangle \xrightarrow{\text{in}} \langle \text{on}, 0 \rangle \xrightarrow{\text{in}} \dots$$

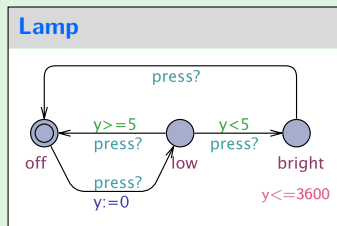
The user presses *in* faster and faster:

$$\langle \text{off}, 0 \rangle \xrightarrow{\text{in}} \langle \text{on}, 0 \rangle \xrightarrow{0.5} \langle \text{on}, 0.5 \rangle \xrightarrow{\text{in}} \langle \text{on}, 0 \rangle \xrightarrow{0.25} \langle \text{on}, 0.25 \rangle \xrightarrow{\text{in}} \langle \text{on}, 0 \rangle \xrightarrow{0.125} \dots$$

How can this be fixed?

Time shall pass!

Ex. 5.5: Recall our lamp



1. Describe a **time-divergent** path, if it exists.
2. Describe a **time-convergent** path, if it exists.
3. Describe a **timelock** path, if it exists.
4. Is this automata **non-zeno**? Justify.

Sufficient criterion for nonzenoness

A timed automaton is nonzeno if on any of its control cycles time advances with at least some **constant amount** (≥ 0). Formally, if for every control cycle

$$\ell_0 \xrightarrow{g_0, a_0, U_0} \ell_1 \xrightarrow{g_1, a_1, U_1} \dots \xrightarrow{g_n, a_n, U_n} \ell_0$$

there exists a clock $x \in C$ such that

1. $x \in U_i$ (for $0 \leq i \leq n$)
2. for all clock valuations η , there is a $c \in \mathbb{N}_{>0}$ such that

$$\eta(x) < c \Rightarrow ((\eta \not\models g_j) \vee \neg \text{Inv}(\ell_j)) \text{ for some } 0 \leq j \leq n$$

Both

- timelocks
- zenoness

are **modelling flaws** and need to be avoided.

Example

In the example above, it is enough to impose a non zero minimal delay between successive button pushings.

Modelling in Uppaal

... an editor, simulator and model-checker for TA with extensions ...

Editor.

- Templates and instantiations
- Global and local declarations
- System definition

Simulator.

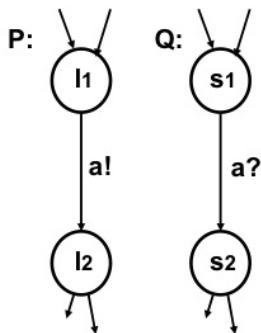
- Viewers: automata animator and message sequence chart
- Control (eg, trace management)
- Variable view: shows values of the integer variables and the clock constraints defining symbolic states

Verifier.

- (see next session)

- templates with parameters and an instantiation mechanism
- data expressions over bounded integer variables (eg, `int [2..45] x`) allowed in guards, assignments and invariants
- rich set of operators over integer and booleans, including bitwise operations, arrays, initializers ... in general a whole subset of C is available
- non-standard types of synchronization
- non-standard types of locations

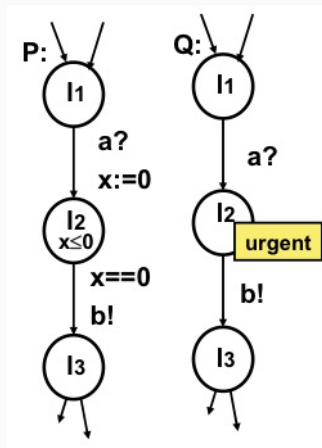
- A sender can synchronize with an arbitrary number of receivers
- Any receiver that can synchronize in the current state must do so
- Broadcast sending is never blocking (the send action can occur even with no receivers).



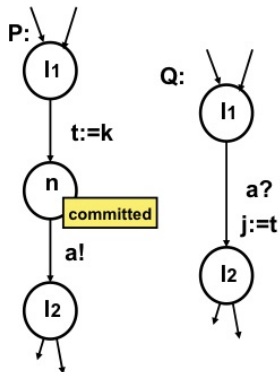
Channel a is declared **urgent chan a** if both edges are to be taken as soon as they are ready (**simultaneously** in locations l_1 and s_1).

Note the problem can **not** be solved with **invariants** because locations l_1 and s_1 can be reached at different moments

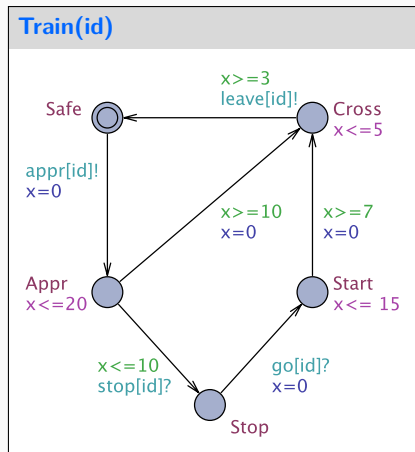
- No delay allowed if a synchronization transition on an urgent channel is enabled
- Edges using urgent channels for synchronization cannot have time constraints (ie, clock guards)



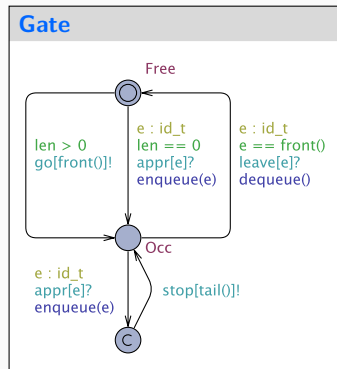
- Time does not progress but interleaving with normal location is allowed
- Both models are equivalent: **no delay at an urgent location**
- but the use of **urgent locations** reduces the number of clocks in a model and simplifies analysis



- delay is not allowed and the committed transition must be left in the next instant (or one of them if there are several), i.e., next transition must involve an outgoing edge of at least one of the committed locations
- Our aim is to pass the value k to variable j (via global variable t)
- Location n is **committed** to ensure that no other automata can assign j before the assignment $j := t$



- Events model **approach/leave**, order to **stop/go**
- A train cannot be stopped or restart instantly
- After **approaching** it has 10m to receive a **stop**.
- After that it takes further 10m to reach the cross
- After **restarting** takes 7 to 15m to reach the cross and 3-5m to cross



- Note the use of parameters and the select clause on transitions
- C-like program under the hood