Timed Automata

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Last lecture

Visited syntax and semantics

Analysed central ideas in concurrency and synchronisation

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Analysed central ideas in concurrency and synchronisation

We will now see how time fits in the items above

Table of Contents

Motivation

Saying that an airbag in a car crash eventually inflates is insufficient – it would be better to say that . . .

. . . in a car crash the airbag 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]

Examples of time-critical systems

(Network-based) traffic lights

Lights activate at specific time intervals

(Re)transmission protocols

Communication of large files between a remote unit and a video/audio equipment.

Many others

Pacemakers, autonomous driving, electric grids . . .

This chapter

We will explore an automaton-based formalism with an explicit notion of a clock

$$\boxed{\text{Timed Automata [Alur \& Dill, 90]}}$$

Associated tool

- UPPAAL [Behrmann, David, Larsen, 04]

Uppaal

$\boxed{\text{UPPAAL} = (\text{Uppsala University} + \text{Aalborg University})\ [1995]}$

- Toolbox for modelling and analysis of timed systems
- Systems modelled as networks of timed automata with channel synchronisations
- Properties specified in a temporal logic

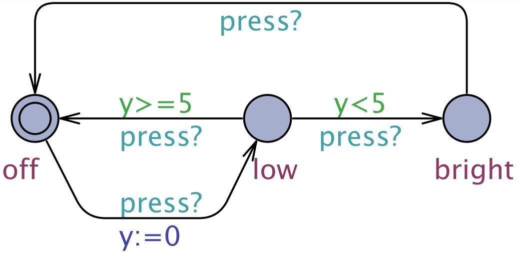
Table of Contents

Timed automata

Finite-state machines equipped with real-valued clocks

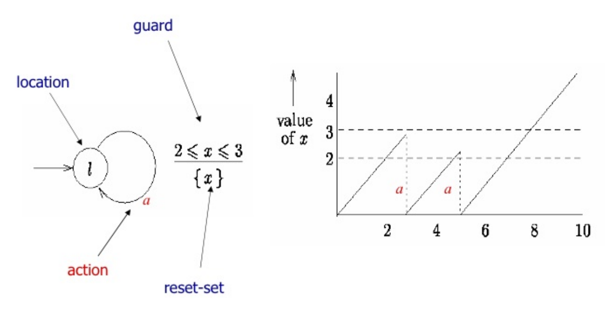
- clocks can only be read or
- reset to zero (after which they start increasing their value again as time progresses)
- a clock's value corresponds to time elapsed since its last reset
- all clocks proceed synchronously (*i.e.* at the same rate)

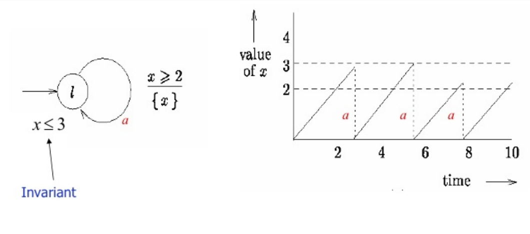
Example: the annoying lamp



(extracted from UPPAAL)

Guards, updates, and invariants





Timed automata

A timed automaton is a tuple $\langle \mathbf{L}, \mathbf{L_0}, \mathbf{Act}, \mathbf{C}, \mathbf{Tr}, \mathbf{Inv} \rangle$

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

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

  transition from location ℓ_1 to ℓ_2, labelled by a, enabled if guard g holds; when performed resets the set U of clocks
- $\mathbf{Inv} : \mathbf{L} \longrightarrow \mathcal{C}(\mathbf{C})$ assignment of invariants to locations

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

Clock constraints

Each constraint is formed according to

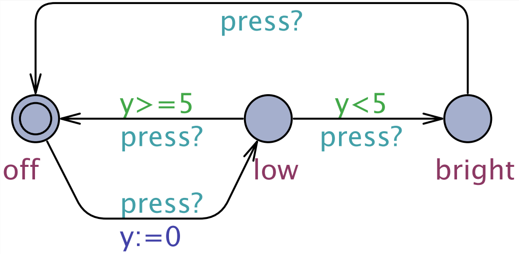
$$g \ ::= \ x \,\square\, n \ \mid \ x - y \,\square\, n \ \mid \ g \wedge g \ \mid \ \mathit{true}$$

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

This is used in

- transitions (enabling conditions) – a transition cannot occur if its guard is false
- locations (safety conditions) – a location must be left before its invariant becomes false

A revisit of the annoying lamp



Exercise: define $\langle L, L_0, Act, C, Tr, Inv \rangle$

Table of Contents

Parallel composition of timed automata

Action labels as channels

Communication mechanism analogous to CCS

Shared clocks

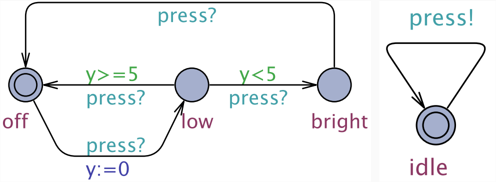
Definition

Let $H = Act_1 \cap Act_2$. The parallel composition of ta_1 and ta_2 synchronising on H is the timed automaton

$$ta_1 \parallel_H ta_2 := \langle L_1 \times L_2, L_{0,1} \times L_{0,2}, \mathbf{Act}, C_1 \cup C_2, \mathbf{Tr}, \mathbf{Inv} \rangle$$

- $\mathbf{Act} = ((Act_1 \cup Act_2) - H) \cup \{\tau\}$
- $\mathbf{Inv}(\ell_1, \ell_2) = Inv_1(\ell_1) \wedge Inv_2(\ell_2)$
- $\mathbf{Tr}$ is given by:
  - $(\ell_1, \ell_2) \xrightarrow{g,a,U} (\ell_1', \ell_2)$ if $a \notin H \wedge \ell_1 \xrightarrow{g,a,U} \ell_1'$
  - $(\ell_1, \ell_2) \xrightarrow{g,a,U} (\ell_1, \ell_2')$ if $a \notin H \wedge \ell_2 \xrightarrow{g,a,U} \ell_2'$
  - $(\ell_1, \ell_2) \xrightarrow{g,\tau,U} (\ell_1', \ell_2')$ if $a \in H \wedge \ell_1 \xrightarrow{g_1,a,U_1} \ell_1' \wedge \ell_2 \xrightarrow{g_2,\overline{a},U_2} \ell_2'$ with $g = g_1 \wedge g_2$ and $U = U_1 \cup U_2$

Example: (re)revisiting the lamp interrupt



In Uppaal

- Complementary actions marked by ? and ! annotations

Exercise: worker, hammer, nail

Write down the parallel composition of the following automata

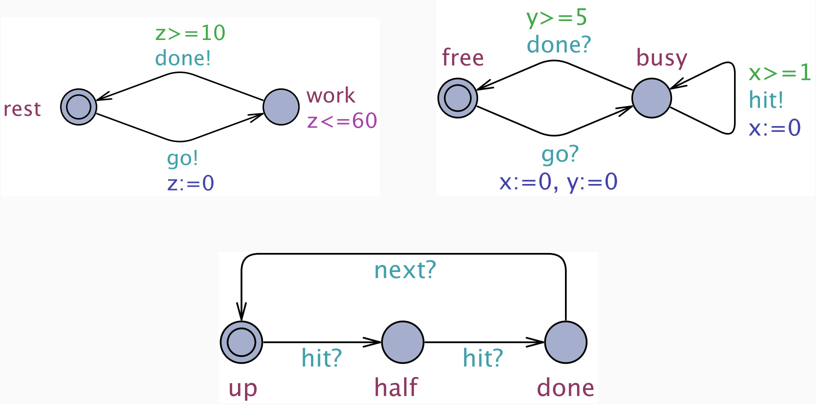


Table of Contents

Semantics of timed automata

Syntax	Semantics
How to write	*How to execute*
CCS	LTS
Timed Automaton	TLTS (Timed LTS)

Timed LTS

Introduce delay transitions to capture the passage of time

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

$s \xrightarrow{d} s'$ for $d \in \mathbb{R}_{\geq 0}$, are delay transitions

subject to sanity constraints ...

Timed LTS pt. II

1. Time additivity

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

2. Delay transitions are deterministic

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

The semantics

Every TA *ta* defines a TLTS

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

whose states are pairs

$$\langle \text{location}, \text{clocks valuations} \rangle$$

Clock valuation

Definition

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

$$\eta : C \longrightarrow \mathbb{R}_{\geq 0}$$

assigning to each clock $x \in C$ its current value $\eta\, x$

Satisfaction of Clock Constraints

$$\eta \models x \,\square\, n \;\Leftrightarrow\; \eta\, x \,\square\, n$$

$$\eta \models x - y \,\square\, n \;\Leftrightarrow\; (\eta\, x - \eta\, y) \,\square\, n$$

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

Operations on clock valuations

Delay

For each $d \in \mathbb{R}_{\geq 0}$, valuation $\eta + d$ is given by

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

Reset

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

$$\begin{cases} \eta[R]\,x \;=\; \eta\,x & \text{if } x \notin R \\ \eta[R]\,x \;=\; 0 & \text{if } x \in R \end{cases}$$

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

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

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

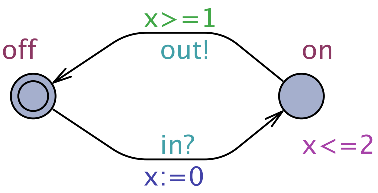
where

- $\mathbf{S} = \{(l,\eta) \in L \times (\mathbb{R}_{\geq 0})^C \mid \eta \models Inv(l)\}$
- $\mathbf{S_0} = \{(\ell_0,\eta) \mid \ell_0 \in L_0 \;\wedge\; \eta\, x = 0 \text{ for all } x \in C\}$
- $\mathbf{N} = Act + \mathbb{R}_{\geq 0}$ (i.e., transitions can be labelled by actions or delays)
- $\mathbf{T} \subseteq S \times N \times S$ is given by

$$(l,\eta) \xrightarrow{a} (l',\eta') \quad \text{if} \quad \exists_{l \xrightarrow{g,a,U} l' \in Tr} \; \eta \models g \;\wedge\; \eta' = \eta[U] \;\wedge\; \eta' \models Inv(l')$$

$$(l,\eta) \xrightarrow{d} (l,\eta + d) \quad \text{if} \quad \eta + d \models Inv(l)$$

Example: the simple switch pt. I

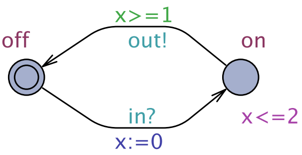


$\mathcal{T}$(Simple switch)

$$S = \{(\mathit{off}, t) \mid t \in \mathbb{R}_{\geq 0}\} \cup \{(\mathit{on}, t) \mid 0 \leq t \leq 2\}$$

where t is a shorthand for η such that $\eta\, x = t$

Example: the simple switch pt. II



$\mathcal{T}$(Simple switch)

$$(\mathit{off}, t) \xrightarrow{d} (\mathit{off}, t + d) \text{ for all } t, d \geq 0$$

$$(\mathit{off}, t) \xrightarrow{in?} (on, 0) \text{ for all } t \geq 0$$

$$(on, t) \xrightarrow{d} (on, t + d) \text{ for all } t, d \geq 0 \text{ and } t + d \leq 2$$

$$(on, t) \xrightarrow{out!} (\mathit{off}, t) \text{ for all } 1 \leq t \leq 2$$