Real-Time Systems

Lecture 14: Extended Timed Automata

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Contents & Goals

Last Lecture:

- Decidability of the location reachability problem:
  - region automaton
  - zones

This Lecture:

- **Educational Objectives:** Capabilities for following tasks/questions.
  - By what are TA extended? Why is that useful?
  - What's an urgent/committed location? What's the difference?
  - What's an urgent channel?
  - Where has the notion of "input action" and "output action" correspondences in the formal semantics?
- **Content:**
  - Extended TA:
    - Data-Variables
    - Structuring Facilities
    - Restriction of Non-Determinism
  - The Logic of Uppaal

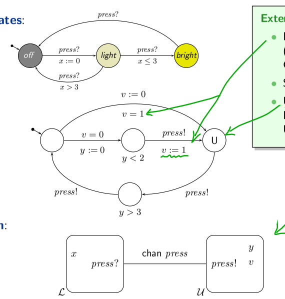
Extended Timed Automata

Example (Partly Already Seen in Uppaal Demo)

Templates:

- $\mathcal{L}$:
- $\mathcal{U}$:

System:



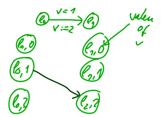
Extensions:

- Data Variables (Expressions, Constraints, Updates)
- Structuring
- Urgent/Committed Location, Urgent Channel

Data-Variables

- When modelling controllers as timed automata, it is sometimes desirable to have (local and shared) variables.
  E.g. count number of open doors, or intermediate positions of gas valve.
- Adding variables with **finite** range (possibly grouped into **finite** arrays) to any finite-state automata concept is straighforward:
  - If we have control locations $L_0 = \{\ell_1, \dots, \ell_n\}$,
  - and want to model, e.g., the valve range as a variable v with $\mathcal{D}(v) = \{0, 1, 2\}$,
  - then just use $L = L_0 \times \mathcal{D}(v)$ as control locations, i.e. encode the current value of v in the control location, and consider updates of v in the $\xrightarrow{\lambda}$.

  L is still finite, so we still have a proper TA.



Data-Variables

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  L is still finite, so we still have a proper TA.
- But: writing $\xrightarrow{\lambda}$ is tedious.
- So: have variables as "first class citizens" and let compilers do the work.
- **Interestingly**, many examples in the literature live without variables: the more abstract the model is, i.e., the fewer information it keeps track of (e.g. in data variables), the easier the verification task.

Data Variables and Expressions

$\psi_{int} ::= v \mid f(\psi_1, \dots, \psi_n)$ $v \in V$, $f \in \{+, -, \dots\}$

- Let $(v, w \in)\ V$ be a set of (integer) variables.
  $(\psi_{int} \in)\ \Psi(V)$: **integer expressions** over V using func. symb. $+, -, \dots$
  $(\varphi_{int} \in)\ \Phi(V)$: **integer** (or **data**) **constraints** over V
  using **integer expressions**, predicate symbols $=, <, \leq, \dots$, and boolean logical connectives. (incl. $\vee, \neg, \wedge, \Rightarrow, \Leftrightarrow, \dot\vee, \dots$)
- Let $(x, y \in)\ X$ be a set of clocks.
  $(\varphi \in)\ \Phi(X, V)$: (**extended**) **guards**, defined by

$$\varphi ::= \varphi_{clk} \mid \varphi_{int} \mid \varphi_1 \wedge \varphi_2$$

  where $\varphi_{clk} \in \Phi(X)$ is a simple clock constraint (as defined before) and $\varphi_{int} \in \Phi(V)$ an **integer (or data) constraint**.

Examples: Extended guard or not extended guard? Why?

(a) $\underbrace{x < y}_{\in \Phi(X)} \wedge \underbrace{v > 2}_{\in \Psi(V)}$, (b) $\underbrace{x < y}_{\in \Phi(X)} \vee \underbrace{v > 2}_{\in \Psi(V)}$, (c) $\underbrace{v < 1 \vee v > 2}_{\in \Psi(V)}$, (d) $x < v$

$(x - y < 0)$ ✓ no NO ✓ $\notin \Phi(X)$ $\notin \Psi(V)$ NO

clocks and data variables are never compared

Modification or Reset Operation

- **New**: a **modification** or **reset (operation)** is

$$x := 0, \qquad x \in X,$$

or

$$v := \psi_{int}, \qquad v \in V, \quad \psi_{int} \in \Psi(V).$$

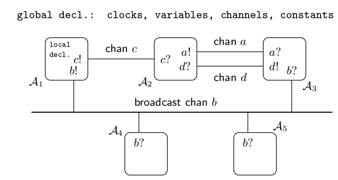
- By $R(X, V)$ we denote the set of all resets.
- By $\vec{r}$ we denote a finite list $\langle r_1, \dots, r_n \rangle$, $n \in \mathbb{N}_0$, of reset operations $r_i \in R(X, V)$; $\langle\rangle$ is the empty list.
- By $R(X, V)^*$ we denote the set of all such lists of reset operations.

Examples: Modification or not? Why?

(a) $x := y$, (b) $x := v$, (c) $v := x$, (d) $v := w$, (e) $v := 0$

$\in X$ not 0 — NO; $\in X$ not 0 — NO; $\in V$ $\notin \Psi(V)$ — NO; $\in V$ $\in \Psi(V)$ ✓; $\in V$ $\in \Psi(V)$ ✓

Structuring Facilities



- Global declarations of of clocks, data variables, channels, and constants.
- Binary and broadcast channels: chan c and broadcast chan b.
- Templates of timed automata.
- Instantiation of templates (instances are called **process**).
- System definition: list of processes.

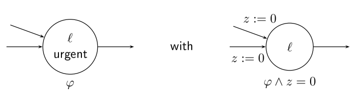
Restricting Non-determinism

- **Urgent locations** — enforce local immediate progress.
  U
- **Committed locations** — enforce **atomic** immediate progress.
  C
- **Urgent channels** — enforce cooperative immediate progress.

```
urgent chan press;
```


Urgent Locations: Only an Abbreviation...

Replace



where z is a fresh clock:

- reset z on all in-going egdes,
- add $z = 0$ to invariant.

$N = 3$

number of urgent loc. is 20

at least one U-loc. per automaton

• 1 • 3 • • 20

Question: How many fresh clocks do we need in the worst case for a network of N extended timed automata?

Extended Timed Automata

so still: $I : L \to \Phi(X)$

> **Definition 4.39.** An **extended timed automaton** is a structure
>
> $$\mathcal{A}_e = (L, C, B, U, X, V, I, E, \ell_{ini})$$
>
> where L, B, X, I, ℓ_{ini} are as in Def. 4.3, except that location invariants in I are **downward closed**, and where
>
> - $C \subseteq L$: **committed locations**,
> - $U \subseteq B$: **urgent channels**,
> - V: a set of data variables,
> - $E \subseteq L \times B_{!?} \times \Phi(X, V) \times R(X, V)^* \times L$: a set of **directed edges** such that
>
> $$(\ell, \alpha, \varphi, \vec{r}, \ell') \in E \wedge \mathrm{chan}(\alpha) \in U \implies \varphi = true.$$
>
> Edges $(\ell, \alpha, \varphi, \vec{r}, \ell')$ from location ℓ to ℓ' are labelled with an **action** α, a **guard** φ, and a list $\vec{r}$ of **reset operations**.

φ is d.c. iff $\forall \nu : X \to \mathrm{Time} \bullet \nu \models \varphi \Rightarrow (\forall t \in \mathrm{Time} \bullet \nu - t \models \varphi)$?

• $x < 3$ is d.c.

• $x > 3$ is not d.c.

Definition 4.40. Let $\mathcal{A}_{e,i} = (L_i, C_i, B_i, U_i, X_i, V_i, I_i, E_i, \ell_{ini,i})$, $1 \le i \le n$, be extended timed automata with pairwise disjoint sets of clocks X_i.
The operational semantics of $\mathcal{C}(\mathcal{A}_{e,1}, \dots, \mathcal{A}_{e,n})$ (closed!) is the labelled transition system

$$\mathcal{T}_e(\mathcal{C}(\mathcal{A}_{e,1}, \dots, \mathcal{A}_{e,n})) = (Conf, \mathsf{Time} \cup \{\tau\}, \{\xrightarrow{\lambda} \mid \lambda \in \mathsf{Time} \cup \{\tau\}\}, C_{ini})$$

where

- $X = \bigcup_{i=1}^n X_i$ and $V = \bigcup_{i=1}^n V_i$,
- $Conf = \{\langle \vec{\ell}, \nu \rangle \mid \ell_i \in L_i, \nu : X \cup V \to \mathsf{Time}, \nu \models \bigwedge_{k=1}^n I_k(\ell_k)\}$, $\cup \mathcal{D}(V)$
- $C_{ini} = \{\langle \vec{\ell}_{ini}, \nu_{ini} \rangle\} \cap Conf$,

and the transition relation consists of transitions of the following three types.

- **Now**: $\nu : X \cup V \to \mathsf{Time} \cup \mathcal{D}(V)$
- Canonically extends to $\nu : \Psi(V) \to \mathcal{D}$ (valuation of expression).
- "$\models$" extends canonically to expressions from $\Phi(X, V)$.

$\psi ::= v \mid f(\psi_1, \dots, \psi_n)$
assume $I(f) : \mathbb{Z}^n \to \mathbb{Z}$

$I(v, \nu) := \nu(v) \in \mathcal{D}(V)$
$I(f(\psi_1, \dots, \psi_n), \nu) := I(f)(I(\psi_1, \nu), \dots, I(\psi_n, \nu))$
$I(v + w, \overbrace{\{v \mapsto 3, w \mapsto 24\}}^{=:\nu})$
$= I(+)(I(v, \nu), I(w, \nu)) = \hat{+}(\nu(v), \nu(w))$
$= \hat{+}(3, 24) = 27$

- **Now**: $\nu : X \cup V \to \mathsf{Time} \cup \mathcal{D}(V)$
- Canonically extends to $\nu : \Psi(V) \to \mathcal{D}$ (valuation of expression).
- "$\models$" extends canonically to expressions from $\Phi(X, V)$.
- Extended **timeshift** $\nu + t$, $t \in \mathsf{Time}$, applies to clocks only:
  - $(\nu + t)(x) := \nu(x) + t$, $x \in X$,
  - $(\nu + t)(v) := \nu(v)$, $v \in V$.
- **Effect of modification** $r \in R(X, V)$ on ν, denoted by $\nu[r]$:

$$\nu[x := 0](a) := \begin{cases} 0, & \text{if } a = x, \\ \nu(a), & \text{otherwise} \end{cases}$$

$$\nu[v := \psi_{int}](a) := \begin{cases} \nu(\psi_{int}), & \text{if } a = v, \\ \nu(a), & \text{otherwise} \end{cases}$$

- We set $\nu[\langle r_1, \dots, r_n \rangle] := \nu[r_1] \dots [r_n] = (((\nu[r_1])[r_2]) \dots)[r_n]$.

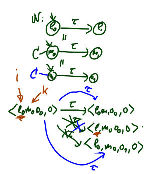
- An **internal transition** $\langle \vec{\ell}, \nu \rangle \xrightarrow{\tau} \langle \vec{\ell}', \nu' \rangle$ occurs if there is $i \in \{1, \dots, n\}$ such that

number of automata in the network

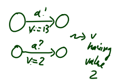
  - there is a τ-edge $(\ell_i, \tau, \varphi, \vec{r}, \ell'_i) \in E_i$,
  - $\nu \models \varphi$,
  - $\vec{\ell}' = \vec{\ell}[\underbrace{\ell_i := \ell'_i}]$,
  - $\nu' = \nu[\vec{r}]$,
  - $\nu' \models I_i(\ell'_i)$,
  - $\boxed{(\clubsuit)}$ if $\ell_k \in C_k$ for some $k \in \{1, \dots, n\}$ then $\ell_i \in C_i$.

location of the i-th automaton in $\vec{\ell}$

modification at the i-th position

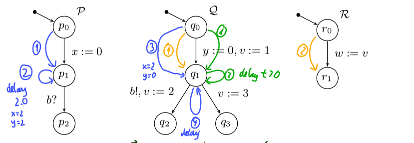


- A **synchronisation transition** $\langle \vec{\ell}, \nu \rangle \xrightarrow{\tau} \langle \vec{\ell}', \nu' \rangle$ occurs if there are $i, j \in \{1, \dots, n\}$ with $i \neq j$ such that
  - there are edges $(\ell_i, b!, \varphi_i, \vec{r}_i, \ell'_i) \in E_i$ and $(\ell_j, b?, \varphi_j, \vec{r}_j, \ell'_j) \in E_j$,
  - $\nu \models \varphi_i \land \varphi_j$,
  - $\vec{\ell}' = \vec{\ell}[\ell_i := \ell'_i][\ell_j := \ell'_j]$,
  - $\nu' = \nu[\vec{r}_i][\vec{r}_j]$, ⟵ "sender updates are applied first"
  - $\nu' \models I_i(\ell'_i) \land I_j(\ell'_j)$,
  - $(\clubsuit)$ if $\ell_k \in C_k$ for some $k \in \{1, \dots, n\}$ then $\ell_i \in C_i$ or $\ell_j \in C_j$.



- A **delay transition** $\langle \vec{\ell}, \nu \rangle \xrightarrow{t} \langle \vec{\ell}, \nu + t \rangle$ occurs if
  - $\nu + t \models \bigwedge_{k=1}^n I_k(\ell_k)$,
  - $(\clubsuit)$ there are no $i, j \in \{1, \dots, n\}$ and $b \in U$ with $(\ell_i, b!, \varphi_i, \vec{r}_i, \ell'_i) \in E_i$ and $(\ell_j, b?, \varphi_j, \vec{r}_j, \ell'_j) \in E_j$,
  - $(\clubsuit)$ there is no $i \in \{1, \dots, n\}$ such that $\ell_i \in C_i$.

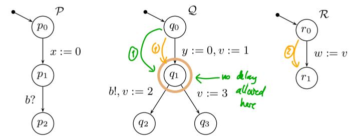
Restricting Non-determinism: Example



"∃ a config $\langle \vec{\ell}, \nu \rangle$ with $\nu \models w=1$ is reachable" "for all reachable configs $\langle \vec{\ell}, \nu \rangle$, $\nu \models (\mathcal{Q}.q_1 \implies y \leq 0)$"

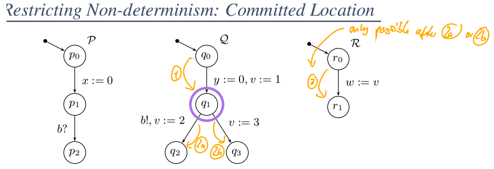
	Property 1	Property 2	Property 3
	$\exists\Diamond\, w = 1$	$\forall\Box\, \mathcal{Q}.q_1 \implies y \leq 0$	$\forall\Box(\mathcal{P}.p_1 \wedge \mathcal{Q}.q_1 \implies (x \geq y \implies y \leq 0))$
$\mathcal{N} := \mathcal{P} \parallel \mathcal{Q} \parallel \mathcal{R}$	✓	✗	✗
$\mathcal{N}$, q_1 urgent			
$\mathcal{N}$, q_1 comm.			
$\mathcal{N}$, b urgent			

Restricting Non-determinism: Urgent Location



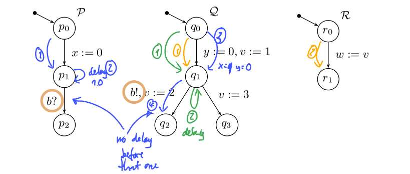
	Property 1	Property 2	Property 3
	$\exists\Diamond\, w = 1$	$\forall\Box\, \mathcal{Q}.q_1 \implies y \leq 0$	$\forall\Box(\mathcal{P}.p_1 \wedge \mathcal{Q}.q_1 \implies (x \geq y \implies y \leq 0))$
$\mathcal{N}$	✔	✘	✘
$\mathcal{N}$, q_1 urgent	✓	✓	✓
$\mathcal{N}$, q_1 comm.			
$\mathcal{N}$, b urgent			

Restricting Non-determinism: Committed Location



	Property 1	Property 2	Property 3
	$\exists\Diamond\, w = 1$	$\forall\Box\, \mathcal{Q}.q_1 \implies y \leq 0$	$\forall\Box(\mathcal{P}.p_1 \wedge \mathcal{Q}.q_1 \implies (x \geq y \implies y \leq 0))$
$\mathcal{N}$	✔	✘	✘
$\mathcal{N}$, q_1 urgent	✔	✔	✔
$\mathcal{N}$, q_1 comm.	✗	✓	✓
$\mathcal{N}$, b urgent			

Restricting Non-determinism: Urgent Channel



	Property 1	Property 2	Property 3
	$\exists\Diamond\, w = 1$	$\forall\Box\, \mathcal{Q}.q_1 \implies y \leq 0$	$\forall\Box(\mathcal{P}.p_1 \wedge \mathcal{Q}.q_1 \implies (x \geq y \implies y \leq 0))$
$\mathcal{N}$	✔	✘	✘
$\mathcal{N}$, q_1 urgent	✔	✔	✔
$\mathcal{N}$, q_1 comm.	✘	✔	✔
$\mathcal{N}$, b urgent	✓	✗	✓

Extended vs. Pure Timed Automata

Extended vs. Pure Timed Automata

$$\mathcal{A}_e = (L, C, B, U, X, V, I, E, \ell_{ini})$$
$$(\ell, \alpha, \varphi, \vec{r}, \ell') \in L \times B_{!?} \times \Phi(X, V) \times R(X, V)^* \times L$$

vs.

$$\mathcal{A} = (L, B, X, I, E, \ell_{ini})$$
$$(\ell, \alpha, \varphi, Y, \ell') \in E \subseteq L \times B_{!?} \times \Phi(X) \times 2^X \times L$$

- $\mathcal{A}_e$ is in fact (or specialises to) a **pure** timed automaton if
  - $C = \emptyset$,
  - $U = \emptyset$,
  - $V = \emptyset$,
  - for each $\vec{r} = \langle r_1, \dots, r_n \rangle$, every r_i is of the form $x := 0$ with $x \in X$.
  - $I(\ell), \varphi \in \Phi(X)$ is then a consequence of $V = \emptyset$.

Operational Semantics of Extended TA

Theorem 4.41. If $\mathcal{A}_1, \ldots, \mathcal{A}_n$ **specialise to pure** timed automata, then the operational semantics of

$$\mathcal{C}(\mathcal{A}_1, \ldots, \mathcal{A}_n)$$

and

$$\mathsf{chan}\, b_1, \ldots, b_m \bullet (\mathcal{A}_1 \parallel \ldots \parallel \mathcal{A}_n),$$

where $\{b_1, \ldots, b_m\} = \bigcup_{i=1}^{n} B_i$, **coincide**, i.e.

$$\mathcal{T}_e(\mathcal{C}(\mathcal{A}_1, \ldots, \mathcal{A}_n)) = \mathcal{T}(\mathsf{chan}\, b_1, \ldots, b_m \bullet (\mathcal{A}_1 \parallel \ldots \parallel \mathcal{A}_n)).$$

Reachability Problems for Extended Timed Automata

Recall

Theorem 4.33. [*Location Reachability*] The location reachability problem for **pure** timed automata is **decidable**.

Theorem 4.34. [*Constraint Reachability*] The constraint reachability problem for **pure** timed automata is **decidable**.

- And what about tea ~W **extended** timed automata?

References

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lderog and Dierks, 2008] Olderog, E.-R. and Dierks, H. (2008). Real-Time Systems - Formal Specification and Automatic Verification. Cambridge University Press.