On the Runtime Enforcement of (Timed) Properties

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based on joint work with T. Jéron, H. Marchand, S. Pinisetty, M. Renard, A. Rollet

Lecture at the ETR summer school

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Runtime verification and enforcement (monitors)

Runtime verification and enforcement:

- No system model.
- A correctness property φ.
- A monitor observes the execution of a system (e.g., trace, log, messages).

Runtime verification

- Does the run satisfy the property?
- Input: stream of events.
- Output: stream of **verdicts**.

Runtime enforcement

- The run should satisfy the property.
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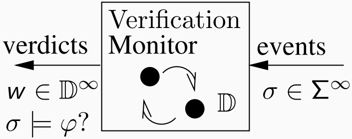

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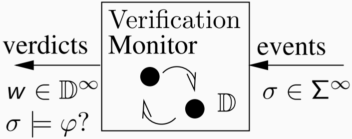

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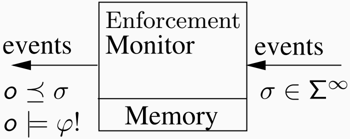

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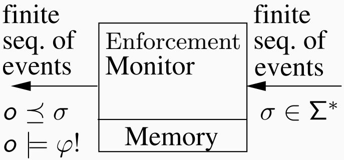
Enforcement monitoring - untimed case

- Dedicated to a property φ.
- Possibly augmented with a **memorization mechanism**.



Enforcement mechanism (EM)

An EM modifies the current execution sequence (intuitively like a "filter").

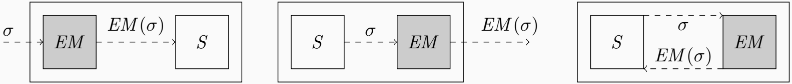
- **reads** an input sequence $\sigma \in \Sigma^*$.
- **outputs** a new sequence $o \in \Sigma^*$.
- endowed with a set of *enforcement primitives*:
  - operate on the memorization mechanism,
  - delete or insert events using the memory content and the current input.

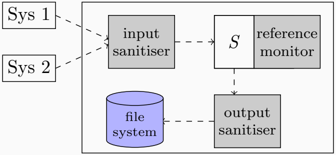
An EM behaves as a function $E : \Sigma^* \to \Sigma^*$.

Application domains and usage scenarios

- Domains: real-time embedded systems, monitor hardware failures, communication protocols, web services and many more.
- Examples of monitor usage:
  - IS: firewall to prevent DOS attack ensuring minimal delay;
  - OS: suppress sensitive information when logging, ensuring a log format;
  - RM: forbid incorrect system change, ensure proper usage of resources.

Input sanitiser (IS) Output sanitiser (OS) Reference monitor (RM)





Outline - On the Runtime Enforcement of Timed Properties

RE of Untimed Properties

Property Enforcement [Schneider00, LigattiBW05, BielovaM08, FalconeFM09a]

Relation between the input and output sequences should adhere:

- **soundness**: the output sequences should be correct wrt. the property
- **transparency**: the correct input sequences should not be modified

$\hookrightarrow$ the memorization mechanism should be designed wrt. those constraints

Definition (Property enforcement)

An EM $E : \Sigma^* \rightarrow \Sigma^*$ for φ is said to enforce

- conservatively (1)
- precisely (2)
- delayed-precisely (3)
- effectively wrt. the equivalence relation $\approx$ (4)

$$\forall \sigma \in \Sigma^* : \quad \begin{array}{rr} \exists o \in \Sigma^* : E(\sigma) = o \wedge \varphi(o) & (1) \\ (1) \wedge \varphi(\sigma) \implies \sigma = o \wedge \forall i < |\sigma| : \quad E(\sigma_{\ldots i}) = \sigma_{\ldots i} & (2) \\ (1) \wedge \varphi(\sigma) \implies \sigma = o \wedge \forall i < |\sigma|, \exists j \leq i : E(\sigma_{\ldots i}) = \sigma_{\ldots j} & (3) \\ (1) \wedge \varphi(\sigma) \implies \sigma \approx o & (4) \end{array}$$

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Security Automata (SA) [Schneider00]

First runtime mechanisms dedicated to property enforcement.

- Variant of non-deterministic Büchi automata executing in parallel with the system.
- Mechanisms able to stop the system as soon as a violation of the property is detected: *execution truncation*.

Example (Security Automata (SA))

- Prohibiting "Send" after "FileRead"
  Atomic propositions: $\{FileRead, Sent\}$
- Enforcement of a finitary property $Pref(a \cdot b \cdot c \cdot d) \cup Pref(b \cdot a \cdot d \cdot c)$

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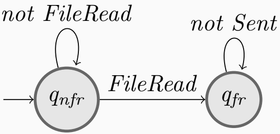

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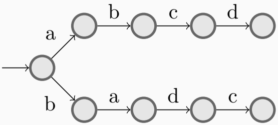

Security Automata (SA) and Decidable Safety Properties

SA cannot take decisions based on possible future executions
↪ decisions of SA are irremediable.

SA can enforce properties s.t.:

- "good" sequences are prefix-closed,
- "bad" sequences are rejected after a finite number of steps.

Theorem (Enforcement ability of SA)
SA can enforce conservatively and precisely safety properties

Hypotheses:

- The SA can halt the target system.
- The target system cannot corrupt the SA's transitions.

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- Security Automata [Schneider00]
- Edit-Automata [LigattiBW05, LigattiBW09]
- Generic Enforcement Monitors [FalconeFM09a]

Specifying Timed Properties

Runtime Enforcement of Timed Properties

Extensions

Conclusions and Future Work

Edit-Automata (EA) [LigattiBW05, LigattiBW09]

Motivated by the limitation of SA that only halt the target system

- SA are "sequence recognizers"
- EA are "sequence transformers"

EAs can

- **insert** an action (by either replacing the current input or inserting it)
- **suppress** an action (possibly *memorized in the control state* for later)

Variants of EA:

- Insertion Automata (only inserting actions)
- Suppression Automata (only suppressing actions)

Hypotheses: actions are *asynchronous*

- next action is available even if some previous actions have been suppressed
- no data-dependency between actions

Memorization of events is realized using control states

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Example of Edit Automaton

Example (Edit Automaton)

Delayed-precise enforcement of a simple co-safety/guarantee property

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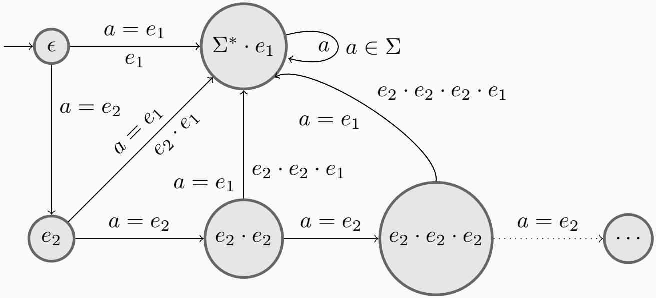
- property= "eventually, event e_1 occurs"



Remark: Automaton's size also depends on the alphabet's size.

Enforcement abilities of EA-like enforcement mechanisms

EA-like mechanisms form a hierarchy wrt. their enforcement ability.

Theorem (Enf. ability of Ligatti Automata [LigattiThesis, BielovaM08])
Edit Automata can delayed-precisely enforce the set of infinite renewal properties.

φ is an infinite renewal property over Σ^∞ if:

$$\forall \sigma \in \Sigma^\infty : \quad (\varphi(\sigma) \Leftrightarrow \forall \sigma' \in \Sigma^* : \sigma' \prec \sigma \Rightarrow \exists \sigma'' : \sigma' \preceq \sigma'' \prec \sigma \wedge \varphi(\sigma''))$$

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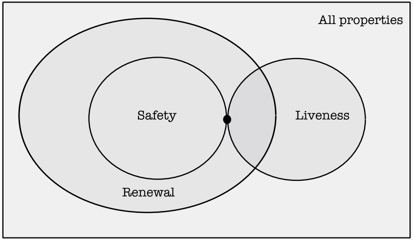

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Generic Enforcement Monitors (GEMs)

Definition (Generic enforcement monitor (EM(Ops)))

A *GEM* $\mathcal{A}_\downarrow$ is a 4-tuple $(Q^{\mathcal{A}_\downarrow}, q_{\text{init}}^{\mathcal{A}_\downarrow}, \rightarrow_{\mathcal{A}_\downarrow}, \mathit{Ops})$ wrt. Σ parameterized by *Ops*

- $\mathit{Ops} : \Sigma \times \mathit{Memory} \rightarrow \Sigma^* \times \mathit{memory}$
- complete transition function $\rightarrow_{\mathcal{A}_\downarrow} : Q^{\mathcal{A}_\downarrow} \times \Sigma \rightarrow Q^{\mathcal{A}_\downarrow} \times \mathit{Ops}$
- Enforcement operations $\{\mathrm{halt}, \mathrm{store}, \mathrm{dump}, \mathrm{off}\}$

Advantages:

- Instantiated GEMs encompass SA and Edit-Automata
  - for SA: use $\mathrm{dump}, \mathrm{halt}$
  - for Edit Automata: use $\mathrm{dump}, \mathrm{halt}, \mathrm{store}$
- closer to implementation (finite-state mechanisms)
- their composition is easy to define:
  - ordering enforcement operations: $\mathrm{halt} \sqsubset \mathrm{store} \sqsubset \mathrm{dump} \sqsubset \mathrm{off}$
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Instantiated GEMs: some examples

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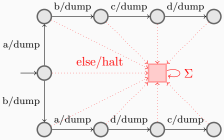

Example (Delayed-precise enforcement of a guarantee property)

- alphabet= $\{e_1, e_2\}$
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Example (Logging authentication requests)

Each occurrence of *r_auth* should be:

1. written in a log file
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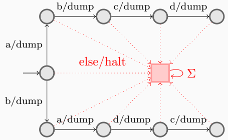

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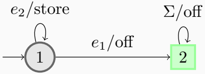

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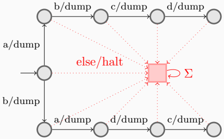

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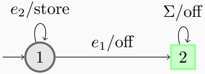

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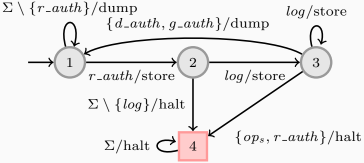
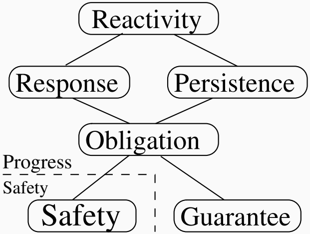


Enf. ability of instantiated GEMs in the Safety-Progress classification

Theorem (Enf. ability of instantiated GEMs [FalconeFM09a])

GEMs instantiated by $\{\mathrm{halt}, \mathrm{store}, \mathrm{dump}, \mathrm{off}\}$ *can delayed-precisely enforce the set of response properties within the Safety-Progress classification.*



Specifying Timed Properties

Specifying timed properties

Specifying the timing behavior

Allow specifying desired behavior of a system more precisely (time constraints between events).

- After action “a”, action “b” should occur with a delay of at least 5 time units between them.
- The system should allow consecutive requests with a delay of at least 10 time units between any two requests.

System Abstraction

- Input/output sequences are timed words: $\sigma = (\delta_1, a_1) \cdot (\delta_2, a_2) \cdots (\delta_n, a_n), \delta_i \in \mathbb{R}_{\geq 0}, a_i \in \Sigma$.
- Property:
  - defined by a regular timed language $\varphi \subseteq (\mathbb{R}_{\geq 0} \times \Sigma)^*$,
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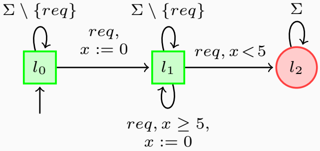
Safety: nothing bad should ever happen (prefix closed).

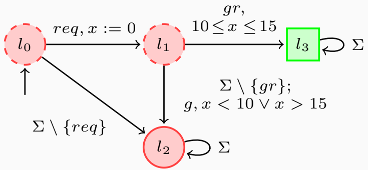


- $\Sigma \supseteq \{req\}$
- "A delay of 5 t.u. between any two requests."

Specifying timed properties

Safety, co-safety and response properties specified by TAs

Co-safety: something good will eventually happen within a finite amount of time (extension closed).



- $\Sigma \supseteq \{req, gr\}$
- "A request, and then a grant should arrive between 10 and 15 t.u."

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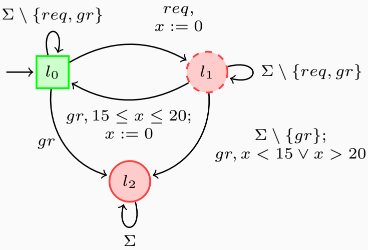
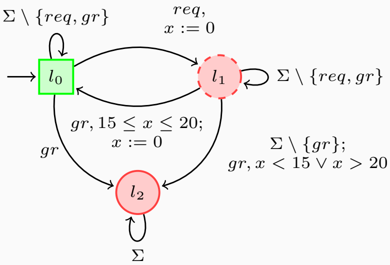
Safety, co-safety and response properties specified by TAs

Response: any property.



- $\Sigma \supseteq \{req, gr\}$
- "Requests and grants should alternate in this order with a delay between 15 and 20 t.u between the request and the grant."

Example: response property



- $\Sigma = \{req, gr\}$
- Input time word: $(3, req) \cdot (15, gr) \cdot (5, req) \cdot (19, gr)$

$\epsilon \models \varphi$.

$(3, req) \not\models \varphi$.

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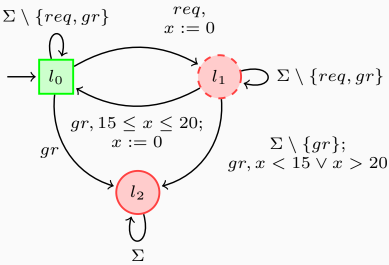
$(3, req) \cdot (15, gr) \cdot (5, req) \cdot (19, gr) \models \varphi$.

Remark: response properties are neither prefix nor extension closed.

Example: response property



- $\Sigma = \{req, gr\}$
- Input time word: $(3, req) \cdot (15, gr) \cdot (5, req) \cdot (19, gr)$

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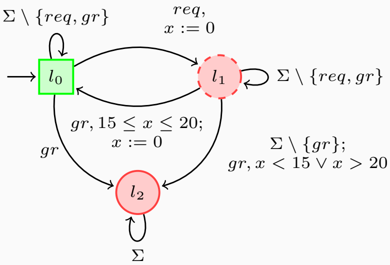

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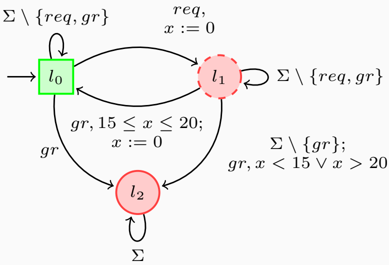

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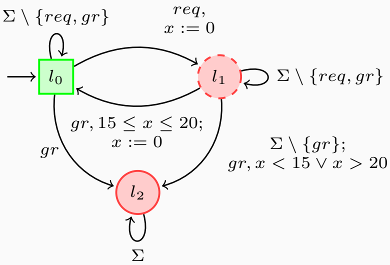

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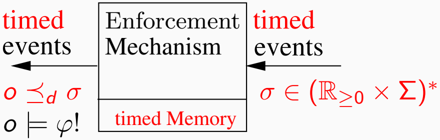
RE of Timed Properties

Outline - On the Runtime Enforcement of Timed Properties

Problem statement

Given some (regular) timed property φ:



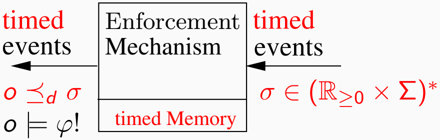
What can an enforcement mechanism do?

- CANNOT insert events.
- CANNOT change the order of events.
- CAN increase the delay between actions.
- CAN delete events.

$\hookrightarrow$ How can we obtain an enforcement mechanism as a "delayer" with suppression for φ.

Problem tackled and Contributions

φ is a timed property



A formal framework for runtime enforcement of timed properties

- Any regular timed property φ as input.
- Enforcement mechanisms i) add additional delays between actions to satisfy φ, ii) suppress actions. – work as "delayers" with suppression.
- A general definition of mechanisms for regular properties.
- Optimizations for safety and co-safety properties.
- Enforcement mechanisms at *several levels of abstraction* (facilitating the design and implementation of such mechanisms).
- Exhibiting a notion of *non-enforceable properties*.

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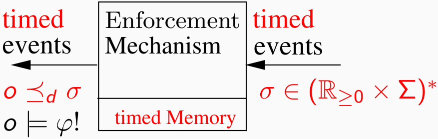

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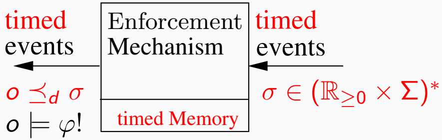

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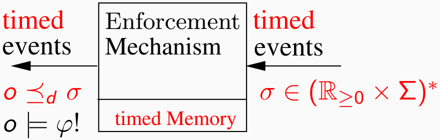

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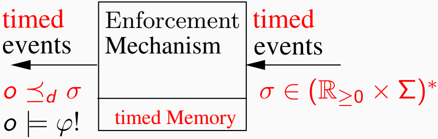

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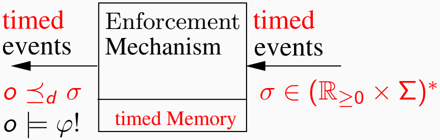

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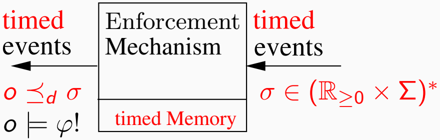

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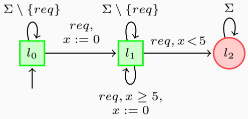
Main challenges when enforcing timed properties

Main challenges when (possibly) correcting an input sequence:

- safety properties: after each event, the decision is made (i.e., whether it can be corrected or not).
- co-safety properties: after each event, we check starting from the first event, whether the sequence read so far can be corrected or not.
- response properties:
  - we cannot decide for each event soon after it is observed;
  - we do not check/correct from the first event since we want to correct and output chunks of sequences as soon as possible.



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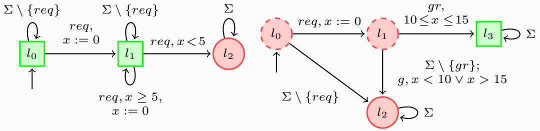

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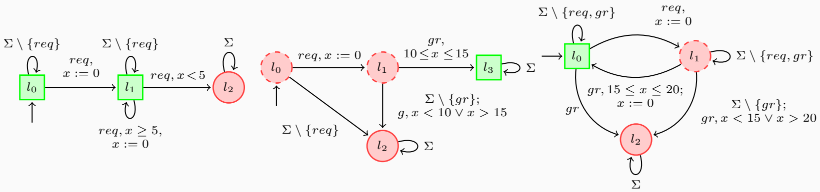
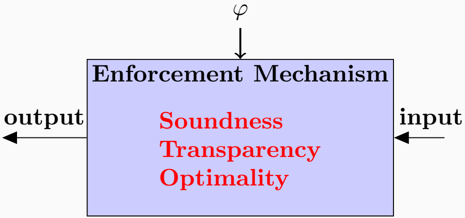


Summary of the approach



- **Requirements** for any enforcement mechanism for φ.
- **Functional definition** (satisfies the requirements):
  - description of the input/output behavior ;
  - composition of 3 functions: process input, computing the delayed timed word, and process output.
- **Enforcement monitor**:
  - description of the operational behavior,
  - a rule-based transition system with enforcement operations.
- **Implementation**: translation of the EM semantic rules into algorithms.

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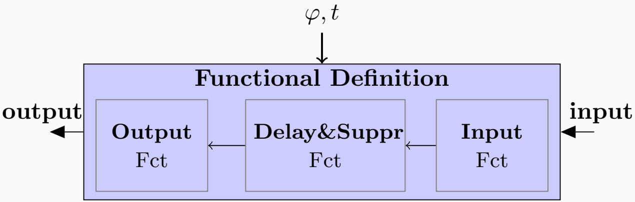

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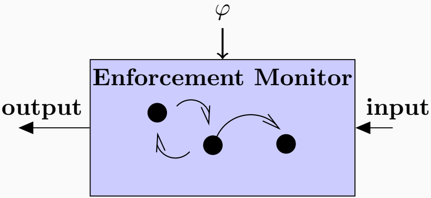

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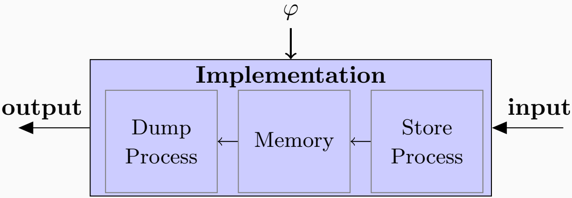

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Outline - On the Runtime Enforcement of Timed Properties

Requirements on an Enforcement Mechanism

Specified on an enforcement function for φ

$$E_\varphi : (\mathbb{R}_{\geq 0} \times \Sigma)^* \times \mathbb{R}_{\geq 0} \to (\mathbb{R}_{\geq 0} \times \Sigma)^*.$$

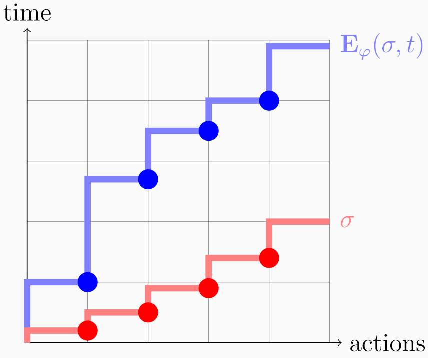
where for $\sigma \in (\mathbb{R}_{\geq 0} \times \Sigma)^*$ and $t \in \mathbb{R}_{\geq 0}$:

$E_\varphi(\sigma, t)$ is the sequence produced by the enforcement mechanism

- at time t,
- if σ is the sequence read as input.

Requirements on an Enforcement Mechanism – physical constraints

Physical constraints: The input and output are timed words. The output is produced in a "streaming fashion"[1]



Phy1 $t \leq t' \implies E_\varphi(\sigma, t) \preccurlyeq E_\varphi(\sigma, t')$.

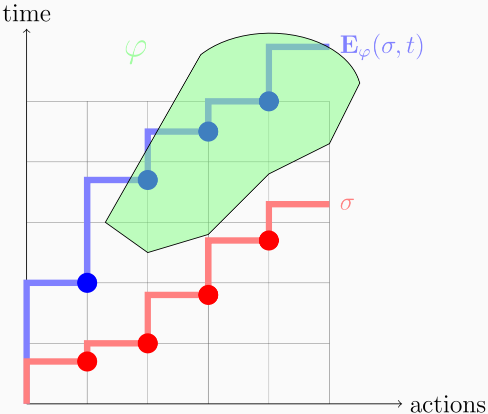
Phy2 $\sigma \preccurlyeq \sigma' \implies E_\varphi(\sigma, t) \preccurlyeq E_\varphi(\sigma', t)$.

[1] Implicit universal quantification over σ and t.

Requirements on an Enforcement Mechanism – soundness

Soundness: The output is (eventually) correct

$$\textbf{Snd} \quad E_\varphi(\sigma, t) \neq \epsilon \implies \exists t' \geq t : E_\varphi(\sigma, t') \models \varphi.$$



Requirements on an Enforcement Mechanism – transparency

Transparency: (prefix) relation between the input and output sequences

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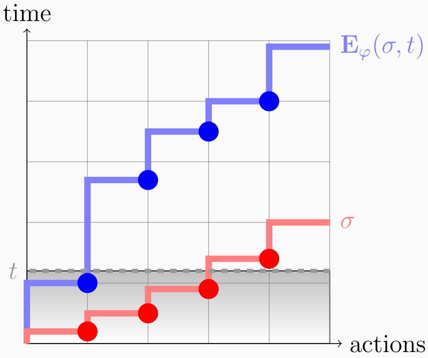
What the enforcement mechanism observes at time t is

$$\mathrm{obs}(\sigma, t) = \max_{\preccurlyeq}\{\sigma' \mid \sigma' \preccurlyeq \sigma \wedge \mathrm{time}(\sigma') \leq t\}$$

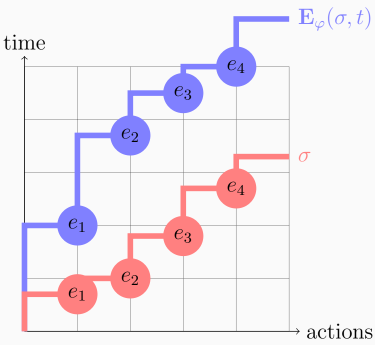
$\hookrightarrow$ the (max) prefix of σ that can be observed with t t.u.

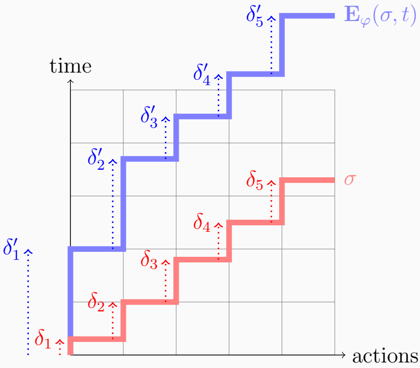


Requirements on an Enforcement Mechanism – transparency

Transparency: (prefix) relation between the input and output sequences

Tr $E_\varphi(\sigma, t) \preccurlyeq_d \mathrm{obs}(\sigma, t)$, where $\sigma' \preccurlyeq_d \sigma$ means:





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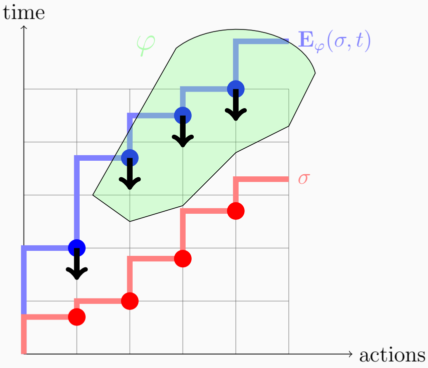

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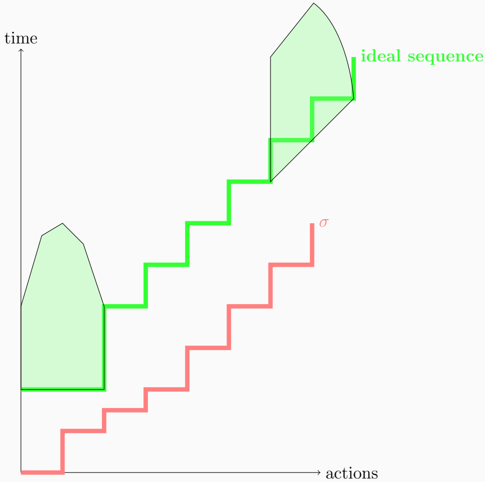

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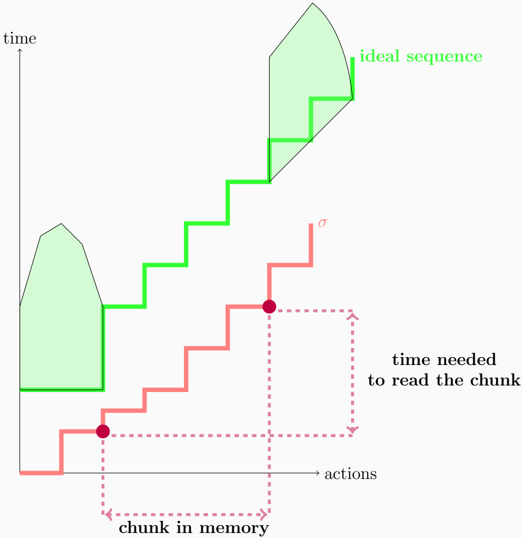

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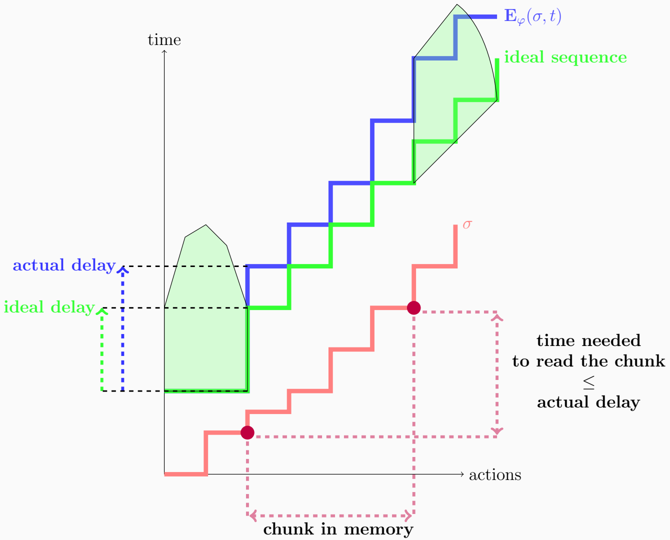
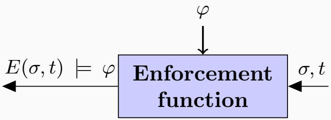


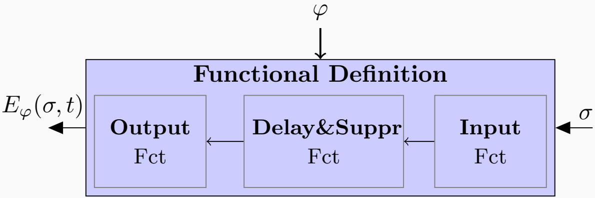
Outline - On the Runtime Enforcement of Timed Properties

Functional definition (1)

The functional definition describes the mechanism as a function

$$E_\varphi : (\mathbb{R}_{\geq 0} \times \Sigma)^* \times \mathbb{R}_{\geq 0} \to (\mathbb{R}_{\geq 0} \times \Sigma)^*.$$





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$$\text{obs}(\sigma, t) = \max_{\preccurlyeq}\{\sigma' \mid \sigma' \preccurlyeq \sigma \wedge \text{time}(\sigma') \leq t\}.$$

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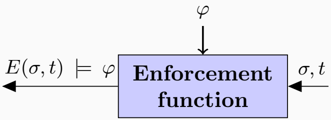

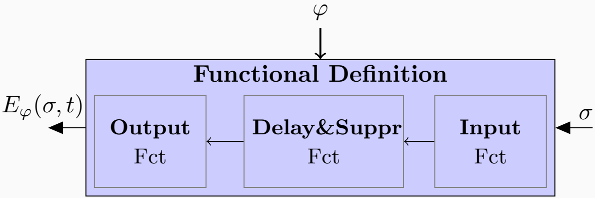

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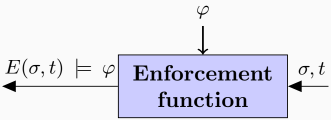

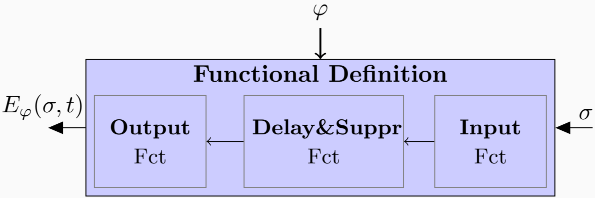

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(Simplified) Functional definition (2) – no suppression

$E_\varphi : (\mathbb{R}_{\geq 0} \times \Sigma)^* \times \mathbb{R}_{\geq 0} \to (\mathbb{R}_{\geq 0} \times \Sigma)^*$

$$E_\varphi(\sigma, t) = \mathrm{obs}\Big(\Pi_1\big(\mathrm{store}_\varphi(\mathrm{obs}(\sigma, t))\big), t\Big).$$

$\mathrm{store}_\varphi : (\mathbb{R}_{\geq 0} \times \Sigma)^* \to (\mathbb{R}_{\geq 0} \times \Sigma)^* \times (\mathbb{R}_{\geq 0} \times \Sigma)^*$

$\mathrm{store}_\varphi(\sigma)$ is a pair:

1. delayed correct prefix of σ,
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$$\mathrm{store}_\varphi(\epsilon) \quad = \quad (\epsilon, \epsilon)$$

Suppose $(\sigma_s, \sigma_c) = \mathrm{store}_\varphi(\sigma)$

$$\mathrm{store}_\varphi(\sigma \cdot (\delta, a)) \quad = \quad \begin{cases} (\sigma_s \cdot \min_{\preceq_{\mathrm{lex}}} K, \epsilon) & \text{if } K \neq \emptyset \\ (\sigma_s, \sigma_c \cdot (\delta, a)) & \text{otherwise} \end{cases}$$

with

$$K = \kappa_\varphi(\mathrm{time}(\sigma) + \delta, \sigma_s, \sigma_c \cdot (\delta, a))$$

$$\kappa_\varphi(T, \sigma_s, \sigma_c) = \{w \in (\mathbb{R}_{\geq 0} \times \Sigma)^* \mid w \preccurlyeq_d \sigma_c \wedge |w| = |\sigma_c| \wedge \sigma_s \cdot w \models \varphi \wedge \mathrm{delay}(w(1)) \geq T - \mathrm{time}(\sigma_s)\}$$

Intuitively, K is the set of possible corrected factors of $\sigma \cdot (\delta, a)$ between positions $|\sigma_s|$ and $|\sigma_c| + 1$ with a delay for the first event greater than $\mathrm{time}(\sigma_c \cdot (\delta, a))$.

(Simplified) Functional definition (3) – no suppression

$E_\varphi : (\mathbb{R}_{\geq 0} \times \Sigma)^* \times \mathbb{R}_{\geq 0} \to (\mathbb{R}_{\geq 0} \times \Sigma)^*$

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$$K = \kappa_\varphi(\mathrm{time}(\sigma) + \delta, \sigma_s, \sigma_c \cdot (\delta, a))$$

$$\kappa_\varphi(T, \sigma_s, \sigma_c) = \{ w \in (\mathbb{R}_{\geq 0} \times \Sigma)^* \mid w \preccurlyeq_d \sigma_c \wedge |w| = |\sigma_c| \wedge \sigma_s \cdot w \models \varphi \wedge \mathrm{delay}(w(1)) \geq T - \mathrm{time}(\sigma_s) \}$$

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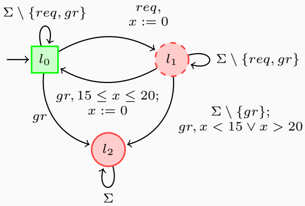
$\sigma = (3, req) \cdot (10, gr) \cdot (3, req) \cdot (5, req)$.



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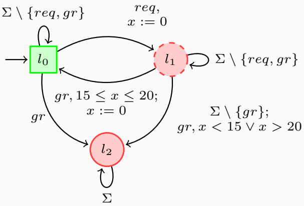

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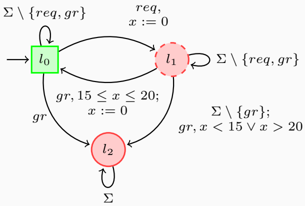

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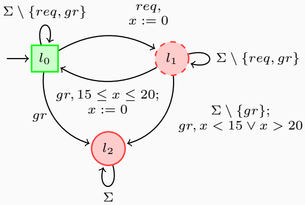

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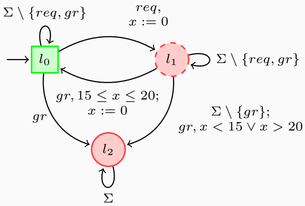

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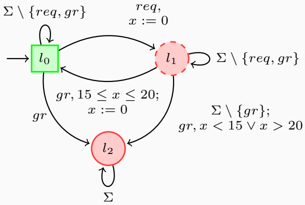

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The enforcement function satisfies the requirements

Proposition: Enforcement function vs requirements

The proposed definition of enforcement function satisfies the **soundness**, **transparency**, and **optimality** requirements.

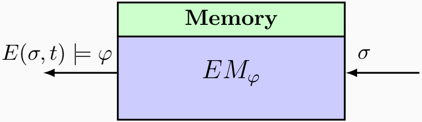
Proof

By induction on the length of the input sequence.

See papers.

Outline - On the Runtime Enforcement of Timed Properties

Enforcement monitor



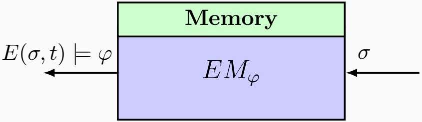
A *rule-based transition system*:

- configurations keep track of
  - the prefix of σ that has been corrected but yet to be output ("good memory"),
  - the suffix of σ that cannot be corrected ("bad memory")
  - a clock reset at the moment of the last *input* event ("store clock"),
  - a clock reset at the moment of the last *output* event ("dump clock"),
  - a state in the semantics of the TA;
- an initial configuration;
- rule-based transitions executing enforcement operations (cf. next slide).

Remark 1: for safety and co-safety, some memories can be discarded.

Remark 2: formal definition in papers.

Enforcement monitor



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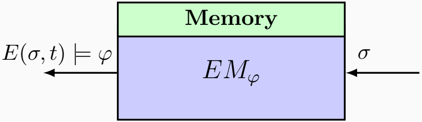

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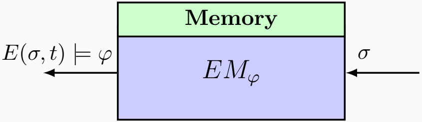

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Enforcement monitor: operations

1. **store-$\overline{\varphi}$**
   - when a new event is received and it *cannot make* φ *satisfied* by delaying.
   - updates "bad" memory and store clock
2. **store-φ**
   - when a new event is received and it *can make* φ *satisfied* by delaying
   - updates "good" memory and store clock
3. **suppress**
   - when an event is received and prevents φ's satisfaction
4. **dump**
   - when an event in the good memory can be released
   - updates "good" memory and dump clock
5. **idle**
   - when no other rule applies (i.e., when time elapses and nothing happens)
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Enforcement Monitor: correctness

Implementation relation between Enforcement Monitor and Enforcement Function

Given φ, at any time t, the input/output behavior of the synthesized enforcement monitor is the same as one of the corresponding enforcement function.

Proof

By induction on the length of the input sequence and "integrating the behavior of enforcement monitors over time".

See papers.

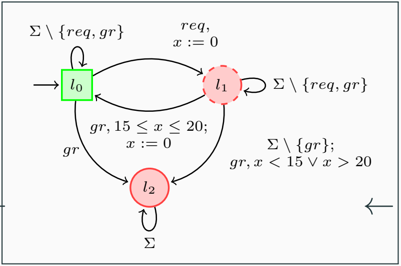
Corollary

Enforcement Monitors respect soundness, transparency, and optimality.

Enforcement Monitor: example

$t = 0$ - Executed operation: none

$\epsilon \longleftarrow$



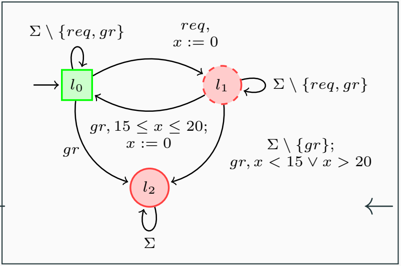
$\longleftarrow (3, r) \cdot (10, g) \cdot (3, r) \cdot (5, r)$

- Good Memory: ϵ
- Bad Memory: ϵ
- State: $(l_0, 0)$

Enforcement Monitor: example

$t = 3$ - Executed operation: idle(3)

ϵ $\longleftarrow$



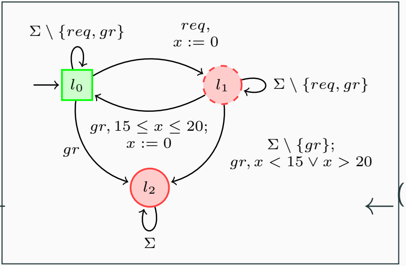
$\longleftarrow$ $(3, r) \cdot (10, g) \cdot (3, r) \cdot (5, r)$

- Good Memory: ϵ
- Bad Memory: ϵ
- State: $(l_0, 3)$

Enforcement Monitor: example

$t = 3$ - Executed operation: *store-*$\overline{\varphi}$

ϵ $\longleftarrow$



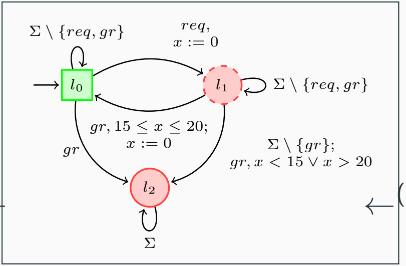
$\longleftarrow (10, g) \cdot (3, r) \cdot (5, r)$

- Good Memory: ϵ
- Bad Memory: $(3, r)$
- State: $(l_0, 0)$

Enforcement Monitor: example

$t = 13$ - Executed operation: $\mathrm{idle}(10)$

ϵ $\longleftarrow$



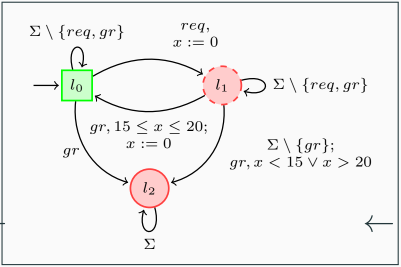
$\longleftarrow (10, g) \cdot (3, r) \cdot (5, r)$

- Good Memory: ϵ
- Bad Memory: $(3, r)$
- State: $(l_0, 0)$

Enforcement Monitor: example

$t = 13$ - Executed operation: *store-φ*

ϵ $\longleftarrow$



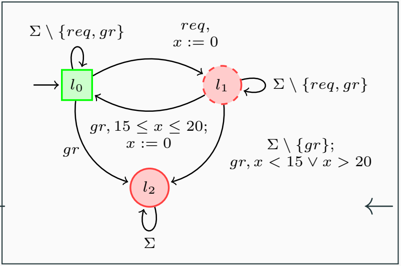
$\longleftarrow$ $(3, r) \cdot (5, r)$

- Good Memory:
  $(13, r) \cdot (15, g)$
- Bad Memory: ϵ
- State: $(l_0, 0)$

Enforcement Monitor: example

$t = 13$ - Executed operation: *dump*

$(13, r)$ $\longleftarrow$



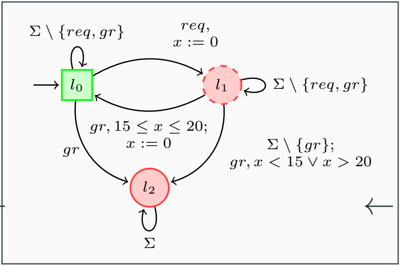
$\longleftarrow$ $(3, r) \cdot (5, r)$

- Good Memory: $(15, g)$
- Bad Memory: ϵ
- State: $(l_0, 15)$

Enforcement Monitor: example

$t = 16$ - Executed operation: $\mathrm{idle}(3)$

$(13, r)$ $\leftarrow$

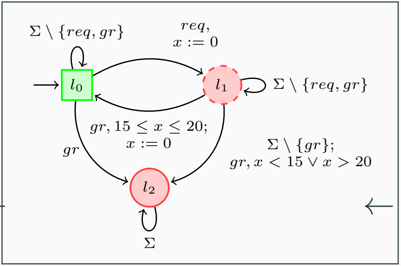


$\leftarrow$ $(3, r) \cdot (5, r)$

- Good Memory: $(15, g)$
- Bad Memory: ϵ
- State: $(l_0, 15)$

Enforcement Monitor: example

$t = 16$ - Executed operation: *store-$\overline{\varphi}$*

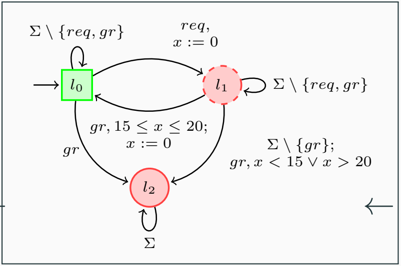
$(13, r)$ $\leftarrow$  $\leftarrow$ $(5, r)$

- Good Memory: $(15, g)$
- Bad Memory: $(3, r)$
- State: $(l_0, 15)$

Enforcement Monitor: example

$t = 21$ - Executed operation: idle(5)

$(13, r)$ $\leftarrow$



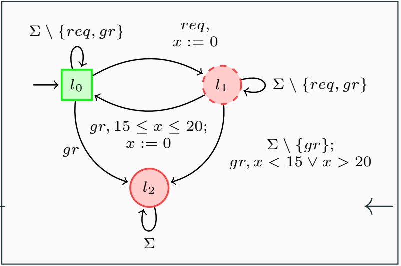
$\leftarrow$ $(5, r)$

- Good Memory: $(15, g)$
- Bad Memory: $(3, r)$
- State: $(l_0, 15)$

Enforcement Monitor: example

$t = 21$ - Executed operation: *suppress*

$(13, r)$ $\leftarrow$



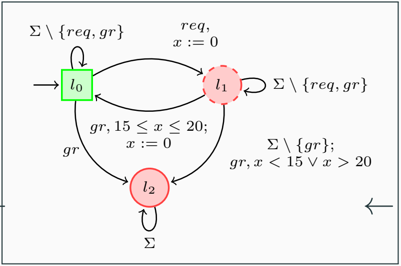
$\leftarrow$ ϵ

- Good Memory: $(15, g)$
- Bad Memory: $(3, r)$
- State: $(l_0, 15)$

Enforcement Monitor: example

$t = 28$ - Executed operation: $\mathrm{idle}(7)$

$(13, r)$ $\leftarrow$



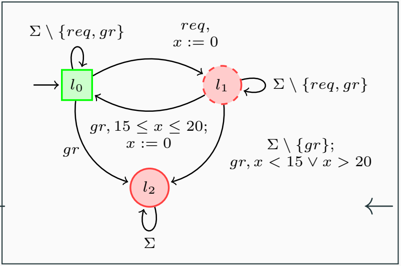
$\leftarrow$ ϵ

- Good Memory: $(15, g)$
- Bad Memory: $(3, r)$
- State: $(l_0, 15)$

Enforcement Monitor: example

$t = 28$ - Executed operation: *dump*

$(13, r) \cdot (15, g)$ $\leftarrow$

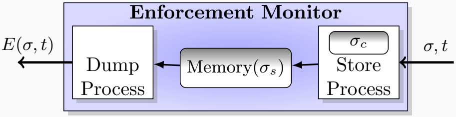


$\leftarrow$ ϵ

- Good Memory: ϵ
- Bad Memory: $(3, r)$
- State: $(l_0, 15)$

Outline - On the Runtime Enforcement of Timed Properties

Implementation – simplified algorithms



Used primitives:

- await(*condition*), wait(*time*)
- post(*loc*, *valuation*, *tw*)
- update(*loc*, *valuation*, *tw*)

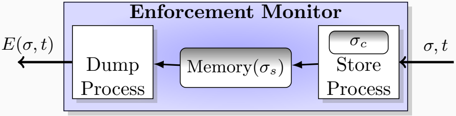
Algorithm: DumpProcess

$d \leftarrow 0$
while tt **do**
  await ($\sigma_s \neq \epsilon$)
  (δ, a) $\leftarrow$ dequeue (σ_s)
  wait ($\delta - d$)
  dump (a)
  $d \leftarrow 0$
end while

Algorithm: StoreProcess

$(l, \nu) \leftarrow (l_0, [X \leftarrow 0])$
$\sigma_s, \sigma_c \leftarrow \epsilon$
while tt **do**
  $(\delta, a) \leftarrow$ await ($event$)
  $\sigma_c \leftarrow \sigma_c \cdot (\delta, a)$
  $(\sigma'_c, isPath) \leftarrow$ update(l, ν, σ_c)
  if $isPath$ = tt **then**
    $\sigma_s \leftarrow \sigma_s \cdot \sigma'_c$
    $(l, \nu) \leftarrow$ post(l, ν, σ'_c)
    $\sigma_c \leftarrow \epsilon$
  end if
end while

Implementation – simplified algorithms



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  $\sigma_c \leftarrow \sigma_c \cdot (\delta, a)$
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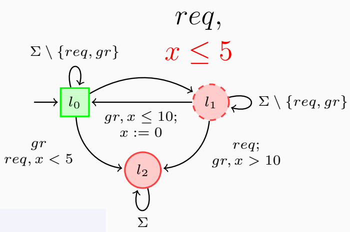
  if $isPath =$ tt **then**
    $\sigma_s \leftarrow \sigma_s \cdot \sigma'_c$
    $(l, \nu) \leftarrow \text{post}(l, \nu, \sigma'_c)$
    $\sigma_c \leftarrow \epsilon$
  end if
end while

Outline - On the Runtime Enforcement of Timed Properties

Non-enforceable response properties

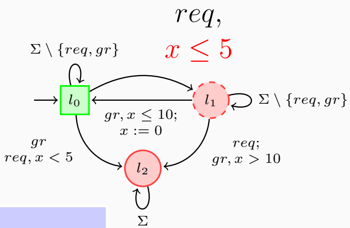
$\Sigma = \{gr, req\}$.

$\sigma = (3, req) \cdot (4, gr) \cdot (2, req) \cdot (6, gr)$.



$t \in [0, 3[$	$\mathrm{obs}(\sigma, t) = \epsilon$ $\mathrm{store}_\varphi(\mathrm{obs}(\sigma, t)) = (\epsilon, \epsilon)$ $E_\varphi(\sigma, t) = \mathrm{obs}(\epsilon, t)$
$t \in [3, 7[$	$\mathrm{obs}(\sigma, t) = (3, req)$ $\mathrm{store}_\varphi(\mathrm{obs}(\sigma, t)) = (\epsilon, (3, req))$ $E_\varphi(\sigma, t) = \mathrm{obs}(\epsilon, t)$
$t \in [7, 9[$	$\mathrm{obs}(\sigma, t) = (3, req) \cdot (4, gr)$ $\mathrm{store}_\varphi(\mathrm{obs}(\sigma, t)) = (\epsilon, (3, req) \cdot (4, gr))$ $E_\varphi(\sigma, t) = \mathrm{obs}(\epsilon, t)$
$t \in [9, 15[$	$\mathrm{obs}(\sigma, t) = (3, req) \cdot (4, gr) \cdot (2, req)$ $\mathrm{store}_\varphi(\mathrm{obs}(\sigma, t)) = (\epsilon, (3, req) \cdot (4, gr) \cdot (2, req))$ $E_\varphi(\sigma, t) = \mathrm{obs}(\epsilon, t)$
$t \in [15, \infty[$	$\mathrm{obs}(\sigma, t) = (3, req) \cdot (4, gr) \cdot (2, req) \cdot (6, gr)$ $\mathrm{store}_\varphi(\mathrm{obs}(\sigma, t)) = (\epsilon, (3, req) \cdot (4, gr) \cdot (2, req) \cdot (6, gr))$ $E_\varphi(\sigma, t) = \mathrm{obs}(\epsilon, t)$

Non-enforceable response properties



$\Sigma = \{gr, req\}$.
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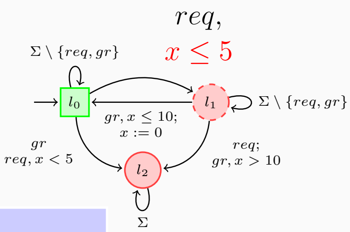
Non-enforceable response properties



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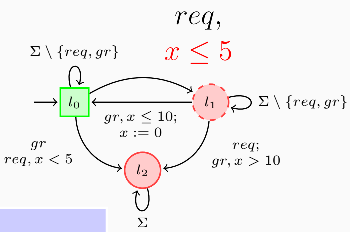

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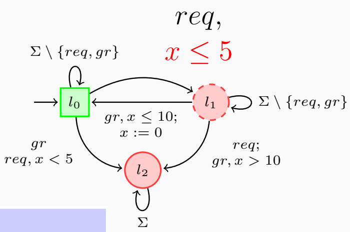
Non-enforceable response properties



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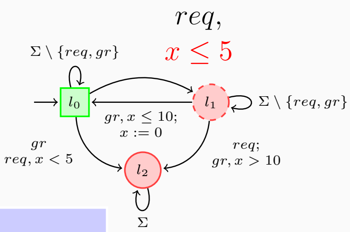
Non-enforceable response properties



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Extensions

Outline - On the Runtime Enforcement of Timed Properties

Outline - On the Runtime Enforcement of Timed Properties

Uncontrollable events

Two sets of events : controllable (Σ_c) and uncontrollable (Σ_u).

Uncontrollable Events

Uncont. events must be emitted upon reception (i.e., only observable events).

New definitions and challenges

- Delays between stored controllable events have to be recomputed upon reception of each uncont. event
- Prevent the system of reaching a bad state upon reception of any sequence of uncont. events → uncont. events must be anticipated
- Enforceability depends on the received uncontrollable events

Contributions

- Redefining soundness, transparency, and optimality.
- Enforcement mechanisms at two levels of abstraction, *functional* and *operational*, for both untimed and timed regular properties

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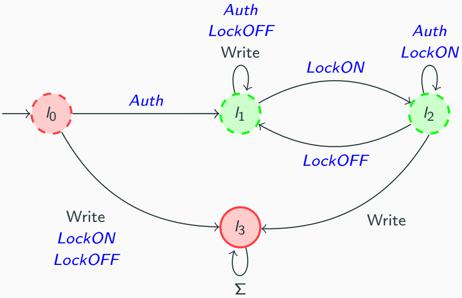
Example of Non-Enforceable Property

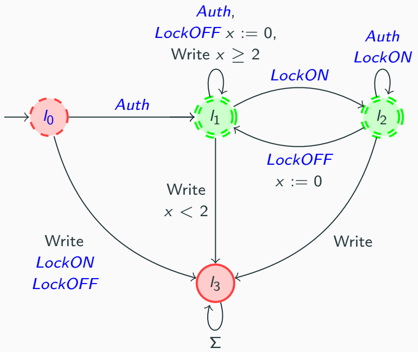
Example of a simple shared storage device example (without time).
$\Sigma_u = \{Auth, LockOFF, LockON\}, \Sigma_c = \{\text{Write}\}$



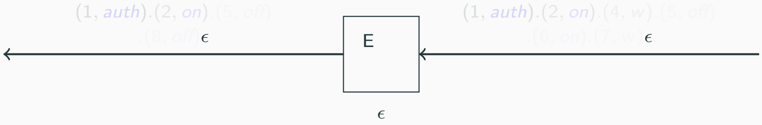
- In l_0, impossible to ensure correctness of this property
- If *Auth* is read, then this property becomes *enforceable*

Property with time: example of execution

$\Sigma_u = \{Auth, LockOFF, LockON\}, \Sigma_c = \{\text{Write}\}$



t = 0



Property with time: example of execution

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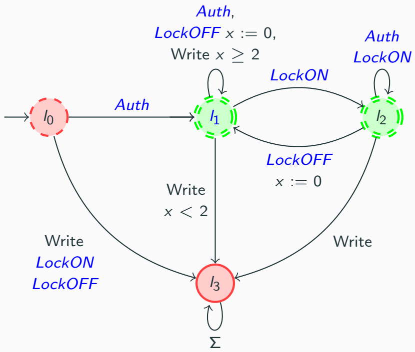
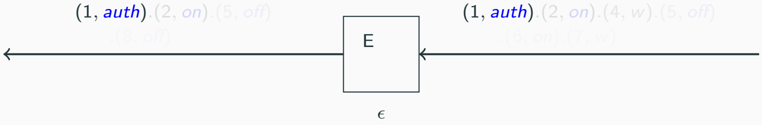


t = 1



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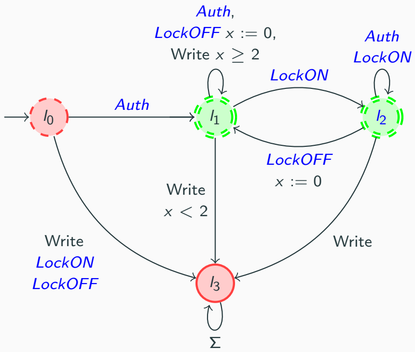
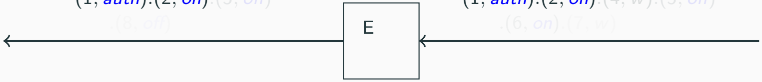


t = 2

$(1, auth).(2, on).(5, off).(8, off)$

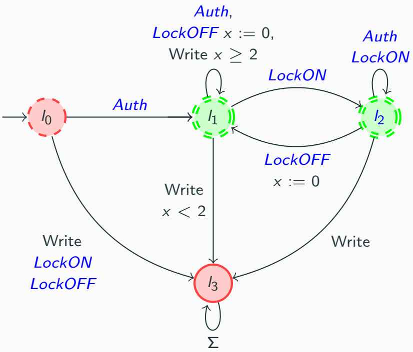
$(1, auth).(2, on).(4, w).(5, off).(6, on).(7, w)$



ϵ

Property with time: example of execution

$\Sigma_u = \{Auth, LockOFF, LockON\}, \Sigma_c = \{\text{Write}\}$



t = 4

$(1, auth).(2, on).(5, off).(8, off)$

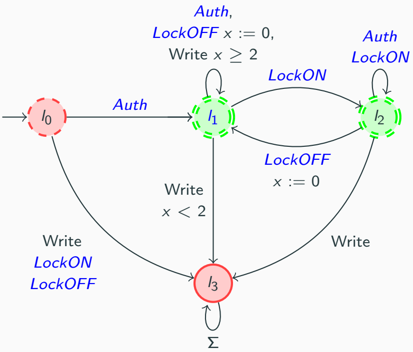
E

$(1, auth).(2, on).(4, w).(5, off).(6, on).(7, w)$

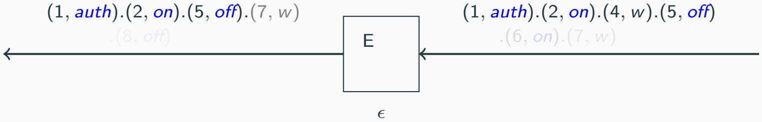
w

Property with time: example of execution

$\Sigma_u = \{Auth, LockOFF, LockON\}, \Sigma_c = \{\text{Write}\}$



t = 5



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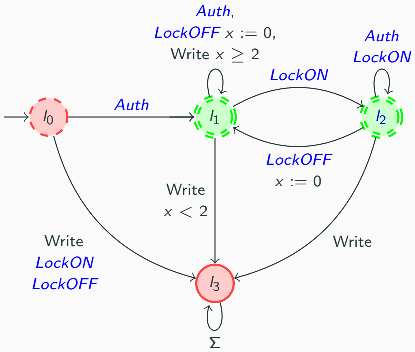

t = 6

(1, *auth*).(2, *on*).(5, *off*).(6, *on*) .(8, *off*)

E

(1, *auth*).(2, *on*).(4, *w*).(5, *off*) .(6, *on*).(7, *w*)

w

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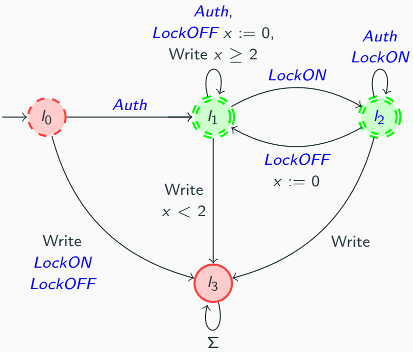

t = 7

(1, *auth*).(2, *on*).(5, *off*).(6, *on*) .(8, *off*)

E

(1, *auth*).(2, *on*).(4, *w*).(5, *off*) .(6, *on*).(7, *w*)

w.w

Property with time: example of execution

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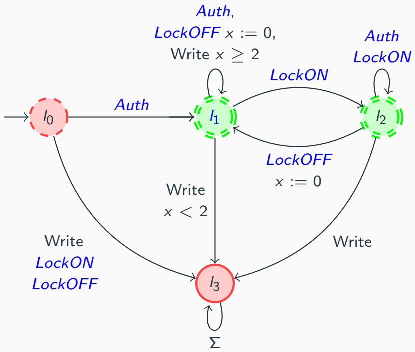
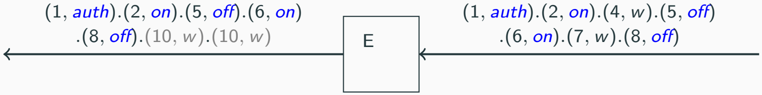


t = 8



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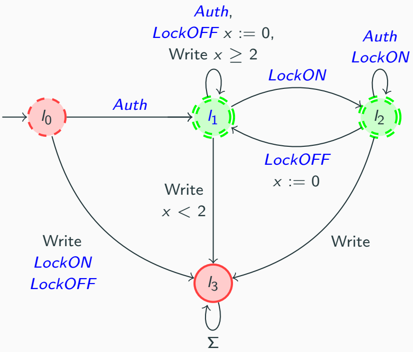
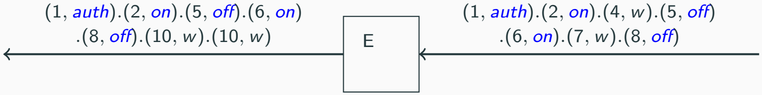


t = 10



Outline - On the Runtime Enforcement of Timed Properties

Motivations for enforcement with time and data

Allow specifying desired behavior of a system more precisely (time constraints between events, allowing events to carry data, expressing constraints).

Specifying constraints over time and data

- *For each client with* **special** *id, after a request, there should be a response after a delay of 5 t.u., if there are more than 10 request messages..*
- *For each client with* **normal** *id, after a request, there should be a response after a delay of X t.u., where X is the number of request messages..*

Many application domains

- Communication protocols.
- Managing resource allocation.
- Real-time embedded systems.
- Monitor hardware failures.
- Web services.
- Several other domains.

Enforcement Monitors

- Firewall (to prevent DOS attacks).
- Scheduler for resource allocation.

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Parameterized Timed Automata with Variables (PTAVs)

- Extension of timed automata.
- Describes a set of *identical* timed automata (differing only in the value of its parameter p) extended with internal and external variables.
- (Inspired from IOSTS, TIOSTS, QEA, Parametric trace slicing.)

Syntax of PTAV

$\mathcal{A}(p) = \langle p, V, C, \Theta, L, l_0, L_G, X, \Sigma_p, \Delta \rangle$.

- p - a parameter (for example to handle multiple clients/instances).
- C - external variables (to model transfer of data from the monitored system along with events).
- V - internal variables (used for internal computation).

A PTAV with parameter p is denoted as $A(p)$, and an instance of $A(p)$ for a value π of p is denoted as $A(\pi)$.

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Events, timed words

- Event: $e_i = (\delta_i, a_i(\pi_i, \eta_i))$, $a_i \in \Sigma$, $\pi_i \in \mathcal{D}_p$, $\eta_i \in \mathcal{D}_V$.
- Timed word: $\sigma = (\delta_1, a_1(\pi_1, \eta_1)) \cdots (\delta_n, a_n(\pi_n, \eta_n))$.
- Instance of PTAV $A(\pi)$ accepts σ if $\sigma \in \mathcal{L}(A(\pi))$.

Projections of σ according to the runtime values of π

- $\sigma = (0.5, a(1, \eta_1)) \cdot (0.3, a(2, \eta_2)) \cdot (0.2, a(1, \eta_3)) \cdot (0.4, a(2, \eta_4))$
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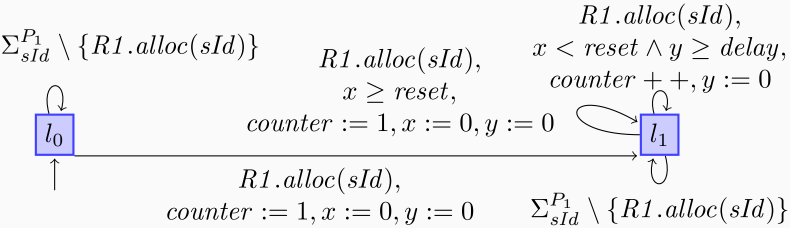
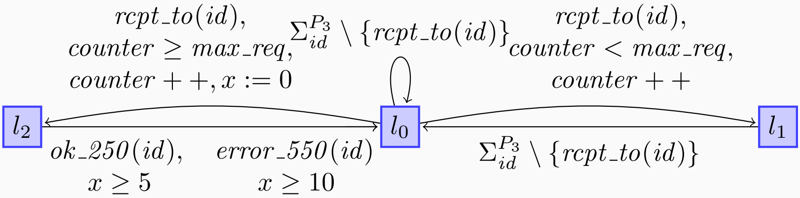
Examples of PTAVs for resource allocation [2]



"There should be a dynamic delay between two allocation requests to the same resource by a service. This delay increases as the number of allocations increases and also depends on the service id."

[2] Squares denote accepting locations. Non-accepting locations are omitted

Examples of PTAVs for resource allocation (ctd) [3]



If

- the number of RCPT_TO messages is greater than *maxreq*, and
- the response of the server is OK_250 (resp. ERROR_550),

then there should be a delay of at least 5 (resp. 10) t.u. before sending the response.

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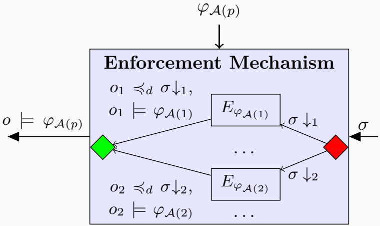
Outline - On the Runtime Enforcement of Timed Properties

Enforcement of parametric timed properties



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- Property φ specified by a PTAV.
- An instance of EM per parameter value (takes as input only the events with same parameter value).
- Output of each EM instance satisfies the soundness, transparency and optimality constraints.
- $o = merge(o_1, o_2)$ is only sound (order of events may not be preserved globally).

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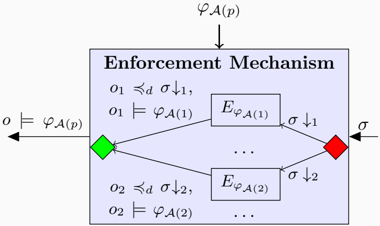

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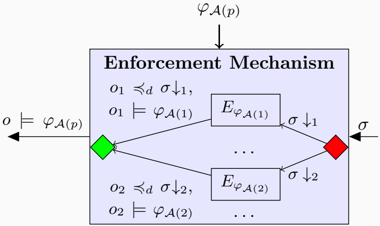

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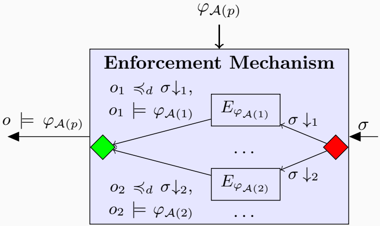

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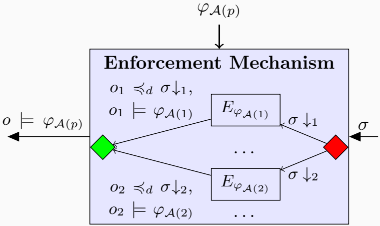

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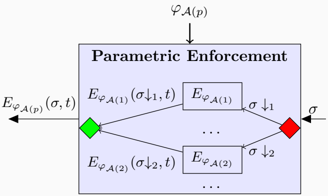
Requirements: Enforcement of parametric timed properties

$$E_{\varphi_p}(\sigma, t) : (\mathbb{R}_{\geq 0} \times \Lambda)^* \times \mathbb{R}_{\geq 0} \rightarrow (\mathbb{R}_{\geq 0} \times \Lambda)^*$$



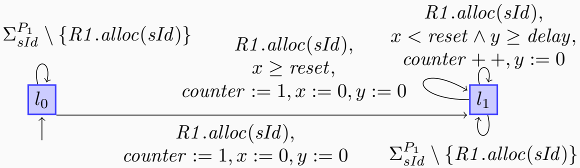
Parametric Soundness, Transparency and Optimality

- Soundness: $\forall \pi \in \mathcal{D}om(p), \forall \sigma \in (\mathbb{R}_{\geq 0} \times \Lambda)^* : sound(E_{\varphi_{\mathcal{A}(\pi)}}, \sigma\downarrow_\pi)$
- Transparency: $\forall \pi \in \mathcal{D}om(p), \forall \sigma \in (\mathbb{R}_{\geq 0} \times \Lambda)^* : transparent(E_{\varphi_{\mathcal{A}(\pi)}}, \sigma\downarrow_\pi)$
- Optimality: $\forall \pi \in \mathcal{D}om(p), \forall \sigma \in (\mathbb{R}_{\geq 0} \times \Lambda)^* : optimal(E_{\varphi_{\mathcal{A}(\pi)}}, \sigma\downarrow_\pi)$

Proposition

Given a safety PTAV $\mathcal{A}(p)$ specifying property $\varphi_{\mathcal{A}(p)}$, for all $\pi \in D_p$, the enforcement function $E_{\varphi_{\mathcal{A}(\pi)}}$, is sound, transparent, and optimal w.r.t. $\mathcal{A}(\pi)$.

Parametric case: Example



- *delay* $= 5$
- *reset* $= 100$

- Let $\sigma = (2, R1.alloc(1)) \cdot (1, R1.alloc(2)) \cdot (1, R1.alloc(1))$.
- $\mathcal{D}om(\sigma) = \{1, 2\}$, we have two monitor instances.

$\Pi = 1$

- $\sigma \downarrow_1 = (2, R1.alloc(1)) \cdot (2, R1.alloc(1))$.
- $E_{\varphi_{\mathcal{A}(1)}} = (2, R1.alloc(1)) \cdot (5, R1.alloc(1))$.

$\Pi = 2$

- $\sigma \downarrow_2 = (3, R1.alloc(2))$.
- $E_{\varphi_{\mathcal{A}(2)}} = (3, R1.alloc(2))$.

$E_{\varphi_{\mathcal{A}(1)}}$ and $E_{\varphi_{\mathcal{A}(2)}}$ are sound, transparent, and optimal.

Remark: properties of the global output trace

- $E_{\varphi_{\mathcal{A}(p)}}(\sigma, t) = merge(E_{\varphi_{\mathcal{A}(1)}}(\sigma\downarrow_1, t), E_{\varphi_{\mathcal{A}(2)}}(\sigma\downarrow_2, t))$
- Only soundness is preserved.

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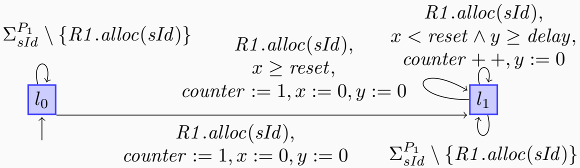

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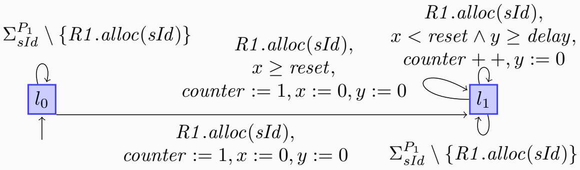

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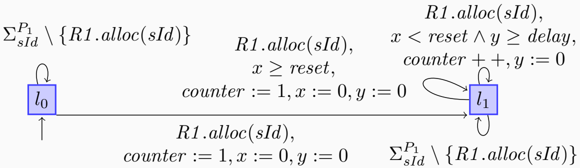

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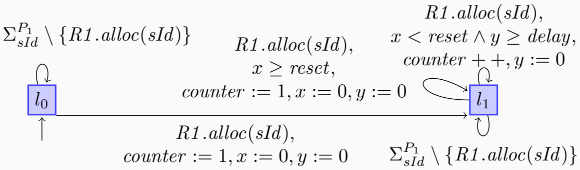

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- $E_{\varphi_{\mathcal{A}(2)}} = (3, R1.alloc(2))$.

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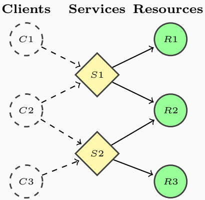
Remark: properties of the global output trace

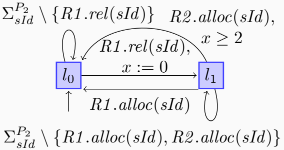
- $E_{\varphi_{\mathcal{A}(p)}}(\sigma, t) = merge(E_{\varphi_{\mathcal{A}(1)}}(\sigma\downarrow_1, t), E_{\varphi_{\mathcal{A}(2)}}(\sigma\downarrow_2, t))$
- Only soundness is preserved.

Outline - On the Runtime Enforcement of Timed Properties

Application Domains

Resource allocation in a client-server model





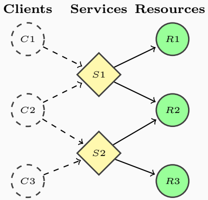
After releasing R1, there should be a delay of at least 2 t.u. before allocating R2.

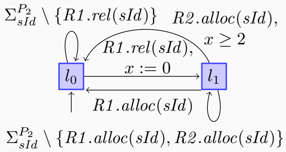
Protecting mail servers

If the number of RCPT_TO messages from a client is greater than maxreq, then there should be a delay of at least del t.u. before responding an OK_250.

Application Domains

Resource allocation in a client-server model





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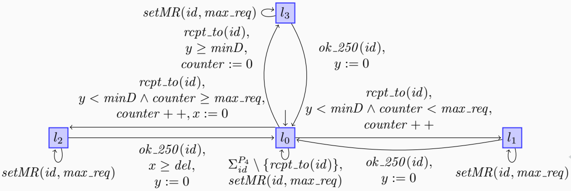

Conclusions and Future Work

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Enforcement monitoring for systems with timing requirements.

- Input any regular timed property modeled as a timed automaton.
- Enforcement mechanisms described at several levels of abstraction (enforcement function, enforcement monitor and algorithms).
- Enforcement Mechanisms are **delayers** (with several *alternative enforcement primitives*: suppress actions, augment/reduce delays).
- Exhibiting a notion of non-enforceable properties.
- Requirements with constraints on *data and time*.

Future Work

- Delineate the set of *enforceable* response properties.
- *More expressive* formalisms such as context-free timed languages.
- Probabilistic models for events.
- Implementing efficient enforcement monitors (in application scenarios).

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- Nov 10, 2017: Notification of paper and SRC acceptance/rejection
- April 9 – 13, 2018: SAC and SVT day

References on Runtime Enforcement (of Timed) Properties

- First definition of mechanisms for safety and co-safety properties: [PinisettyFJMRN12].
- Extension to regular properties: [PinisettyFJM14a].
- Enforcement mechanism as delayers (preserving delay between events): [PinisettyFJMRN14] (summarizing [PinisettyFJMRN12, PinisettyFJM14a])
- Events with Data: [PinisettyFJM14b].
- Uncontrollable events: [RenardFRPJM15].
- Enforcement mechanism as delayers+suppression (reducing delay between events): [FalconeJMP16].
- Using Game Theory to synthesize mechanisms

References on Runtime Enforcement (of Untimed Properties)

General Models of Enforcement Mechanisms:

- Security Automata (SAs): [Schneider00].
- Edit Automata (EAs): [LigattiBW05, LigattiBW09, LigattiThesis].
- Generic Enforcement Monitors (GEMs): [FalconeMFR11].

Models taking memory limitations into account:

- Shallow History Automata: [Fong04].
- Finite Edit Automata: [BeauquierCL09].
- Limiting the amount of Memory: [TalhiTD06].

Synthesis of Enforcement Mechanisms:

- Synthesis from Process Algebraic Descriptions: [MartinelliM07].
- Synthesizing GEMs from Streett Automata: [FalconeFM08].
- Synthesizing SAs from Rabin Automata: [ChabotKT09].
- Synthesizing GEMs from Safety-Progress Properties: [FalconeFM12].

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References on Runtime Verification

Tutorials and surveys:

- [PlatnerN81]
- [SchroederB95]
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