Expressiveness of Deterministic Single-Clock Timed Automata

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From FORMATS 20 and LATA 20

Plan

Plan

1. Definitions and Motivation
2. Expressiveness
3. Conciseness

Single-Clock Timed Automata

- A set of *locations* L with an initial location ℓ_0 and a final location ℓ_f
- A set of *propositions* AP and a set of *actions* Act
- A set of *synchronized transitions* $\{\ell \xrightarrow{\varphi^-,\gamma,B,r,\varphi^+} \ell'\}$ with:
  - φ^- and φ^+ the pre and post conditions, boolean formulas over AP;
  - the guard $\gamma \in \{\alpha \bowtie x \bowtie' \beta\}$ with $\bowtie, \bowtie' \in \{<, \leq,\}, \alpha \in \mathbb{N}$ and $\beta \in \mathbb{N} \cup \{\infty\}$;
  - $B \subseteq Act$ the subset of possible actions;
  - $r \in \{\emptyset, \downarrow\}$, the resetting action on clock x.
- A set of *autonomous transitions* $\{\ell \xrightarrow{\varphi^-,\gamma,\sharp,r} \ell'\}$ (or $\{\ell \xrightarrow{\varphi^-,\gamma,\{\sharp\},r,\varphi^-} \ell'\}$) with:
  - φ^- the pre condition;
  - the guard $\gamma \in \{x = \alpha\}$;
  - $r \in \{\emptyset, \downarrow\}$, the resetting action on clock x.

Deterministic Single-Clock Timed Automata (DTA)

Determinism on synchronized transitions.

For all $\ell \xrightarrow{\varphi^-,\gamma,B,r,\varphi^+} \ell'$ and $\ell \xrightarrow{\varphi'^-,\gamma',B',r',\varphi'^+} \ell''$,

- either $\varphi^- \wedge \varphi'^- \Leftrightarrow \texttt{false}$;
- or $\gamma \wedge \gamma' \Leftrightarrow \texttt{false}$;
- or $B \cap B' = \emptyset$;
- or $\varphi^+ \wedge \varphi'^+ \Leftrightarrow \texttt{false}$.

Determinism on autonomous transitions.

For all $\ell \xrightarrow{\varphi^-,x=\alpha,\sharp,r} \ell'$ and $\ell \xrightarrow{\varphi'^-,x=\alpha',\sharp,r'} \ell''$, $\varphi^- \wedge \varphi'^- \Leftrightarrow \texttt{false}$ or $\alpha \neq \alpha'$.

Condition on the final location.

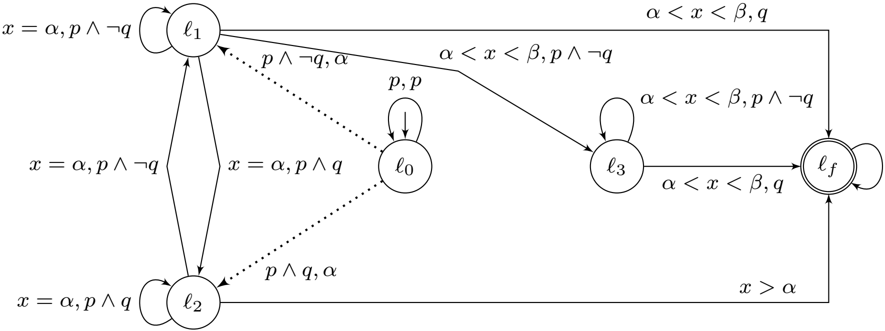
There is a single transition outgoing from the final location:

$$\ell_f \xrightarrow{\texttt{true},\texttt{true},Act,\emptyset,\texttt{true}} \ell_f$$

A First Motivation with Illustration

A DTA is a way to express a linear timed temporal formula on infinite timed paths.

$$p\mathbf{U}^{]\alpha,\beta[}q \text{ with } \alpha > 0$$



Timed Paths

A *timed path* is a sequence $(v_0, \delta_0) \xrightarrow{a_0} (v_1, \delta_1) \xrightarrow{a_1} \cdots (v_i, \delta_i) \xrightarrow{a_i} \cdots$ such that for all $i \in \mathbb{N} : v_i \in \{\texttt{true}, \texttt{false}\}^{AP}, a_i \in Act$ and $\delta_i \in \mathbb{R}_{\geq 0}$.

δ_0 is the time of the occurrence of the first transition.

For $i > 0$, δ_i is the duration between the occurrence of the i^{th} transition and the occurrence of the $i + 1^{th}$ transition.

Illustration.

$$\sigma = (\{p\}, 0.4) \xrightarrow{a} (\{p, q\}, 5.6) \xrightarrow{b} (\{p\}, 2.4) \xrightarrow{c} (\emptyset, 0.7) \cdots$$

Observation.

$$\sigma \models p\mathbf{U}^{]1,2[}q$$

Runs

A *run* of a DTA is a sequence:
$(\ell_0, v'_0, \bar{x}_0, \delta'_0) \xrightarrow{\varphi_0^-,\gamma_0,B_0,r_0,\varphi_0^+} (\ell_1, v'_1, \bar{x}_1, \delta'_1) \cdots (\ell_i, v'_i, \bar{x}_i, \delta'_i) \xrightarrow{\varphi_i^-,\gamma_i,B_i,r_i,\varphi_i^+} \cdots$ such that

- $\ell_i \xrightarrow{\varphi_i^-,\gamma_i,B_i,r_i,\varphi_i^+} \ell_{i+1}$ is a synchronized or autonomous transition.
- v'_0 satisfies the precondition of the first transition.
  For $i > 0$, v'_i satisfies the postcondition of the i^{th} transition and the precondition of the $i+1^{th}$ transition.
- δ'_0 is the time of the occurrence of the first transition.
  For $i > 0$, δ'_i is the duration between the occurrence of the i^{th} transition and the occurrence of the $i+1^{th}$ transition.
- $\bar{x}_0 = 0$ and for $i > 0$, $\bar{x}_i = \mathbf{1}_{r_{i-1}=\emptyset}(\bar{x}_{i-1} + \delta_{i-1})$ is the the clock value after the i^{th} transition.
  For all i, $\bar{x}_i + \delta'_i$ satisfies the guard of the $i+1^{th}$ transition.
- If the first transition is synchronized, no autonomous transition could take place before it.
  If the $i+1^{th}$ transition is synchronized, no autonomous transition could take place between the i^{th} and the $i+1^{th}$ transition.

Paths Recognized by Runs

Let σ be the path
$(v_0, \delta_0) \xrightarrow{a_0} (v_1, \delta_1) \xrightarrow{a_1} \cdots (v_i, \delta_i) \xrightarrow{a_i} \cdots$

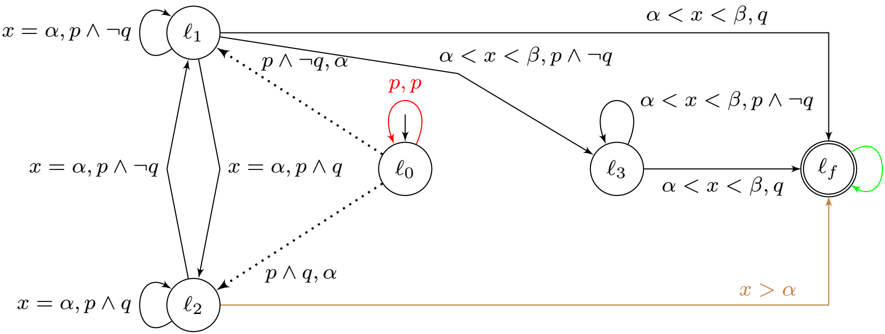
Let ρ be the run
$(\ell_0, v'_0, \bar{x}_0, \delta'_0) \xrightarrow{\varphi_0^-, \gamma_0, B_0, r_0, \varphi_0^+} (\ell_1, v'_1, \bar{x}_1, \delta'_1) \cdots (\ell_i, v'_i, \bar{x}_i, \delta'_i) \xrightarrow{\varphi_i^-, \gamma_i, B_i, r_i, \varphi_i^+} \cdots$

σ is *recognized* by ρ if there exists an increasing $\kappa : \mathbb{N} \to \mathbb{N}$ such that for all i:

- $a_i \in B_{\kappa(i)}$, $\delta_i = \sum_{\kappa(i-1)<h\leq\kappa(i)} \delta'_h$ and $v_i = v'_{\kappa(i)}$;
- for all $h \notin \kappa(\mathbb{N})$, $B_h = \{\sharp\}$.

σ is *accepted* by ρ if ρ visits ℓ_f.

Illustration ($p\mathbf{U}^{]1,2[}q$)



Let $\sigma = (\{p\}, 0.4) \xrightarrow{a} (\{p, q\}, 5.6) \xrightarrow{b} (\{p\}, 2.4) \xrightarrow{c} (\emptyset, 0.7) \cdots$

Let ρ be:

$(\ell_0, \{p\}, 0.0, 0.4) \rightarrow$ $(\ell_0, \{p, q\}, 0.4, 0.6)$ $\dashrightarrow$ $(\ell_2, \{p, q\}, 1.0, 5.0) \rightarrow$
$(\ell_f, \{p\}, 6.0, 2.4) \rightarrow$ $(\ell_f, \emptyset, 8.4, 0.7)$ $\cdots$

Then σ is accepted by ρ with $\kappa(0) = 0$ and for all $i > 0$, $\kappa(i) = i + 1$.

Continuous Time Markov Chains (CTMC)

A *continuous time Markov chain* $\mathcal{M}$ is defined by:

- S, a finite set of *states* with s_0 the initial state;
- $lab : S \to \{\texttt{true}, \texttt{false}\}^{AP}$, a valuation over S;
- $R : S \times Act \times S \to \mathbb{R}_{\geq 0}$, the rate function ;
- Let $R_s = \sum R(s, a, s')$. Then for all s, $R_s > 0$.

$\mathcal{M}$ generates a path $\sigma_{\mathcal{M}} = (v_0, \delta_0) \xrightarrow{a_0} (v_1, \delta_1) \xrightarrow{a_1} \cdots (v_i, \delta_i) \xrightarrow{a_i} \cdots$ as follows:

- the initial state is s_0;
- $v_i = lab(s_i)$ and δ_i is sampled w.r.t. distribution $F_{s_i}(\tau) = 1 - e^{-R_{s_i}\tau}$;
- (a_i, s_{i+1}) is selected with probability $\frac{R(s_i, a_i, s_{i+1})}{R_{s_i}}$.

Let $\mathcal{A}$ be a DTA. Then $\mathbf{Pr}_{\mathcal{M}}(\mathcal{A}) \stackrel{\text{def}}{=} \mathbf{Pr}(\sigma_{\mathcal{M}} \models \mathcal{A})$.

Why Deterministic Single-Clock Timed Automata?

There is an efficient way to evaluate $\mathbf{Pr}_{\mathcal{M}}(\mathcal{A})$.

Principles of the evaluation.

- The synchronized product of $\mathcal{M}$ and $\mathcal{A}$, $\mathcal{M} \otimes \mathcal{A}$, is a semi-Markovian process.
- $\mathbf{Pr}_{\mathcal{M}}(\mathcal{A})$ is the probability to reach ℓ_f in $\mathcal{M} \otimes \mathcal{A}$.
- This probability only depends on $\mathcal{M}_d$ the discrete-time Markov chain of transition probabilities between *regeneration points* of $\mathcal{M} \otimes \mathcal{A}$.
- $\mathcal{M}_d$ is computed via a transient analysis of *subordinated* CTMCs.

As soon as $\mathcal{A}$ has two clocks,
there could be no more regeneration points in $\mathcal{M} \otimes \mathcal{A}$.

Plan

Relating Families of DTA

Let $\mathbb{A}_1$ and $\mathbb{A}_2$ be families of DTA. Then:

- $\mathbb{A}_2$ is *at least as expressive as* $\mathbb{A}_1$ w.r.t. timed language, denoted $\mathbb{A}_1 \prec_{\mathcal{L}} \mathbb{A}_2$, if for all $\mathcal{A}_1 \in \mathbb{A}_1$ there exists $\mathcal{A}_2 \in \mathbb{A}_2$ such that $\mathcal{L}(\mathcal{A}_2) = \mathcal{L}(\mathcal{A}_1)$;
- $\mathbb{A}_2$ is *at least as expressive* as $\mathbb{A}_1$ w.r.t. CTMCs, denoted $\mathbb{A}_1 \prec_{\mathcal{M}} \mathbb{A}_2$, if for all $\mathcal{A}_1 \in \mathbb{A}_1$ there exists $\mathcal{A}_2 \in \mathbb{A}_2$ s.t. for all $\mathcal{M}$, $\mathbf{Pr}_{\mathcal{M}}(\mathcal{A}_2) = \mathbf{Pr}_{\mathcal{M}}(\mathcal{A}_1)$.

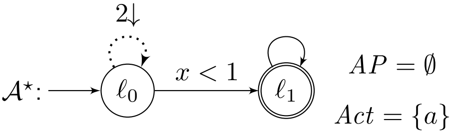
$\prec_{\mathcal{L}}$ is more discriminative than $\prec_{\mathcal{M}}$.

- Let $\mathbb{A}$ be the general family of DTA;
- Let $\mathbb{A}^{na}$ be the family of DTA without autonomous transitions;
- Let $\mathbb{A}^{na}_{ne}$ be the family of DTA without autonomous transitions and without equality constraints on synchronized transitions.

Then $\mathbb{A}^{na}_{ne} \sim_{\mathcal{M}} \mathbb{A}^{na}$ but $\mathbb{A}^{na}_{ne} \precnsim_{\mathcal{L}} \mathbb{A}^{na}$.

Are autonomous transitions necessary w.r.t. CTMC: $\mathbb{A} \prec_{\mathcal{M}} \mathbb{A}^{na}$?

Necessity of Autonomous Transitions w.r.t. $\prec_{\mathcal{L}}$



$$\mathcal{L}(\mathcal{A}^*) = \{(\delta_0) \xrightarrow{a} (\delta_1) \xrightarrow{a} \cdots \mid \exists n \in \mathbb{N}\ 2n \leq \delta_0 < 2n+1\}$$

Assume there exists $\mathcal{A}' \in \mathbb{A}^{na}$ such that $\mathcal{L}(\mathcal{A}') = \mathcal{L}(\mathcal{A}^*)$.

Let C be the maximal constant occurring in $\mathcal{A}'$ that we assume w.l.o.g. to be odd.

The timed path $(C+1) \xrightarrow{a} (0) \xrightarrow{a} (0) \cdots \xrightarrow{a} (0) \cdots$ belongs to $\mathcal{L}(\mathcal{A}^*) = \mathcal{L}(\mathcal{A}')$.

Let $\rho = (\ell_0, 0, C+1) \xrightarrow{\gamma_0, \{a\}, r_0} (\ell_1, \bar{x}_1, 0) \cdots$
be the corresponding accepting run in $\mathcal{A}'$.

Let $\rho' = (\ell_0, 0, C+2) \xrightarrow{\gamma_0, \{a\}, r_0} (\ell_1, \bar{x}'_1, 0) \cdots$
where $\bar{x}'_i = C+2 = \bar{x}_i + 1$ up to the first reset and $\bar{x}'_i = \bar{x}_i$ after it.
Then ρ' is accepting.

Thus $(C+2) \xrightarrow{a} (0) \xrightarrow{a} (0) \cdots \xrightarrow{a} (0) \cdots$ belongs to $\mathcal{L}(\mathcal{A}')$
which contradicts $\mathcal{L}(\mathcal{A}') = \mathcal{L}(\mathcal{A})$.

Laplace Transform

From time domain to complex domain.

Let $f(t)$ be a real function defined for $t \geq 0$.

When its exists $F(s)$ with $s \in \mathbb{C}$, its *Laplace transform*, is defined by:

$$F(s) = \int_0^\infty e^{-st} f(t) dt$$

Some properties.

- For all region $Re(s) > \alpha$ included in the region of convergence, F is analytical.
- Two functions have the same Laplace transform only if they differ on a set of null Lebesgue measure.

A property of analytical functions.

Let U be a connected open set of $\mathbb{C}$ and f, g be analytical over U.

If f and g coincide over $A \subseteq U$ such that A has an accumulation point in U then f and g coincide over U.

A 0-1 Law for DTA (1)

Let $\mathcal{A} \in \mathbb{A}^{na}$ and $z \in [0,1]$ such that for all $\mathcal{M}$, $\mathbf{Pr}_{\mathcal{M}}(\mathcal{A}) = z$ then $z \in \{0,1\}$.

Sketch of proof.

We establish by induction on the transition relation of the region graph $G_{\mathcal{A}}$ that:

For all configuration (ℓ, t) in some region of $G_{\mathcal{A}}$ reachable from $(\ell_0, 0)$ and all $\mathcal{M}$ and state s of $\mathcal{M}$, the probability that $\mathcal{M}$ starting in s satisfies $\mathcal{A}$ with initial state ℓ and initial clock value t is equal to z.

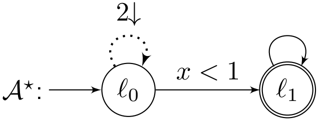
The base case of the induction follows from the hypothesis.

The induction step consists in showing that:

- the Laplace transform of this probablity, is the Laplace transform of z,
- using appropriate Markov chains and the properties of Laplace transforms.

The conclusion follows since either a region with ℓ_f is reachable and $z = 1$ or no region with ℓ_f is reachable and $z = 0$.

Necessity of Autonomous Transitions w.r.t. $\prec_{\mathcal{M}}$



Assume there exists $\mathcal{A}' \in \mathbb{A}^{na}$ such that for all $\mathcal{M}$, $\mathbf{Pr}_{\mathcal{M}}(\mathcal{A}') = \mathbf{Pr}_{\mathcal{M}}(\mathcal{A}^*)$.

Pick an arbitrary $\mathcal{M}$.

Let $\mathcal{M}_{\lambda,s_0}$ be the Markov chain starting in s_0 and entering $\mathcal{M}$ at rate λ.

$\mathbf{Pr}_{\mathcal{M}_{\lambda,s_0}}(\mathcal{A}^*) = \frac{1-e^{-\lambda}}{1-e^{-2\lambda}}$ and so $\lim_{\lambda\to 0} \mathbf{Pr}_{\mathcal{M}_{\lambda,s_0}}(\mathcal{A}) = \frac{1}{2}$.

$\mathbf{Pr}_{\mathcal{M}_{\lambda,s_0}}(\mathcal{A}') = p_{1,\lambda} + p_{2,\lambda}$ where:

- $p_{1,\lambda}$ is the probability to accept the random timed path and that the first action takes place at most at time C;
- $p_{2,\lambda}$ is the probability to accept the random timed path and that the first action takes place after C.

Since $\lim_{\lambda\to 0} p_{1,\lambda} = 0$, $\lim_{\lambda\to 0} p_{2,\lambda} = \frac{1}{2}$
which can be shown to contradict the 0-1 law (since $\mathcal{M}$ is arbitrary).

Plan

A Hierarchy of Families of DTA

Let $\mathbb{A}^{rc}$ be the family of DTA such that every circuit that includes a resetting autonomous transition also includes a synchronized transition,

- either resetting x;
- or with guard $x > C$ (the maximal constant).

Let $\mathbb{A}^{nra}$ be the family of DTA in which no autonomous transition resets the clock.

Let $\mathbb{A}^{nc}$ be the family of DTA in which:

- no autonomous transition resets the clock;
- and there is no cycle of autonomous transitions.

Then:

$$\boxed{\mathbb{A}^{na} \sim_{\mathcal{L}} \mathbb{A}^{nc} \sim_{\mathcal{L}} \mathbb{A}^{nra} \sim_{\mathcal{L}} \mathbb{A}^{rc} \precnsim_{\mathcal{M}} \mathbb{A}}$$

From $\mathbb{A}^{rc}$ to $\mathbb{A}^{nra}$

Consider an elementary path of $\mathcal{A} \in \mathbb{A}^{rc}$

not including synchronized transitions with reset or with guard $x > C$.

Its *delay* is the sum of constants occurring in its resetting autonomous transitions.

Let K be the maximal delay of such paths.

The locations of $\mathcal{A}' \in \mathbb{A}^{nra}$ are: $L' = \{\langle \ell, i \rangle \mid 0 \leq i \leq K \wedge \ell \in L \setminus \{\ell_f\}\} \cup \{\ell_f\}$
with its initial location $\langle \ell_0, 0 \rangle$ and final location ℓ_f.

• For all transition outgoing ℓ, there is a corresponding transition outgoing $\langle \ell, i \rangle$
except for resetting autonomous transition with guard $x = c$ such that $i + c > K$.

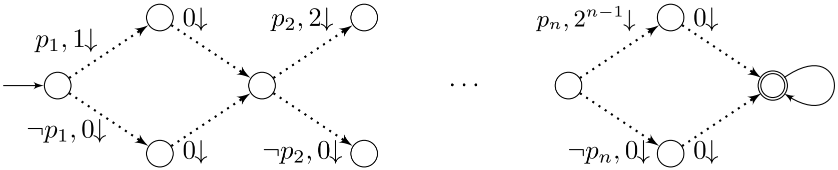
• The guard of the transitions outgoing $\langle \ell, i \rangle$ is "incremented" by i.

• The corresponding transition of a resetting autonomous transition
with guard $x = c$ such that $i + c \leq K$ does not reset but leads to $\langle \ell, i + c \rangle$.

• The corresponding transition of a synchronized transition
with reset or with guard $x > C$ leads to $\langle \ell, 0 \rangle$.

The Exponential Blow-up is Unavoidable from $\mathbb{A}^{rc}$ to $\mathbb{A}^{nra}$

Let $\mathcal{A}_n \in \mathbb{A}^{rc}$ be the following DTA.



Then for all $\mathcal{A}'_n \in \mathbb{A}^{nra}$ such that $\mathcal{L}(\mathcal{A}'_n) = \mathcal{L}(\mathcal{A}_n)$, $(|Aut| + 1)|Synch| \geq 2^n$.

- where Aut is the set of autonomous transitions
- and $Synch$ is the set of synchronized transitions.

From $\mathbb{A}^{nra}$ to $\mathbb{A}^{nc}$ in quadratic time

Idea. Visiting a circuit of autonomous transitions means non acceptance.

Let $\mathcal{A} \in \mathbb{A}^{nra}$ and K be the number of autonomous transitions.

The set of locations of $\mathcal{A}'$ is $L' = \{(\ell, i) \mid 0 \leq i \leq K \wedge \ell \in L \setminus \{\ell_f\}\} \cup \{\ell_f, \ell_\perp\}$ with initial location $(\ell_0, 0)$ and final location ℓ_f.

For all synchronized transition $\ell \xrightarrow{\varphi^-,\gamma,B,r,\varphi^+} \ell'$ of $\mathcal{A}$ and $i \leq K$:

- if $\ell' = \ell_f$ then there is a synchronized transition $(\ell, i) \xrightarrow{\varphi^-,\gamma,B,r,\varphi^+} \ell_f$;
- otherwise there is a synchronized transition $(\ell, i) \xrightarrow{\varphi^-,\gamma,B,r,\varphi^+} (\ell', 0)$.

For all autonomous transition $\ell \xrightarrow{\varphi^-,x=c,\sharp,\emptyset} \ell'$ of $\mathcal{A}$ and $i \leq K$:

- if $i = K$ then there is an autonomous transition $(\ell, i) \xrightarrow{\varphi^-,x=c,\sharp,\emptyset} \ell_\perp$;
- else if $\ell' = \ell_f$ then there is an autonomous transition $(\ell, i) \xrightarrow{\varphi^-,x=c,\sharp,\emptyset} \ell_f$;
- otherwise there is an autonomous transition $(\ell, i) \xrightarrow{\varphi^-,x=c,\sharp,\emptyset} (\ell', i+1)$.

From $\mathbb{A}^{nc}$ to $\mathbb{A}^{na}$ in polynomial time (1)

First stage. Duplicating locations w.r.t. clock regions: ℓ yields $\{\langle \ell, rg \rangle\}$.

For all synchronized transition $\ell \xrightarrow{\varphi^-,\gamma,B,r,\varphi^+} \ell'$ and regions rg and rg'

a transition $\langle \ell, rg \rangle \xrightarrow{\varphi^-,\gamma \wedge x \in rg',B,r,\varphi^+} \langle \ell', rg' \rangle$.

For all autonomous transition $\ell \xrightarrow{\varphi,x=i,\sharp,\emptyset} \ell'$ and region rg,

a transition $\langle \ell, rg \rangle \xrightarrow{\varphi,x=i,\sharp,\emptyset} \langle \ell', \{i\} \rangle$.

Second stage. Making explicit the priority of the autonomous transitions.

Let $\langle \ell, rg \rangle$ be a location and $\{\langle \ell, rg \rangle \xrightarrow{\varphi_k,x=\alpha_k,\sharp,\emptyset} \langle \ell_k, \{\alpha_k\} \rangle\}_{k \leq K}$
be the autonomous transitions outgoing from $\langle \ell, rg \rangle$ with $rg \leq \alpha_1 \leq \cdots \leq \alpha_K$.

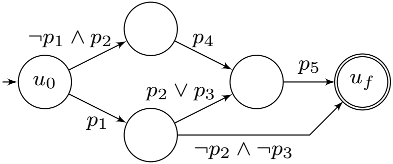
For all k, an autonomous transition $\langle \ell, rg \rangle \xrightarrow{\varphi_k \wedge \bigwedge_{k'<k} \neg \varphi_{k'},x=\alpha_k,\sharp,\emptyset} \langle \ell_k, \{\alpha_k\} \rangle$.

For all synchronized transition $\langle \ell, rg \rangle \xrightarrow{\varphi^-,\gamma,B,r,\varphi^+} \langle \ell', rg' \rangle$,

a transition $\langle \ell, rg \rangle \xrightarrow{\varphi^- \wedge \bigwedge_{\alpha_k \leq rg'} \neg \varphi_k,\gamma,B,r,\varphi^+} \langle \ell', rg' \rangle$.

From $\mathbb{A}^{nc}$ to $\mathbb{A}^{na}$ in polynomial time (2)

Third stage. Eliminating autonomous transitions using decision diagrams (DD):



For all $\langle \ell, rg\rangle$ and $\langle \ell', \{i\}\rangle$ such that there is a path of autonomous transitions from $\langle \ell, rg\rangle$ to $\langle \ell', \{i\}\rangle$. Let the formula $\varphi^{\ell',i}_{\ell,rg}$ be the DD:

- whose vertices are locations both reachable from $\langle \ell, rg\rangle$ and can reach $\langle \ell', \{i\}\rangle$ (both by autonomous transitions);
- whose edges of the DD are the autonomous transitions between such vertices labelled by their formula.

For all synchronized transition $\langle \ell', \{i\}\rangle \xrightarrow{\varphi^-,\gamma,B,r,\varphi^+} \langle \ell'', rg''\rangle$,

a transition $\langle \ell, rg\rangle \xrightarrow{\varphi^{\ell',i}_{\ell,rg}\wedge\varphi^-,x\geq i\wedge\gamma,B,r,\varphi^+} \langle \ell'', rg''\rangle$.

Illustration (1)

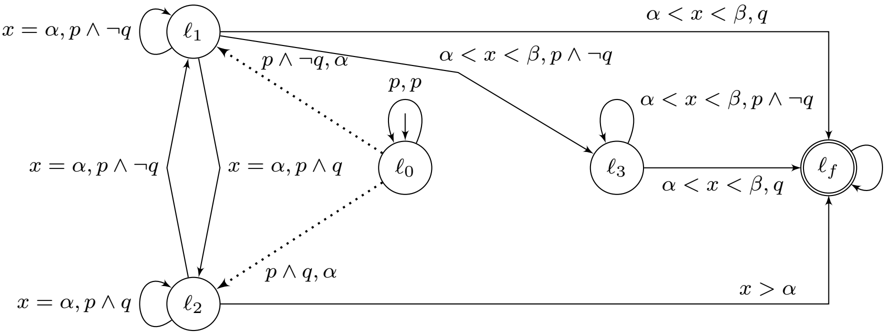
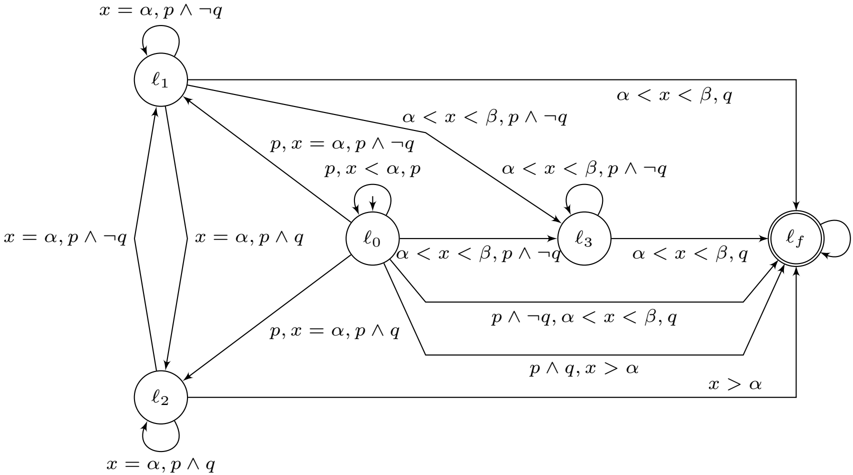


Illustration (2)



Conclusion and Perspectives

Contributions

- Analysis of the interest of autonomous transitions in single-clock DTA w.r.t. expressiveness and conciseness;
- Analysis of the relation between state formulas and transition formulas w.r.t. conciseness *(not presented here)*.

Perspectives

- From a practical point of view, efficiency increasing of tools using logics like CSL or extensions;
- From a theoretical point of view, decision problems like “given a DTA, does there exist an equivalent DTA without autonomous transitions?”