Model checking timed linear properties of time Petri nets using the state class method

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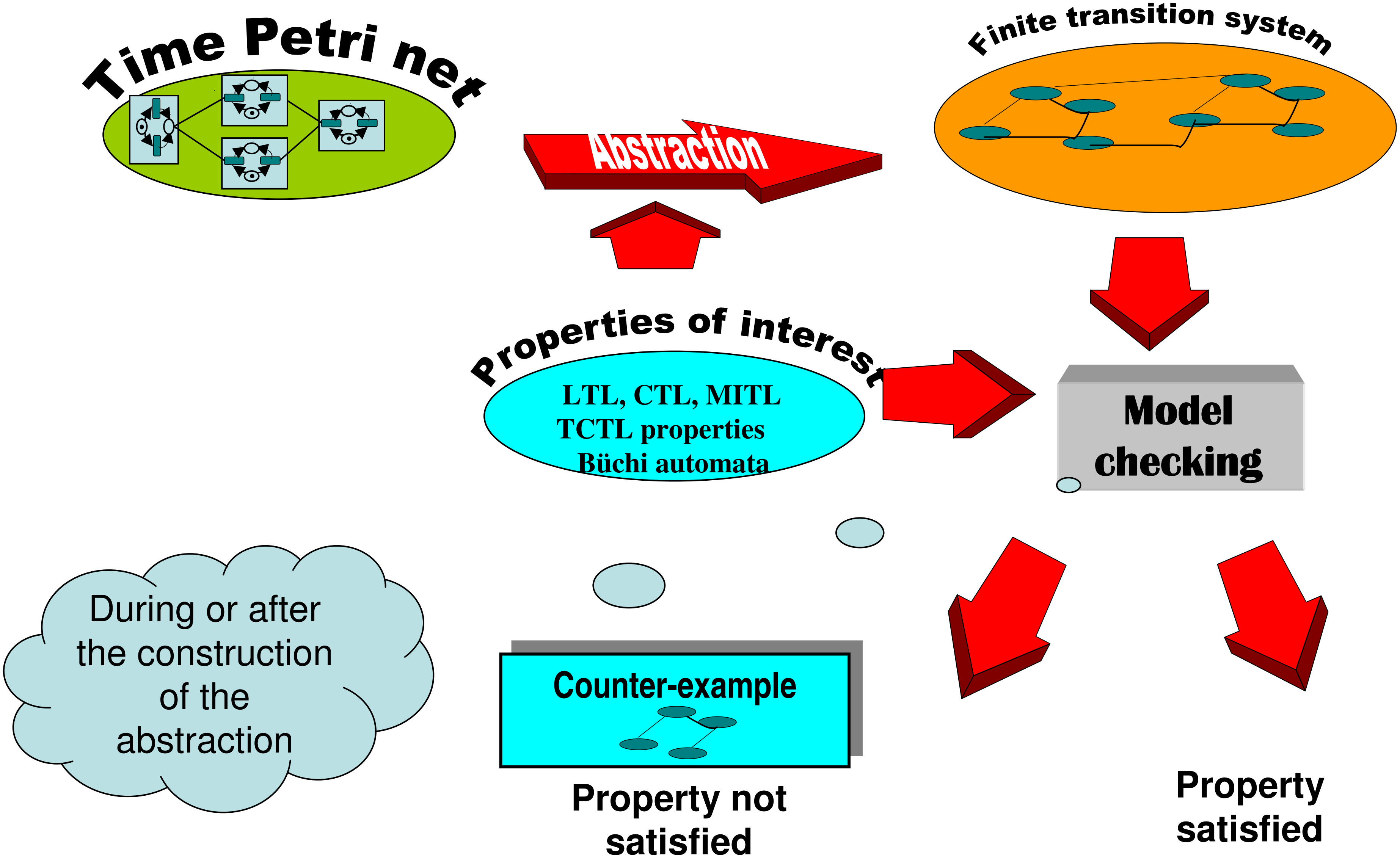
Model checking of time Petri nets based on the state class method



Plan

- Time Petri Nets (TPN model)
- TPN state space abstractions
- The state class graph method (SCG)
- Contracting the state class graph (CSCG)
- Model checking using an interval timed extension of Büchi Automata (ITBA)
- Conclusion

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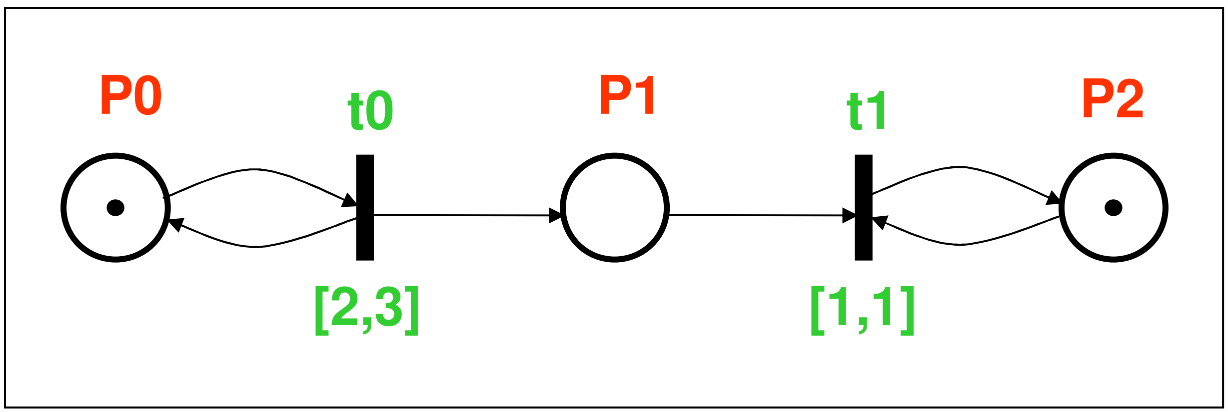
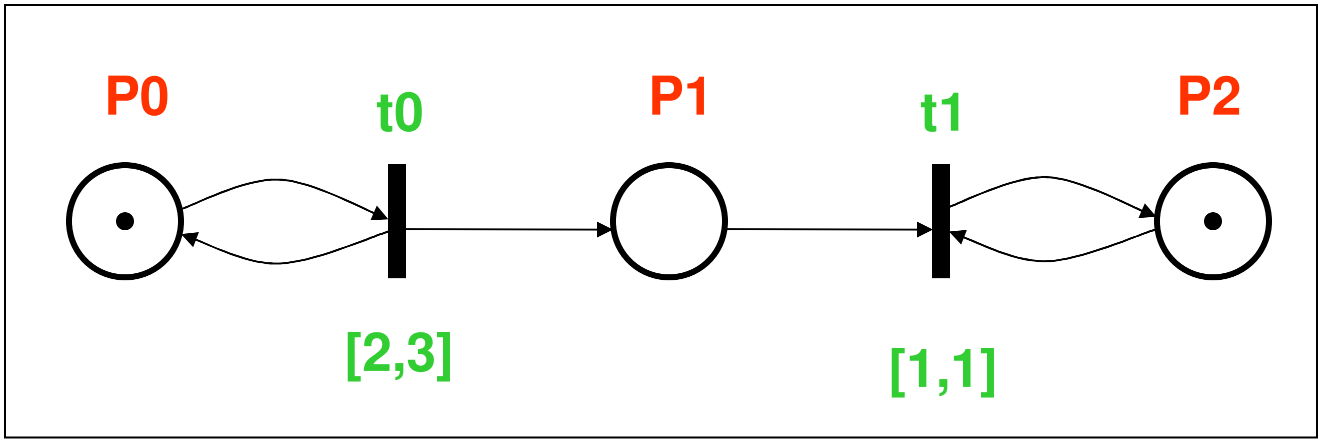
Time Petri Nets (Merlin & Farber 1976)

- Extension of Petri Nets by associating timing constraints with transitions in the form of intervals (static firing intervals)



➔ a good compromise between modeling Power and verification possibilities

TPN State : Interval state vs. Clock state



Two state definitions:

Interval State (M,I)	Clock State (M,v)
P0=1, P1=0, P2=1	P0=1, P1=0, P2=1
I(t0) = [2 , 3]	v(t0) = 0

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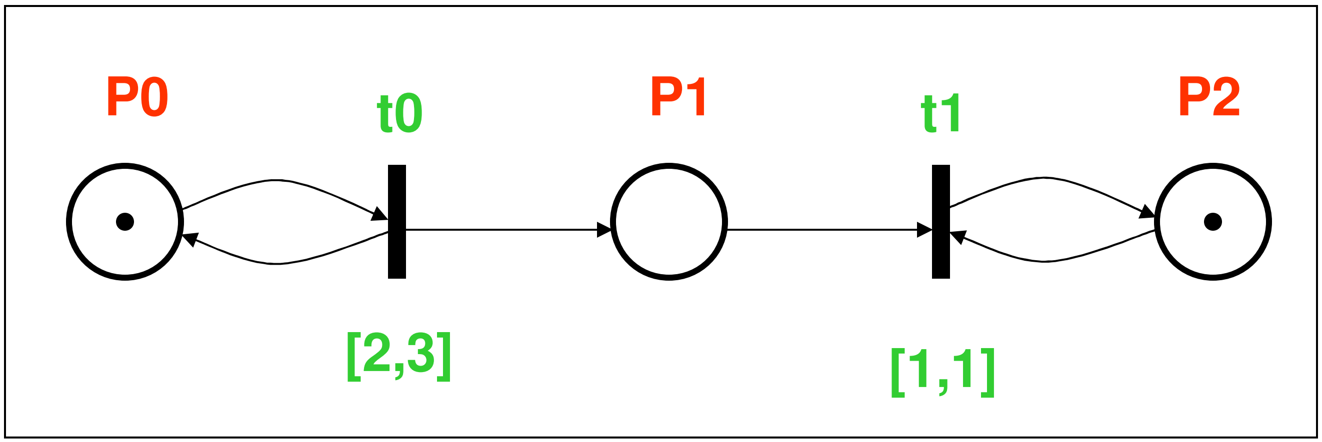
State evolution

TPN state evolves either by time progression or by firing transitions



bounds of intervals decrease with time

Interval State (M,I)

P0=1, P1=0, P2=1

I(t0) = [0 , 0.5]

Clock State (M,v)

P0=1, P1=0, P2=1

v(t0) = 2.5

Clocks increase with time

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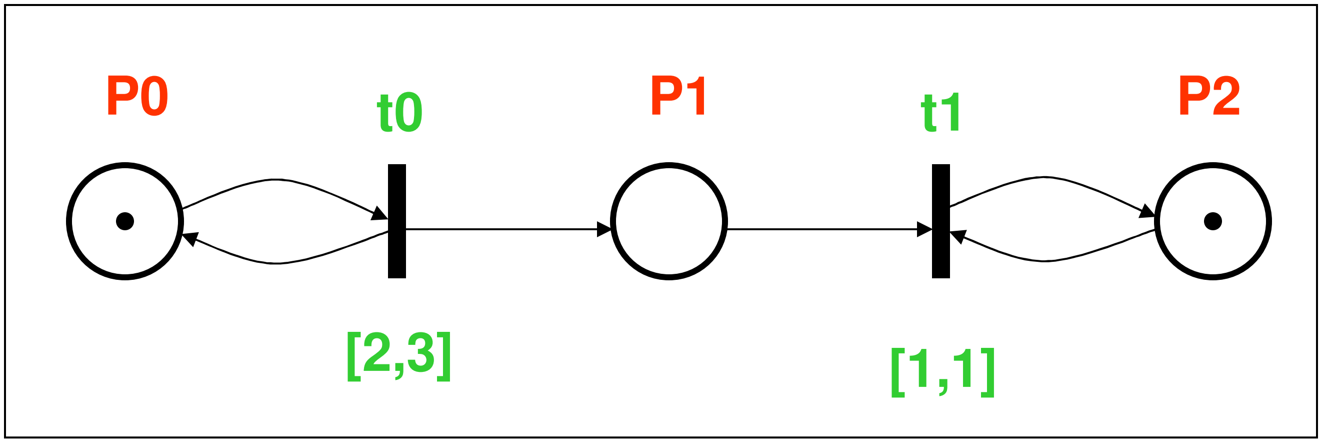
State evolution

TPN state evolves either by time progression or by firing transitions



lower bound reaches 0
➔ t0 is firable

Interval State (M,I)

P0=1, P1=0, P2=1

I(t0) = [0 , 0.5]

Clock State (M,v)

P0=1, P1=0, P2=1

v(t0) = 2.5

Clock reaches the interval of t0
➔ t0 is fiable

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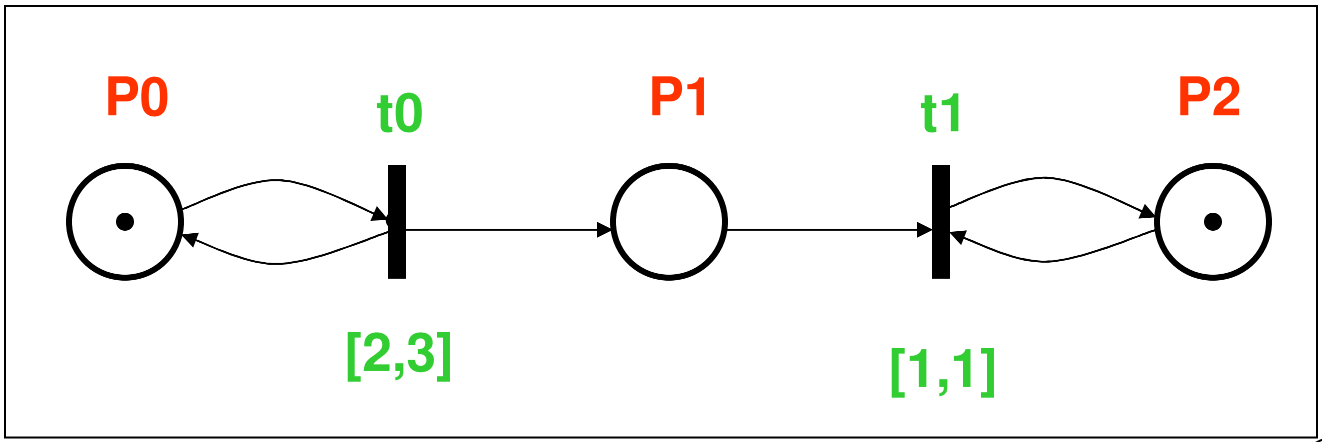
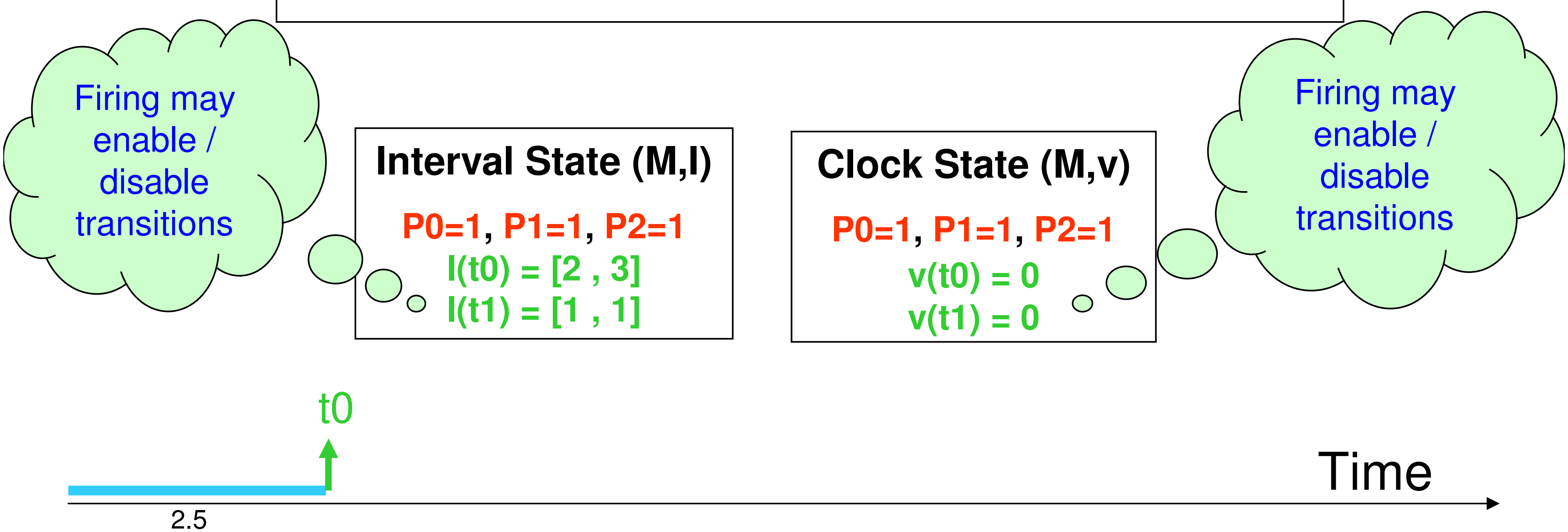
State evolution

TPN state evolves either by time progression or by firing transitions





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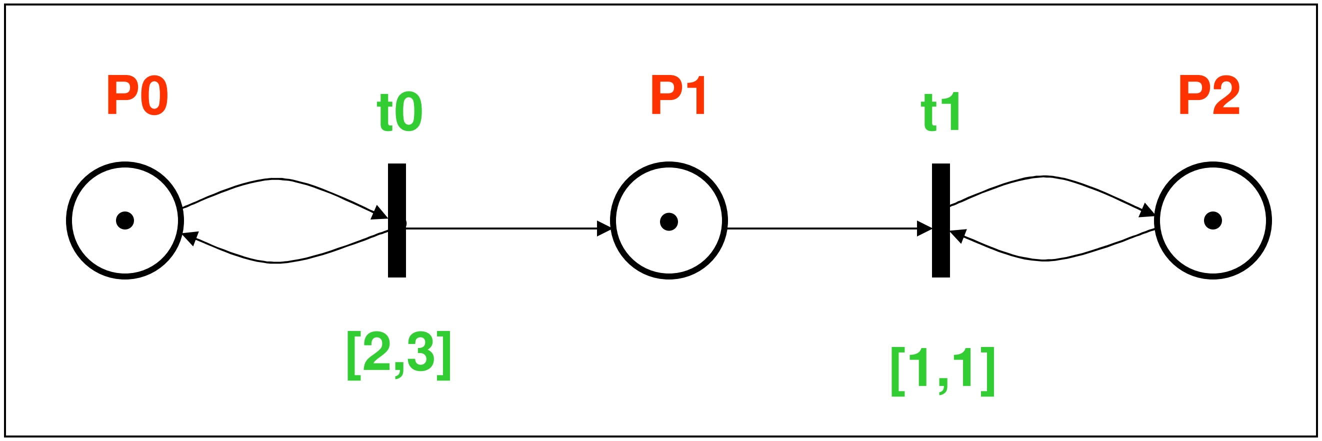
State evolution

TPN state evolves either by time progression or by firing transitions



Upper bound reaches 0
➔ t1 must be fired

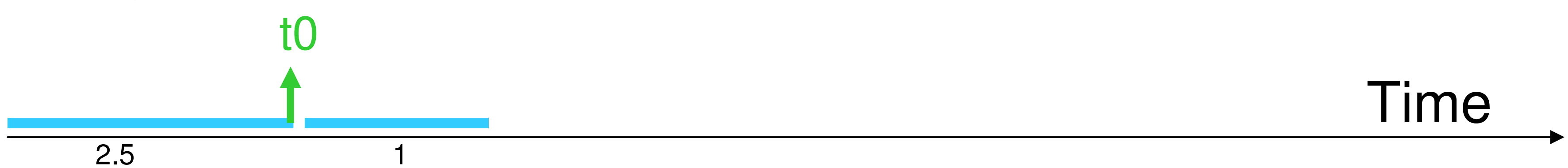
Interval State (M,I)

P0=1, P1=1, P2=1
I(t0) = [1 , 2]
I(t1) = [0 , 0]

Clock State (M,v)

P0=1, P1=1, P2=1
v(t0) = 1
v(t1) = 1

Clock reaches the upper bound
➔ t1 must be fired



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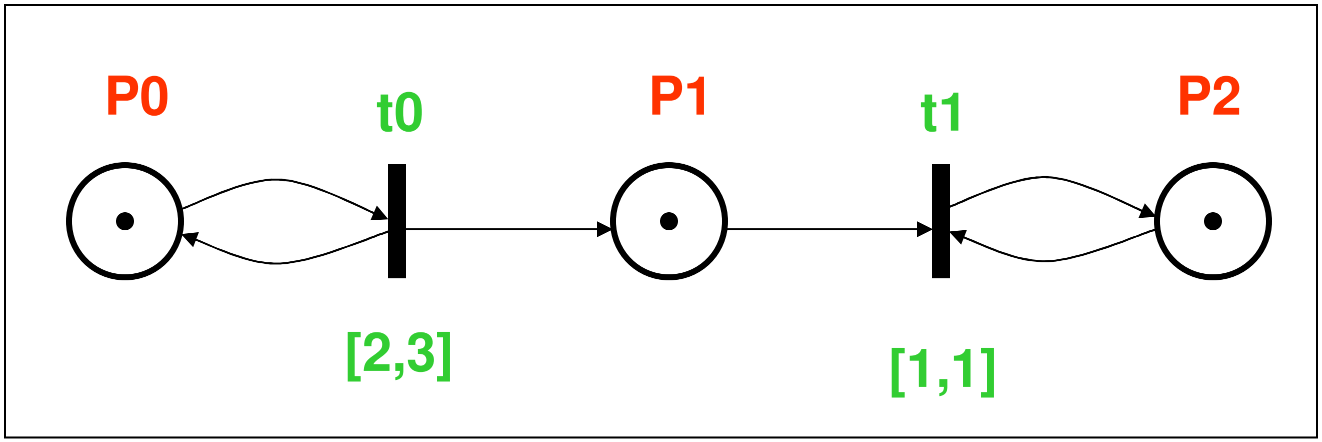
State evolution

TPN state evolves either by time progression or by firing transitions



Interval State (M,I)	Clock State (M,v)
P0=1, P1=0, P2=1	P0=1, P1=0, P2=1
I(t0) = [1 , 2]	v(t0) = 1

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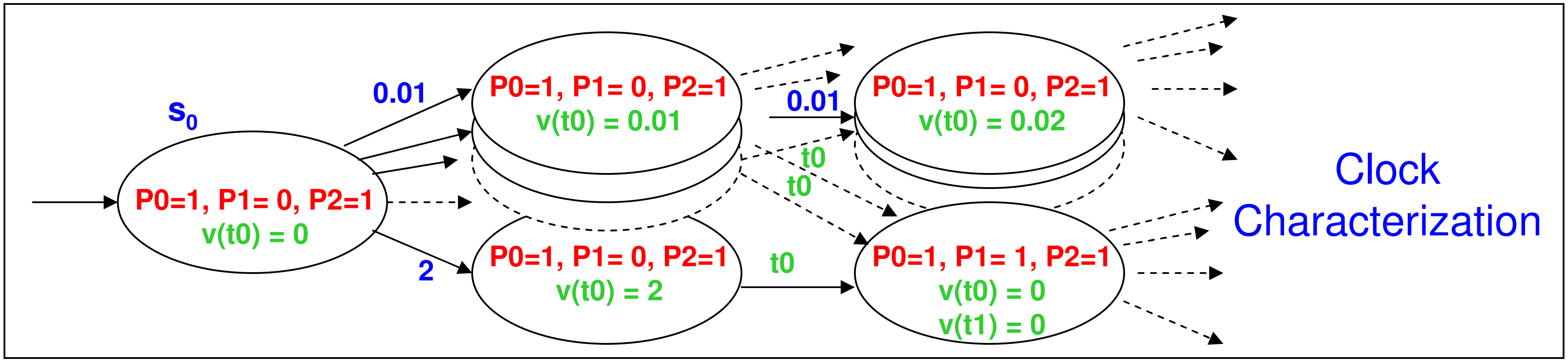
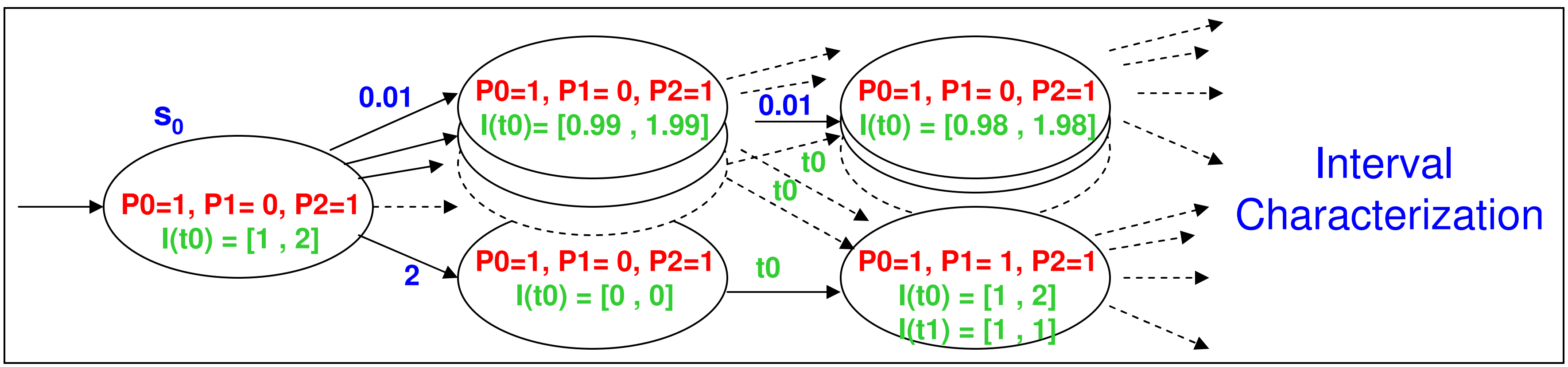
TPN state space

Transition system $(S, \rightarrow, s_0)$

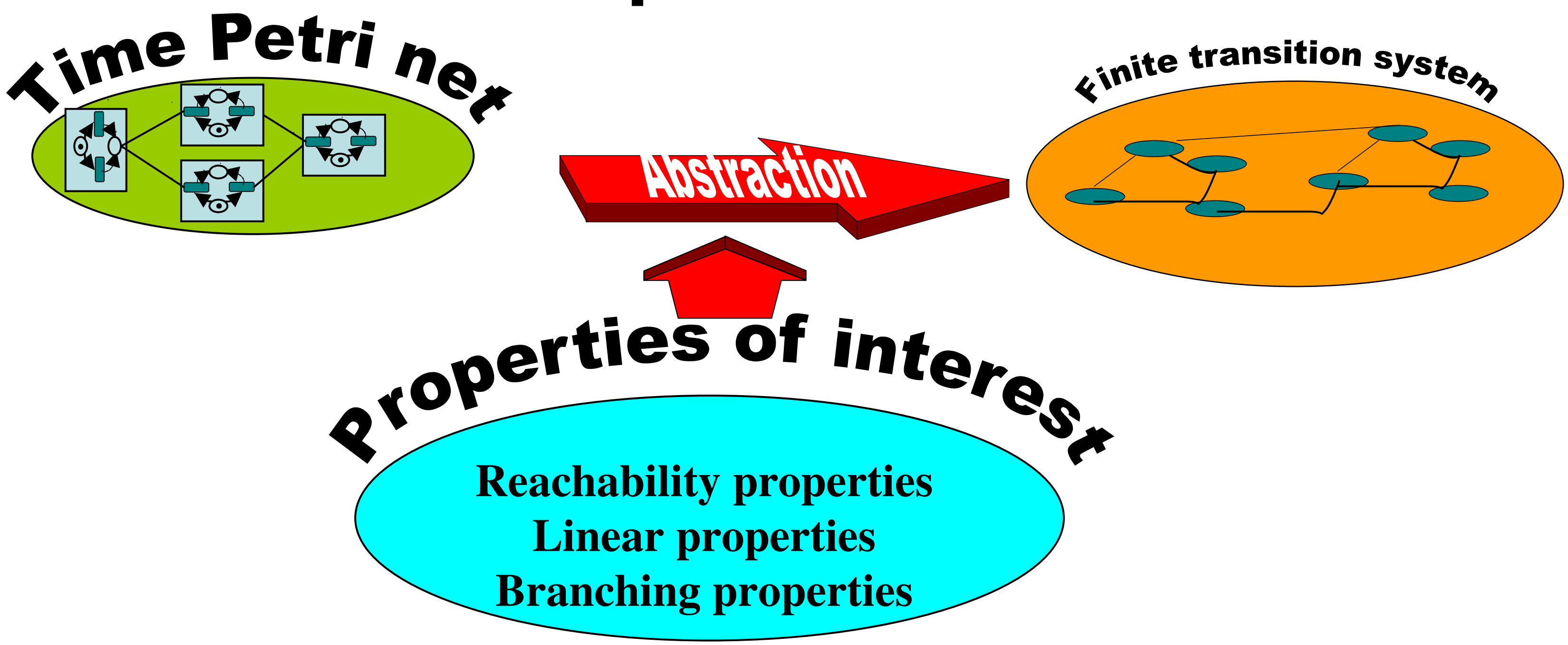




Infinite state space with infinite branching

How to abstract the TPN state space ?

TPN state space **abstractions**



Abstraction → Abstract irrelevant information while preserving properties of interest:

- Reachability: markings or states of the model.
- **Linear properties: firing sequences of the model.**
- Branching properties: execution trees of the model.

Challenge:

- **More coarser finite abstraction preserving properties of interest.**
- **Computed with minor resources (time and space).**

TPN state space abstractions

TPN state space abstractions in the literature preserving linear properties:

- **SCG [Berthomieu & Diaz 1991],**
- **GRG [Yoneda & Ryuba 1998],**
- **SSCG [Berthomieu & Vernadat 2003],**
- **ZBG [Gardey & Roux 2003],**
- **CSZG [Hadjidj & Boucheneb 2005].**
- **ASCGs**

→ may differ in:

- **Characterization of states (interval state abstractions, clock state abstractions) ,**
- **Agglomeration criteria of states**
- **Preserved properties.**

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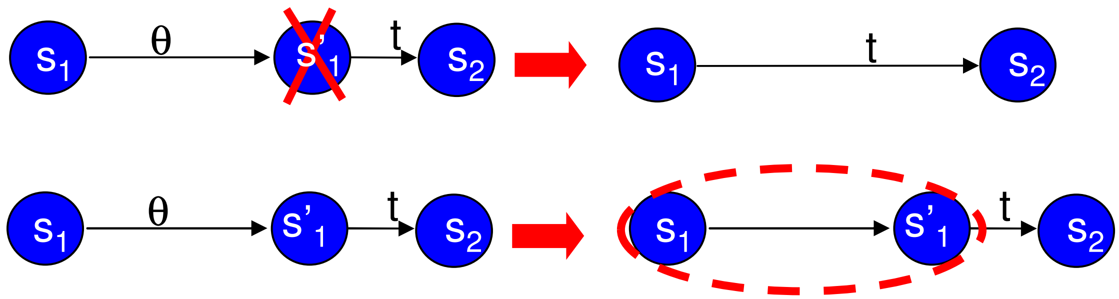
TPN state space **abstractions**

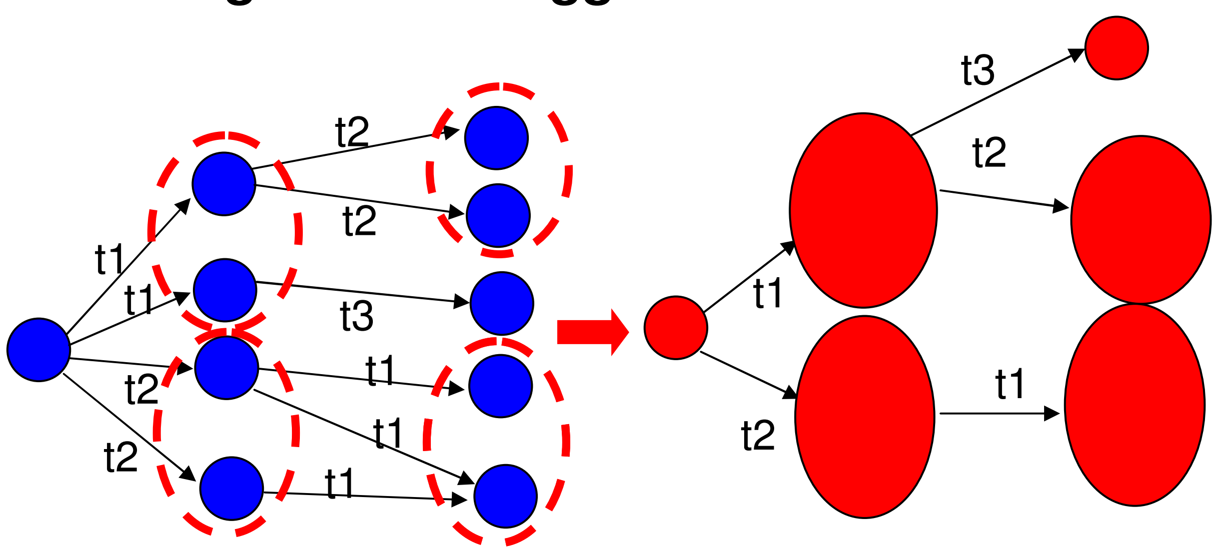
Three levels of abstraction:

1. **Time abstraction**



OR

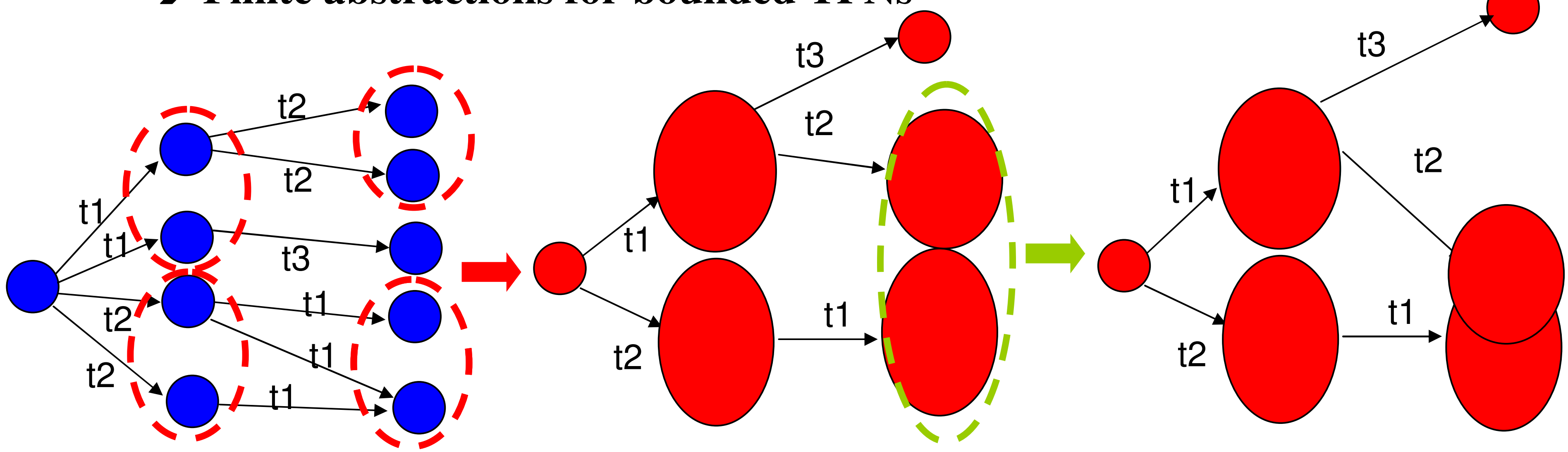
2. **States reachable by the same firing sequence independently of their firing times are agglomerated in the same node.**



TPN state space **abstractions**

3. **Agglomerated states are then considered modulo some relation of equivalence:**
   - **Firing domain of the SCG** [Berthomieu & Diaz 1991],
   - **k-approximation of the ZBG** [Gardey & Roux 2003],
   - **Approximation of the SSCG** [Berthomieu & Vernadat 2003],
   - **k-normalization of the CSZG** [Hadjidj & Boucheneb 2005],
   - **Relation of equivalence of the GRG** [Yoneda & Ryuba 1998].

➔ **Finite abstractions for bounded TPNs**



TPN state space abstractions

The SCG is the more interesting abstraction. Why?

- **The SCG is an interval state abstraction; all others are clock state abstractions.**

- **Abstractions based on clocks do not enjoy naturally the finiteness property for bounded TPNs with unbounded intervals. The finiteness is enforced using:**
  - k-approximation of the ZBG [Gardey & Roux 2003],
  - Approximation of the SSCG [Berthomieu & Vernadat 2003],
  - k-normalization of the CSZG [Hadjidj & Boucheneb 2005].

➔ **may involve some overhead computation.**

- **The interval characterization of states has a more abstracting power than the clock characterization, and allows to construct more compact abstractions.**

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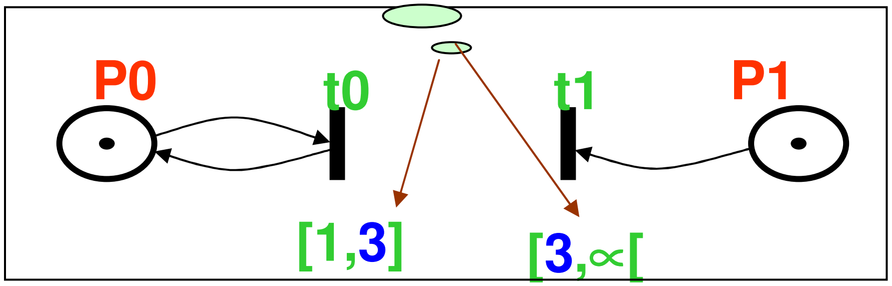
TPN state space **abstractions**

The number of zones depends on the value of these bounds (3+1)



SCG state classes for t0⁺

$\alpha 0 = (P0{=}1, P1{=}1, \; 1 \le t0 \le 3 \wedge 3 \le t1 < \propto)$

t0 [1,3]

$\alpha 1 = (P0{=}1, P1{=}1, \; 1 \le t0 \le 3 \wedge 0 \le t1 < \propto)$

t0 [1,3]

Firing domain

ZBG zones for t0⁺

$z0 = (P0{=}1, P1{=}1, \; 0 \le t0 = t1 \le 3)$

t0 [1,3]

$z1 = (P0{=}1, P1{=}1, \; 0 \le t0 \le 3 \wedge 1 \le t1 \wedge 1 \le t1 - t0 \le \propto)$

t0 [1,3]

$z2 = (P0{=}1, P1{=}1, \; 0 \le t0 \le 3 \wedge 2 \le t1 \wedge 2 \le t1 - t0 \le \propto)$

t0 [1,3]

$z3 = (P0{=}1, P1{=}1, \; 0 \le t0 \le 3 \wedge 3 \le t1 \wedge 3 \le t1 - t0 \le \propto)$

t0 [1,3]

Clock domain

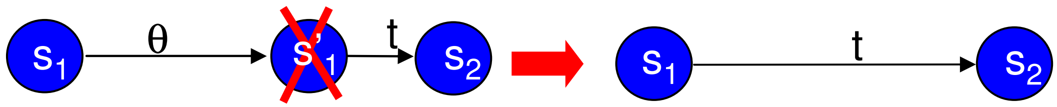
- Many ZBG zones may map to a single SCG state class.

The state class graph method

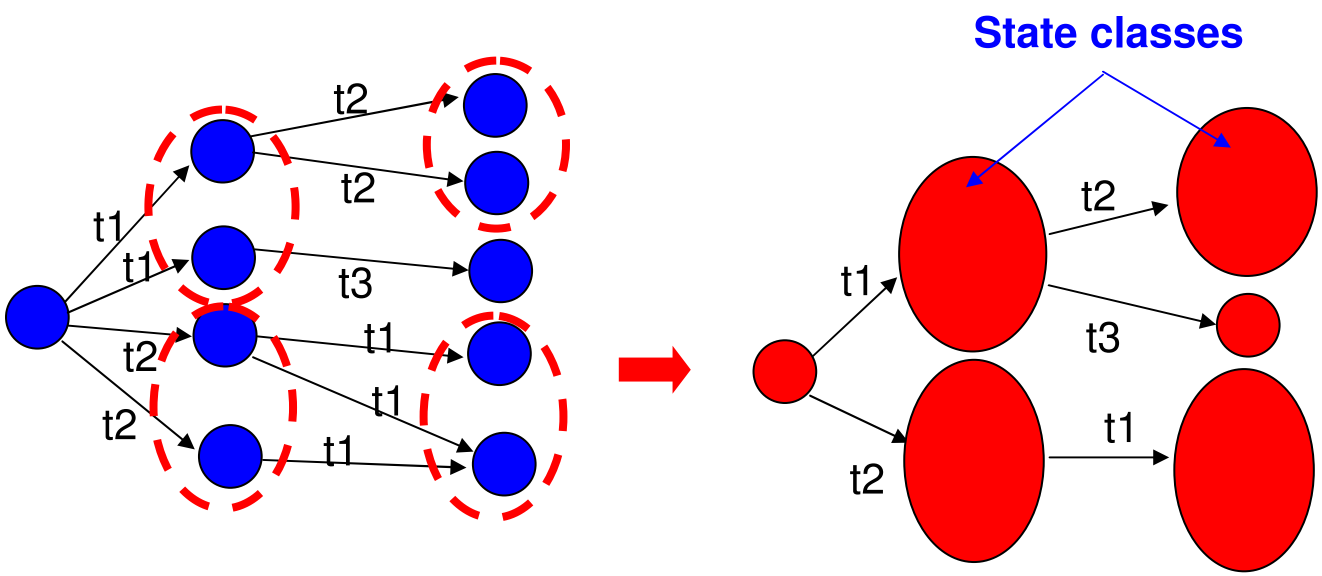
The state class graph method

1. State characterization: interval state (M,I)

2. Time abstraction:

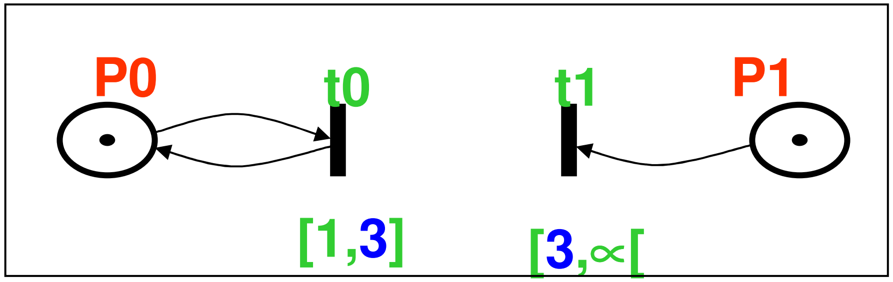


3. States reachable by the same firing sequence are agglomerated and considered modulo some relation of equivalence → **firing domain**



→ A state class = (marking, set of constraints which characterizes its states)

The state class graph method



- The initial state class: $\alpha 0 = ($ P0=1,P1=1, $1 \leq t0 \leq 3 \wedge 3 \leq t1 < \infty)$

- succ(α0,t0) $\neq \emptyset$ iff t0 is enabled and the following formula is consistent

$1 \leq t0 \leq 3 \wedge 3 \leq t1 < \infty \wedge t0 \leq t1$

- The firing of t0 leads to the state class $\alpha 1$ = (P0=1,P1=1, F1) where F1 is computed in four steps:

  1. **F1 ← $1 \leq t0 \leq 3 \wedge 3 \leq t1 < \infty \wedge t0 \leq t1$**
  2. Replace t1 with t1+t0: **$1 \leq t0 \leq 3 \wedge 3 \leq t1+t0 < \infty \wedge t0 \leq t1+t0$**
  3. Eliminate by substitution t0 and conflicting transitions: **$0 \leq t1 < \infty$**
  4. Add constraints of newly enabled transitions: **$0 \leq t1 < \infty \wedge 1 \leq t0 \leq 3$**

t1= new t1+t0

The state class graph method

- *F* is a conjunction of atomic constraints: $t_i - t_j \prec c$, $t_i \prec c$, $- t_j \prec c$,
  where $t_i, t_j \in T$, $c \in Q \cup \{\propto, -\propto\}$, $\prec \in \{=, \leq, \geq\}$
- Canonical form of F: $$\bigwedge_{x,x' \in En(M) \cup \{o\}} x - x' \leq Sup_F(x - x')$$

  where *o* represents the value zero and
  $Sup_F(x\text{-}x')$ is the least upper bound of ***x-x'*** in the domain of ***F***

- It can be represented by a Difference Bound Matrix (DBM) *D*:
  $$\forall x,x' \in En(M) \cup \{o\}, \quad D_{xx'} = Sup_F(x\text{-}x')$$
- *F* and all formulae equivalent to *F* have **the same canonical form.**
- Canonical form of *F* may be computed using:
  - The shortest path Floyd-Warshall's algorithm in $O(n^3)$, n being the number of variables in F, or
  - The algorithm, proposed in [Boucheneb & Mullins 2003], in $O(n^2)$.

The state class graph method

Algorithm proposed in [Boucheneb & Mullins 2003]

Let α=*(M,D)* be a state class in canonical form and t_f a transition.

- t_f *is firable from* (M, D) *(i.e.:* $Succ(\alpha, t_f) \neq \emptyset$*) iff* $t_f \in En(M)$ *and* $Min_{t \in En(M)} D_{t\, t_f} = 0$.

- *If* t_f *is firable from* (M, D)*, its firing leads to the state class* $Succ(\alpha, t_f) = (M', D')$ *computed as follows:*

$\forall p \in P, M'(p) = M(p) - Pre(p, t_f) + Post(p, t_f)$;

$\forall t \in En(M')$,

$$D'_{t\, o} = \begin{cases} tmax(t) & \text{if } t \in New(M', t_f); \\ D_{t\, t_f} & \text{otherwise} \end{cases}$$

$$D'_{o\, t} = \begin{cases} -tmin(t) & \text{if } t \in New(M', t_f); \\ Min_{u \in En(M)} D_{u\, t} & \text{otherwise} \end{cases}$$

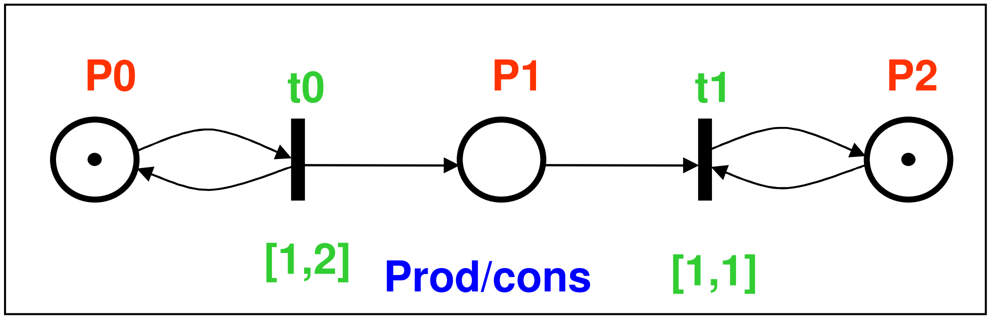
$\forall (t, t') \in (En(M'))^2$,

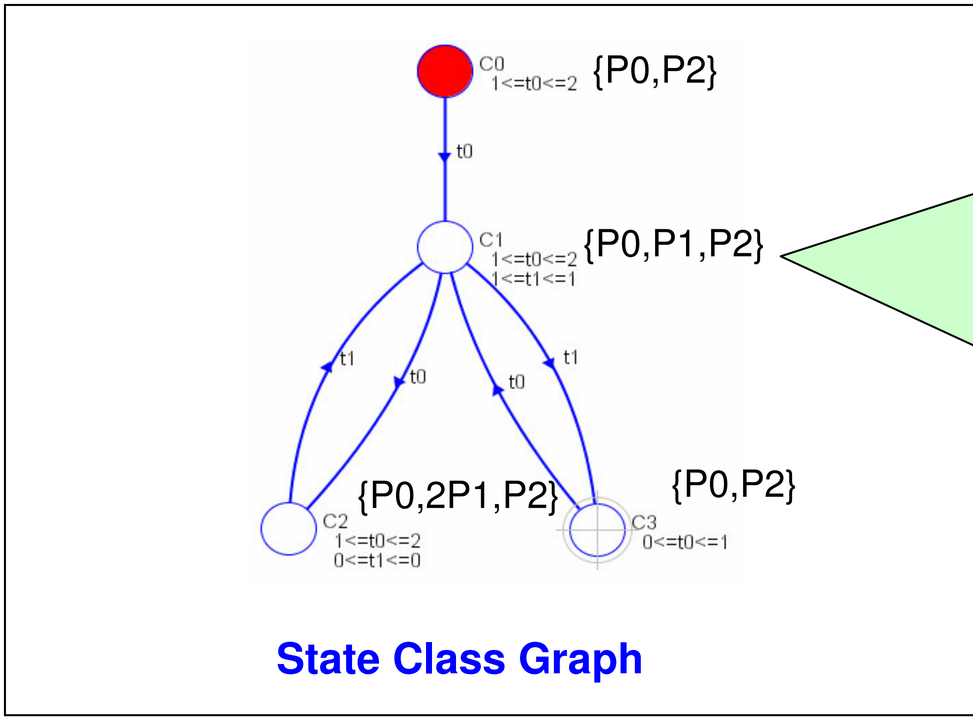
$$D'_{t\, t'} = \begin{cases} 0 & \text{if t is t}' \\ D'_{t\, o} + D'_{o\, t'} & \text{if t or t}' \in New(M', t_f); \\ Min(D_{t\, t'}, D'_{t\, o} + D'_{o\, t'}) & \text{otherwise} \end{cases}$$

Time complexity O(n)

Time complexity O(n²)

An example





Reachable markings:

1. P0 =1, P2=1
2. P0=1, P1=1, P2=1
3. P0=1, P1=2, P2=1

Firing sequences: t0; { t0; t1, t1;t0} $^{\infty}$

Path / cycle times of firing sequences [Boucheneb & Mullins 2003]:

From C0: t0; t1 → [2,3]

From C1: t0; t1 → [1,2]

→ SCG is finite iff the TPN is bounded.

→ SCG preserves markings and traces of the TPN → Linear properties

Contracting the state class graph

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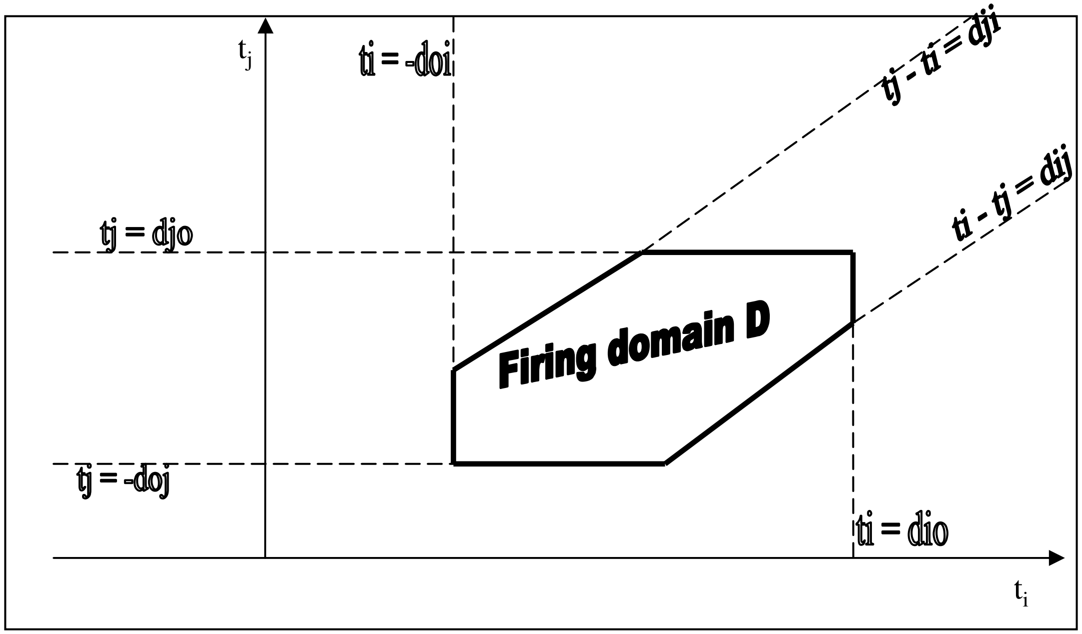
Contracting the state class graph

- *Define a relation of equivalence over state classes such that equivalent classes have the same firing sequences.*

- *Construct a quotient graph w.r.t. the relation of equivalence.*

→ *Over-approximation of state classes [Boucheneb & Rakkay; ACSD 2007]:*

D: $- doi \le ti \le dio$
$- doj \le tj \le djo$
$- dji \le ti - tj \le dij$



Over-approximation of state classes

- *The idea of this operation comes from:*

  1- The line and column o of each DBM D are not necessary to compute successor state classes of (M,D) (they can be eliminated)

  ➔ a gain in space

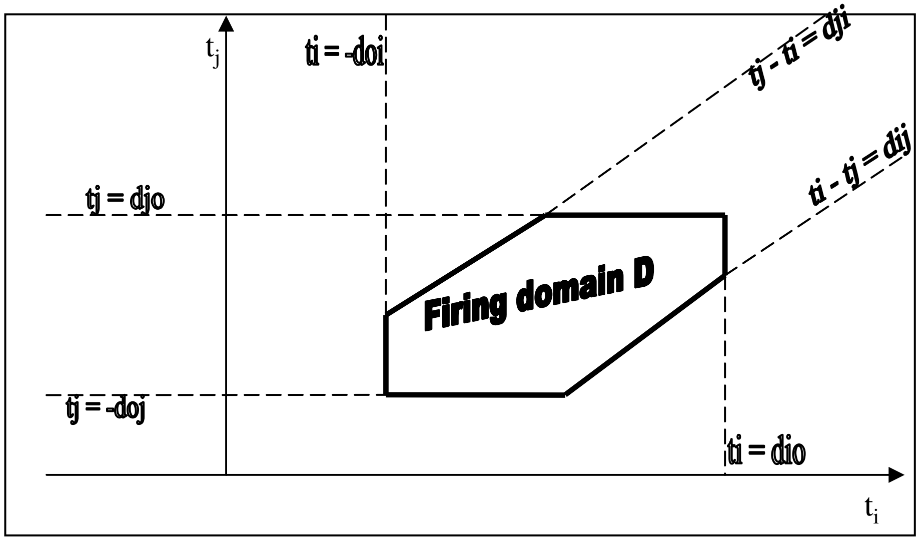
  2- The firing of any transition t_f from a state class α=*(M,D),* will disable all transitions conflicting with t_f.

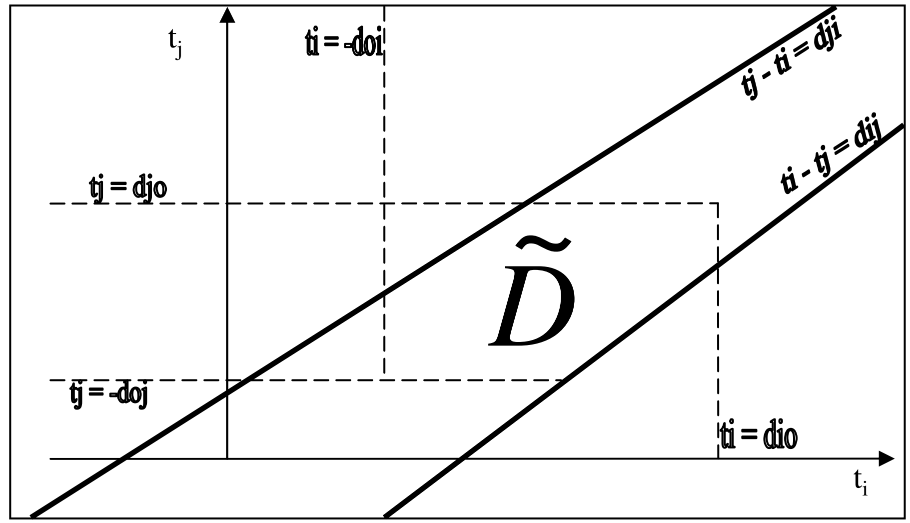
  ➔ There is no need to compute, for the s*uccessor of* α *by* t_f distances between t_f and its conflicting transitions,

  ➔ but we need to know whether t_f *is firable or not before all enabled transitions (including those in conflict with* t_f*).*

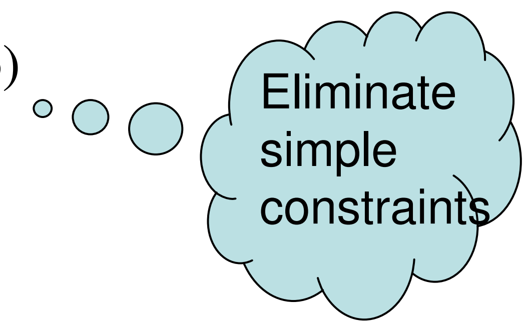
$\Rightarrow$ *State classes with lesser constraints*

Over-approximation of state classes





$$\tilde{d}ij = \begin{cases} \infty & \text{if } (i = o \text{ and } j \neq o) \text{ or } (j = o \text{ and } i \neq o) \\ 0 & \text{if } (i, j \neq o) \text{ and } dij \geq 0 \\ & \text{and (ti and tj in conflict)} \\ dij & \text{otherwise} \end{cases}$$



CSCG is the quotient graph of SCG w.r.t $\approx$:

$$\forall \alpha_1, \alpha_2 \in C,\ \alpha_1 \approx \alpha_2 \text{ iff } \tilde{\alpha}_1 = \tilde{\alpha}_2$$

Lemma: $\approx$ is a bisimulation over the SCG

Contracting the state class graph

Proposition 2 *Let $\alpha = (M, D)$ be a state class, $\widetilde{\alpha} = (M, \widetilde{D})$ its equivalence class and t_f a transition.*
$Succ(\alpha, t_f) \neq \emptyset$ iff $Min_{u \in En(M)} \widetilde{D}_{u\, t_f} = 0$.
If $Succ(\alpha, t_f) \neq \emptyset$ and $Succ(\alpha, t_f) = (M', D')$ then the equivalence class $(M', \widetilde{D}')$ of (M', D') can be computed using $\widetilde{D}$ as follows:

$\forall (t, t') \in (En(M'))^2 - conf(M'), \quad \widetilde{D}'_{t\, t'} =$

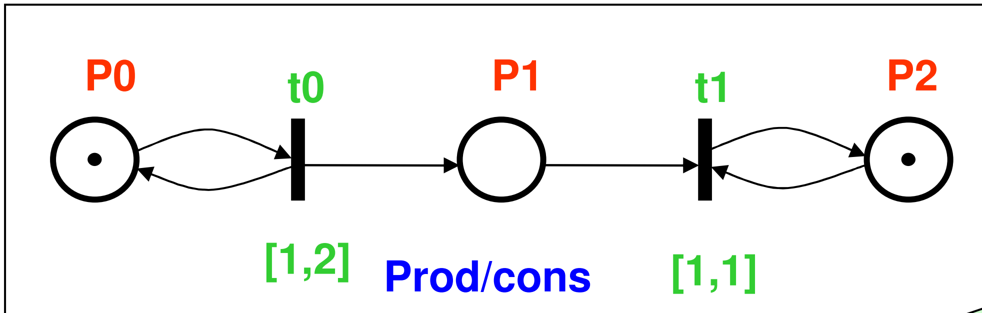
$$\begin{cases} 0 & \text{if t is t}' \\ tmax(t) - tmin(t') & \text{if t, t}' \in \text{New}(\text{M}', \text{t}_\text{f}); \\ tmax(t) + Min_{u \in En(M)} \widetilde{D}_{u\, t'} & \text{if t} \in \text{New}(\text{M}', \text{t}_\text{f}); \\ \widetilde{D}_{t\, t_f} - tmin(t') & \text{if t}' \in \text{New}(\text{M}', \text{t}_\text{f}); \\ Min(\widetilde{D}_{t\, t'}, \widetilde{D}_{t\, t_f} + Min_{u \in En(M)} \widetilde{D}_{u\, t'}) & \text{otherwise} \end{cases}$$

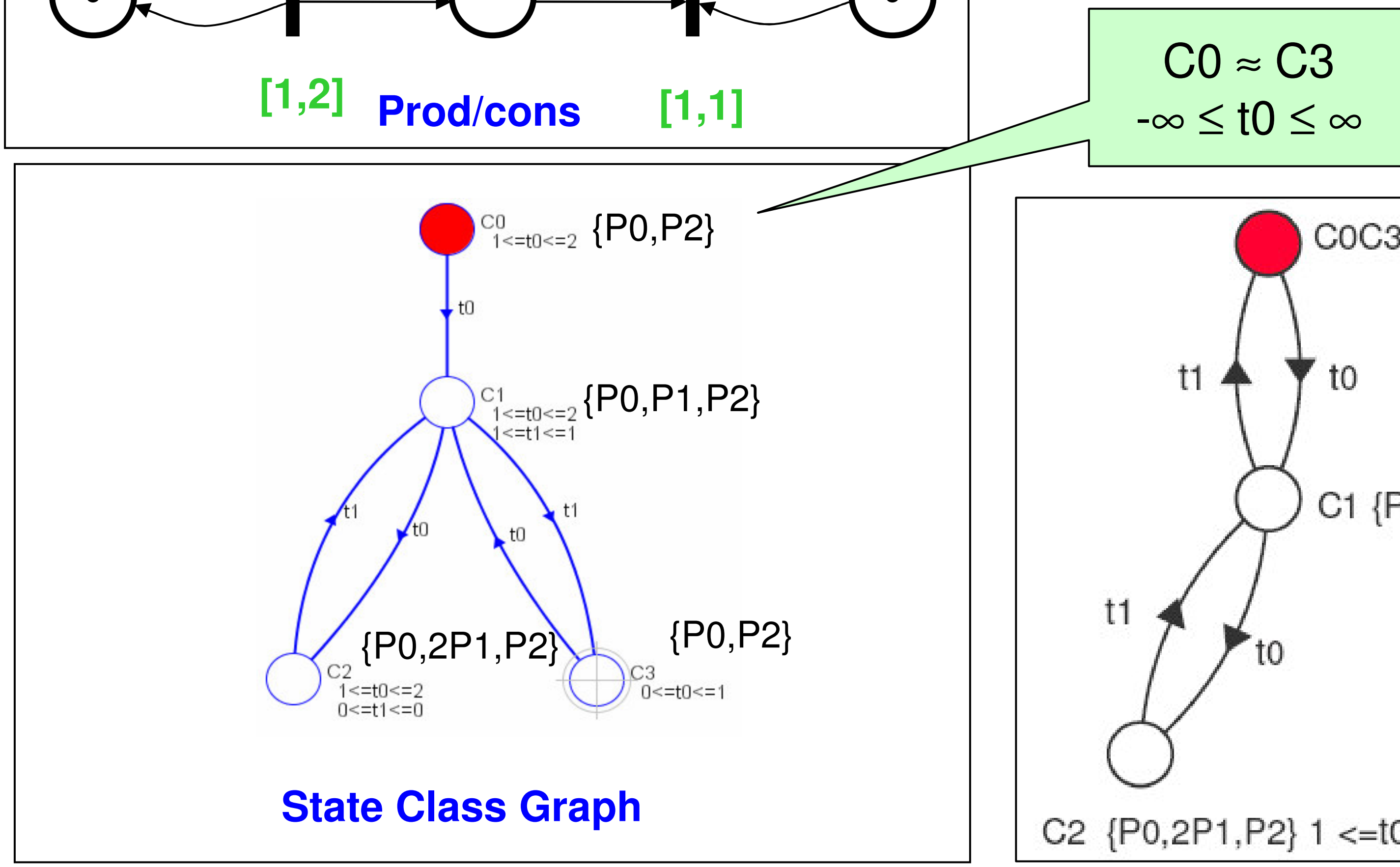
$\forall (t, t') \in conf(M'), \quad \widetilde{D}'_{t\, t'} =$

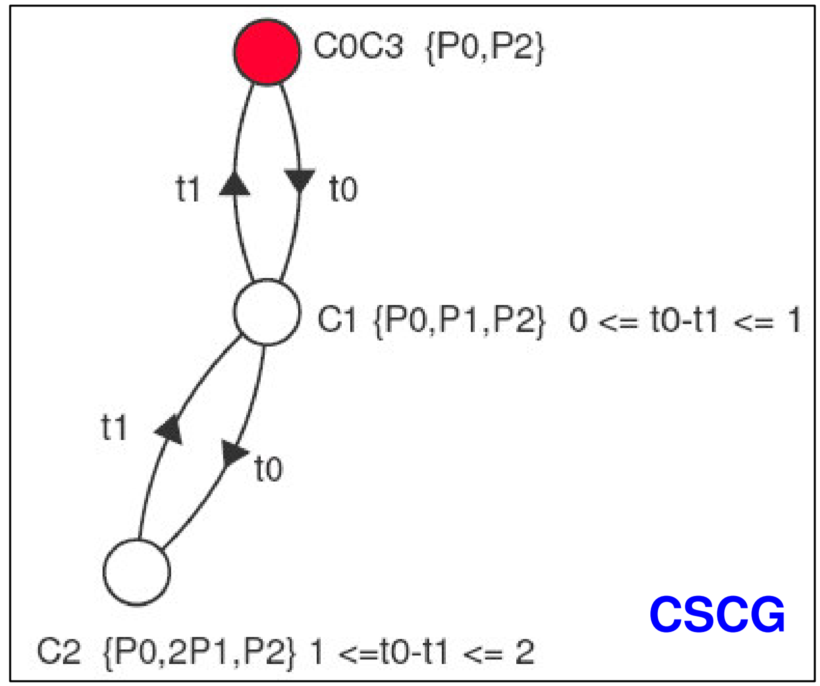
$$\begin{cases} 0 & \text{if t is t}' \\ Min(0, tmax(t) - tmin(t')) & \text{if t, t}' \in \text{New}(\text{M}', \text{t}_\text{f}); \\ Min(0, tmax(t) + Min_{u \in En(M)} \widetilde{D}_{u\, t'}) & \text{if t} \in \text{New}(\text{M}', \text{t}_\text{f}); \\ Min(0, \widetilde{D}_{t\, t_f} - tmin(t')) & \text{if t}' \in \text{New}(\text{M}', \text{t}_\text{f}); \\ Min(0, \widetilde{D}_{t\, t'}, \widetilde{D}_{t\, t_f} + Min_{u \in En(M)} \widetilde{D}_{u\, t'}) & \text{otherwise} \end{cases}$$

Classes of equivalence can be computed in $O(n^2)$ directly from equivalence classes of their predecessors

An example (no conflicting transitions)





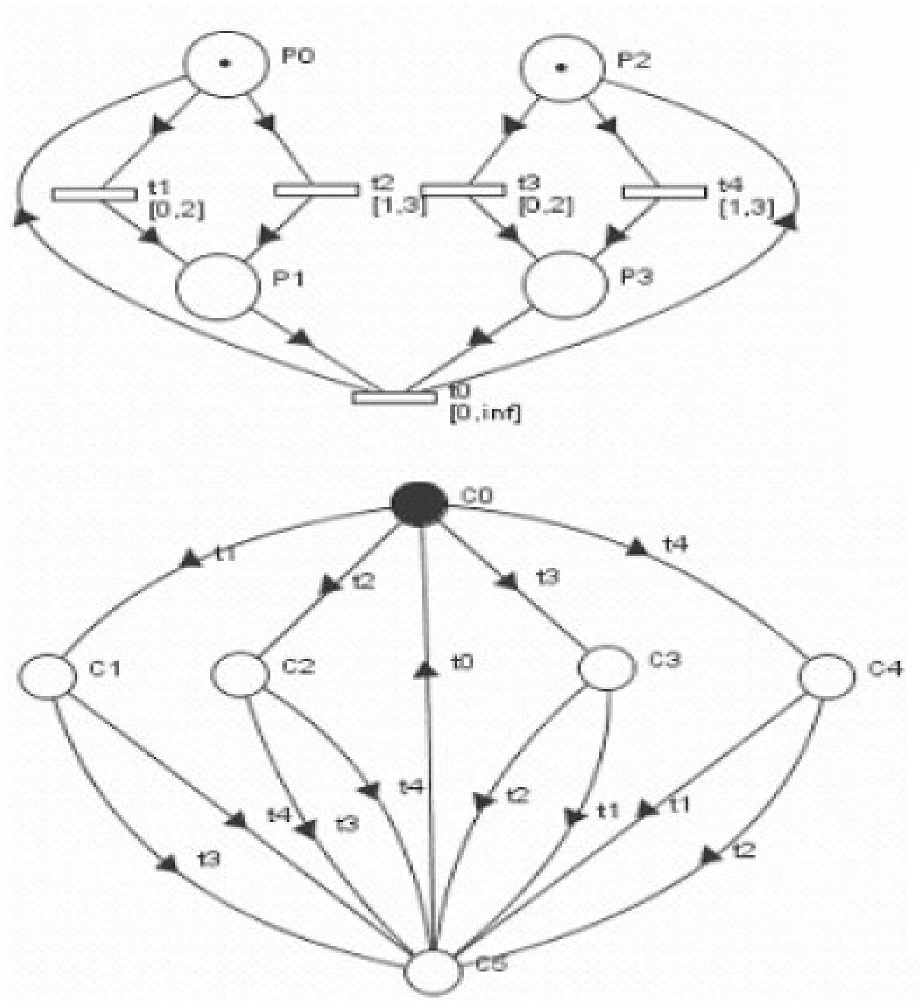


→ CSCG is smaller than CSG.

→ CSCG preserves markings and traces of the TPN → Linear properties

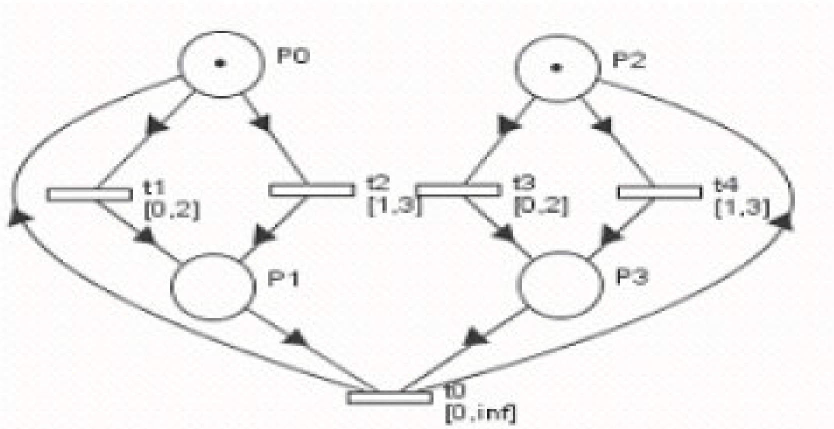
Another example with conflicting transitions

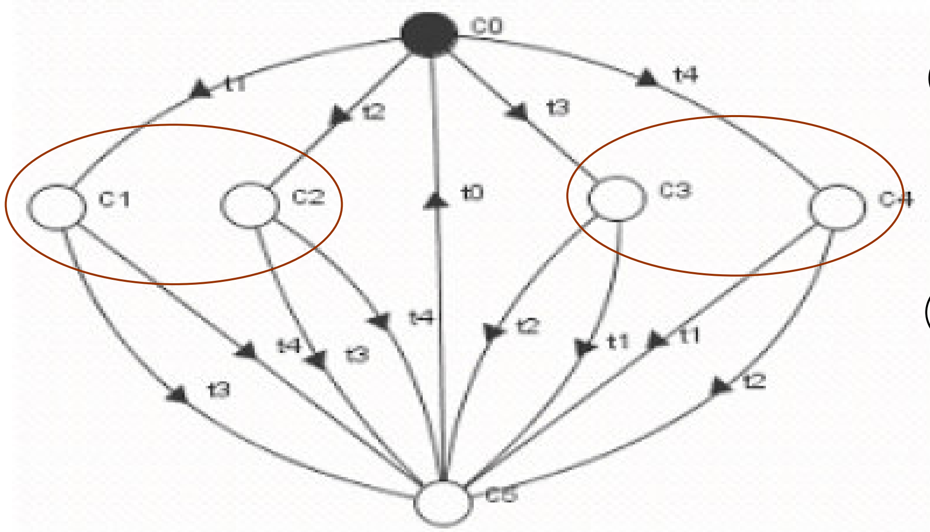
Eliminating simple constraints



- $C0 : P0 + P2$ — ~~$0 \le t1 \le 2$~~, ~~$1 \le t2 \le 3$~~, ~~$0 \le t3 \le 2$~~, ~~$1 \le t4 \le 3$~~, $-3 \le t1 - t2 \le 1$, $-2 \le t1 - t3 \le 2$, $-3 \le t1 - t4 \le 1$, $-1 \le t2 - t3 \le 3$, $-2 \le t2 - t4 \le 2$, $-3 \le t3 - t4 \le 1$
- $C1 : P1 + P2$ — ~~$0 \le t3 \le 2$~~, ~~$0 \le t4 \le 3$~~, $-3 \le t3 - t4 \le 1$
- $C2 : P1 + P2$ — ~~$0 \le t3 \le 1$~~, ~~$0 \le t4 \le 2$~~, $-2 \le t3 - t4 \le 1$
- $C3 : P0 + P3$ — ~~$0 \le t1 \le 2$~~, ~~$0 \le t2 \le 3$~~, $-3 \le t1 - t2 \le 1$
- $C4 : P0 + P3$ — ~~$0 \le t1 \le 1$~~, ~~$0 \le t2 \le 2$~~, $-2 \le t1 - t2 \le 1$
- $C5 : P1 + P3$ — ~~$0 \le t0 \le \infty$~~

Another example with conflicting transitions



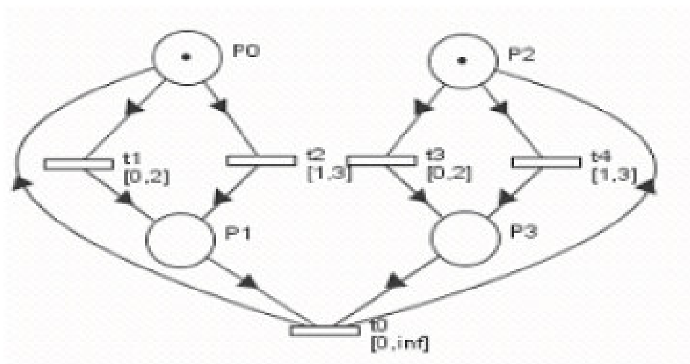


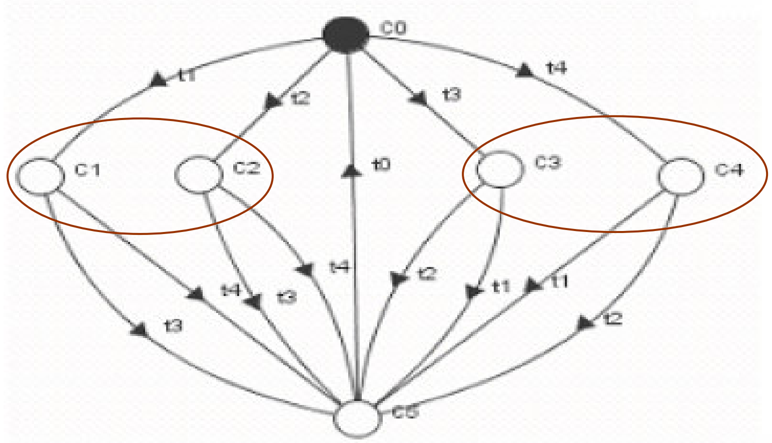
t3, t4 are in conflict

$$
\begin{cases}
C0: P0+P2 & 0 \le t1 \le 2 & 1 \le t2 \le 3 \\
 & 0 \le t3 \le 2 & 1 \le t4 \le 3 \\
 & -3 \le t1 - t2 \le 1 & -2 \le t1 - t3 \le 2 \\
 & -3 \le t1 - t4 \le 1 & -1 \le t2 - t3 \le 3 \\
 & -2 \le t2 - t4 \le 2 & -3 \le t3 - t4 \le 1 \\
C1: P1+P2 & 0 \le t3 \le 2 & 0 \le t4 \le 3 \\
 & -3 \le t3 - t4 \le 1 & \\
C2: P1+P2 & 0 \le t3 \le 1 & 0 \le t4 \le 2 \\
 & -2 \le t3 - t4 \le 1 & \\
C3: P0+P3 & 0 \le t1 \le 2 & 0 \le t2 \le 3 \\
 & -3 \le t1 - t2 \le 1 & \\
C4: P0+P3 & 0 \le t1 \le 1 & 0 \le t2 \le 2 \\
 & -2 \le t1 - t2 \le 1 & \\
C5: P1+P3 & 0 \le t0 \le \infty &
\end{cases}
$$

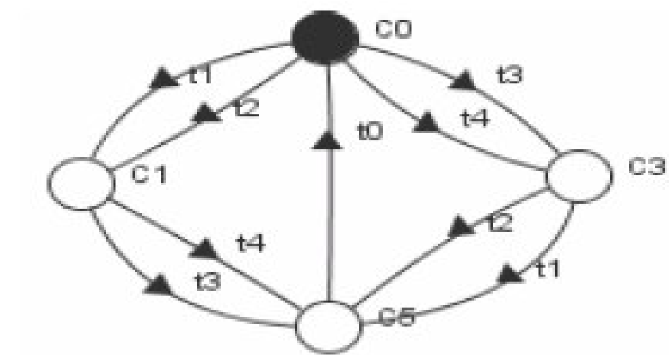
t1, t2 are in conflict

Another example with conflicting transitions





SCG



CSCG

$$
\begin{cases}
C0 : P0 + P2 & 0 \leq t1 - t2 \leq 0 \quad -2 \leq t1 - t3 \leq 2 \\
 & -3 \leq t1 - t4 \leq 1 \quad -1 \leq t2 - t3 \leq 3 \\
 & -2 \leq t2 - t4 \leq 2 \quad 0 \leq t3 - t4 \leq 0 \\
C1 : P1 + P2 & 0 \leq t3 - t4 \leq 0 \\
C3 : P0 + P3 & 0 \leq t1 - t2 \leq 0 \\
C5 : P1 + P3 &
\end{cases}
$$

Contracting the state class graph

Experimental results

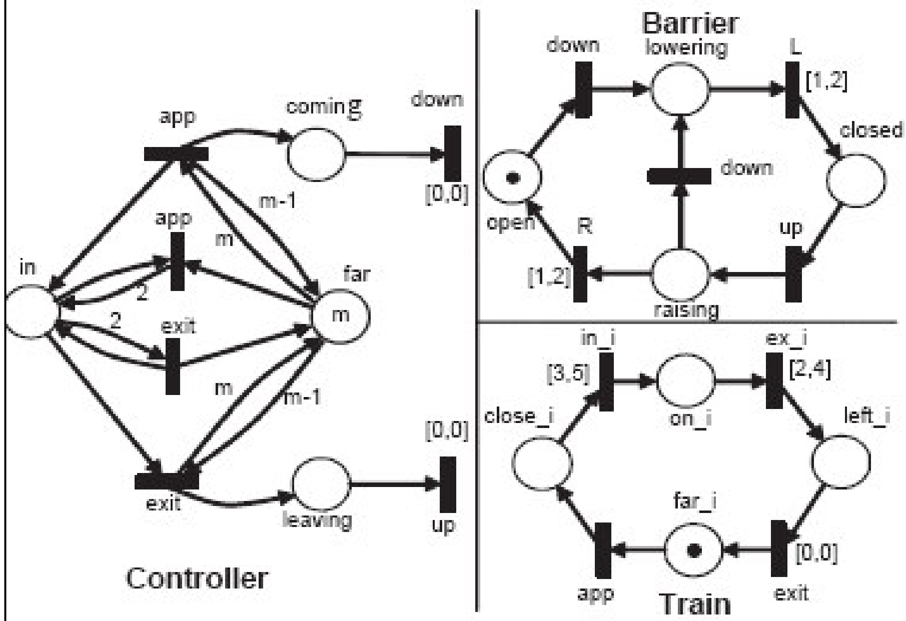
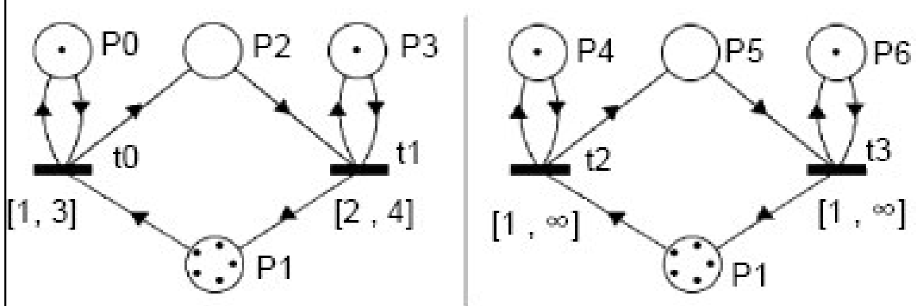


Figure 2. The level crossing models



a) ProdCons1

b) ProdCons2

Figure 3. Producer consumer model

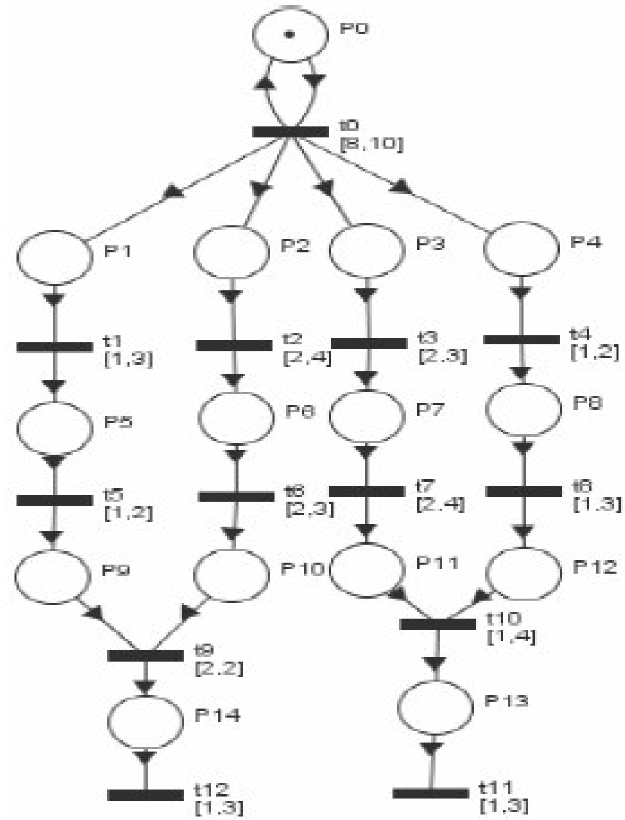


Figure 4. A TPN model of some periodical tasks

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Contracting the state class graph

Experimental results

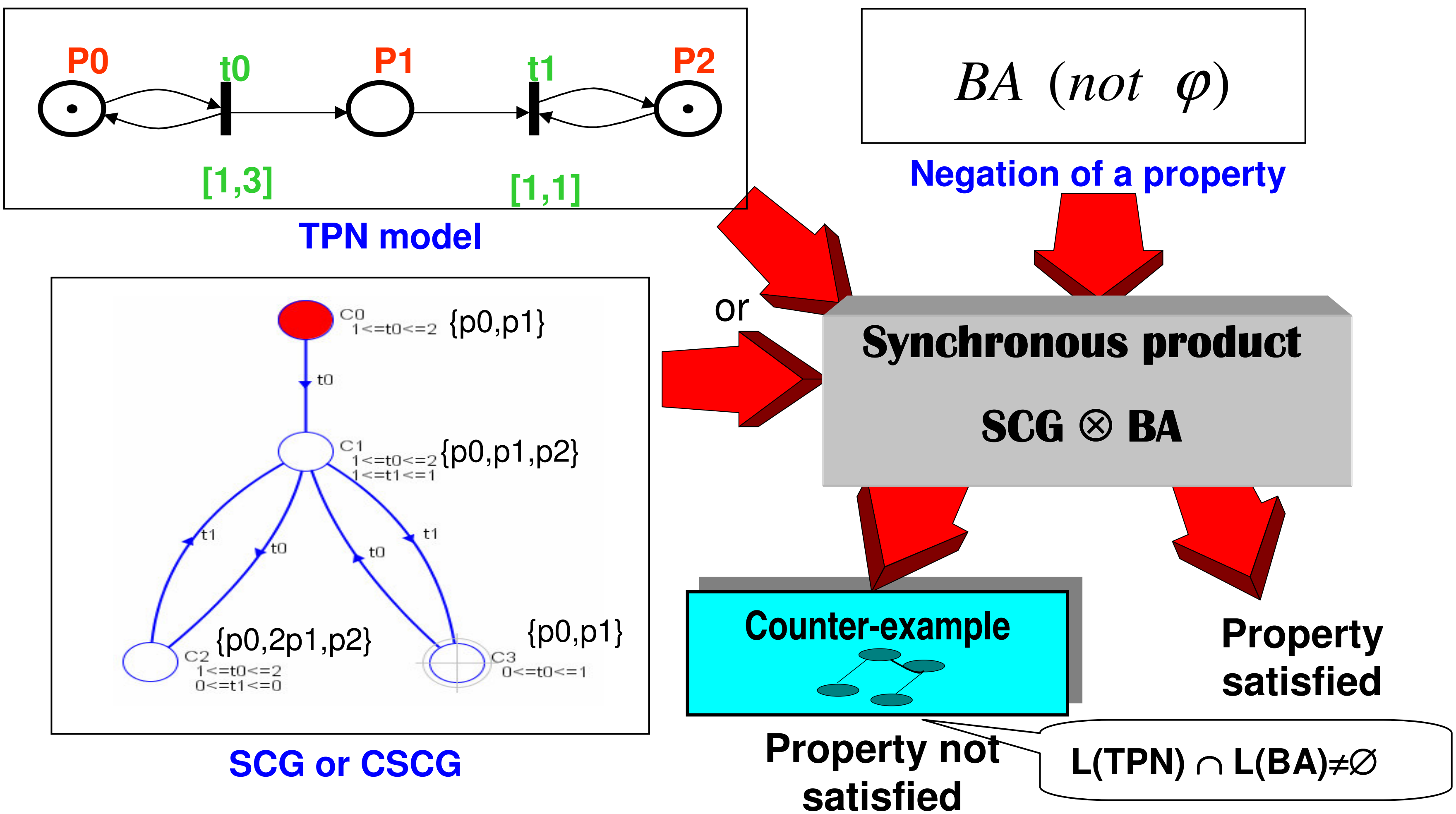
TPN	ZBG	SCG	*CSCG*	*Ratio*1
Fig.2(m=2)	147	123	113	1.09
Arcs	266	218	198	1.10
CPU(s)	0	0	0	-
Fig.2(m=3)	6299	3101	2816	1.10
Arcs	16565	7754	6941	1.12
CPU(s)	0.22	0.04	0.02	2
Fig.2(m=4)	?	134501	122289	1.10
Arcs		436896	391240	1.11
CPU(s)		4.47	2.41	1.85
Fig.3(n=2)	2941	748	519	1.44
Arcs	9952	2460	1678	1.47
CPU(s)	0.02	0.01	0	-
Fig.3(n=3)	100060	4604	2834	1.62
Arcs	485732	21891	13208	1.66
CPU(s)	20.57	0.09	0.04	2.25
Fig.3(n=4)	?	14086	8159	1.73
Arcs		83375	47592	1.75
CPU(s)		1.41	0.59	2.39
Fig.3(n=5)	?	31657	17643	1.79
Arcs		217423	120804	1.80
CPU(s)		8.77	3.22	2.72
Fig.3(n=6)	?	77208	37876	2.04
Arcs		624158	294363	2.12
CPU(s)		53.47	16.37	3.27
Fig.4	24015	18543	12910	1.44
Arcs	86621	65403	45970	1.42
CPU(s)	5.75	3.27	1.62	2.02

Ratio1 = SCG / CSCG

Gain in time and size grows with the size of the model

Model checking of SCG/CSCG using Büchi Automata method

Büchi Automata (BA) method



Interval Timed Büchi Automata (ITBA)

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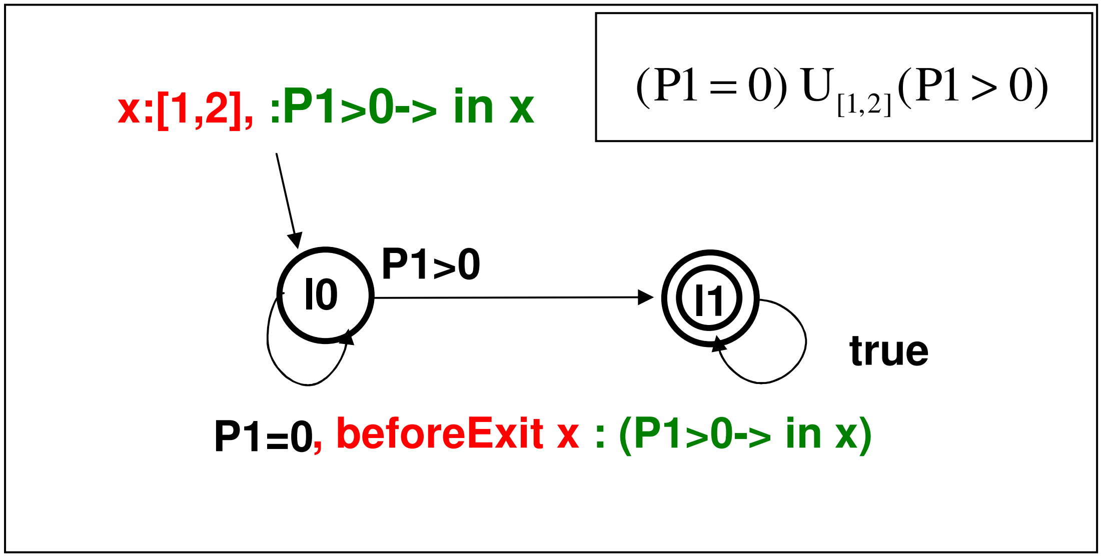
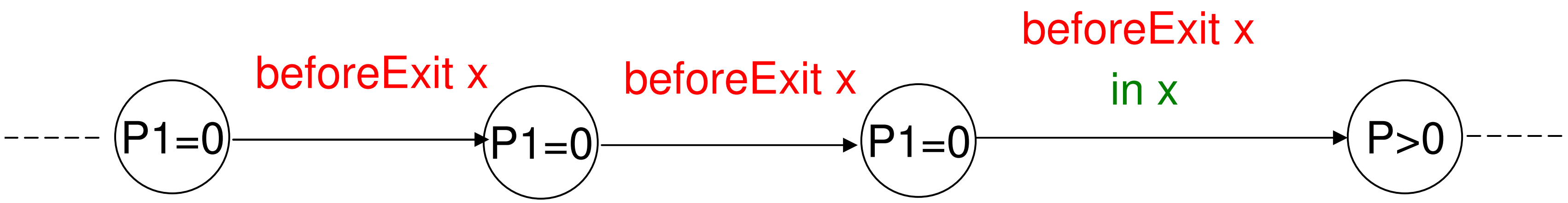
Interval Timed Büchi Automata

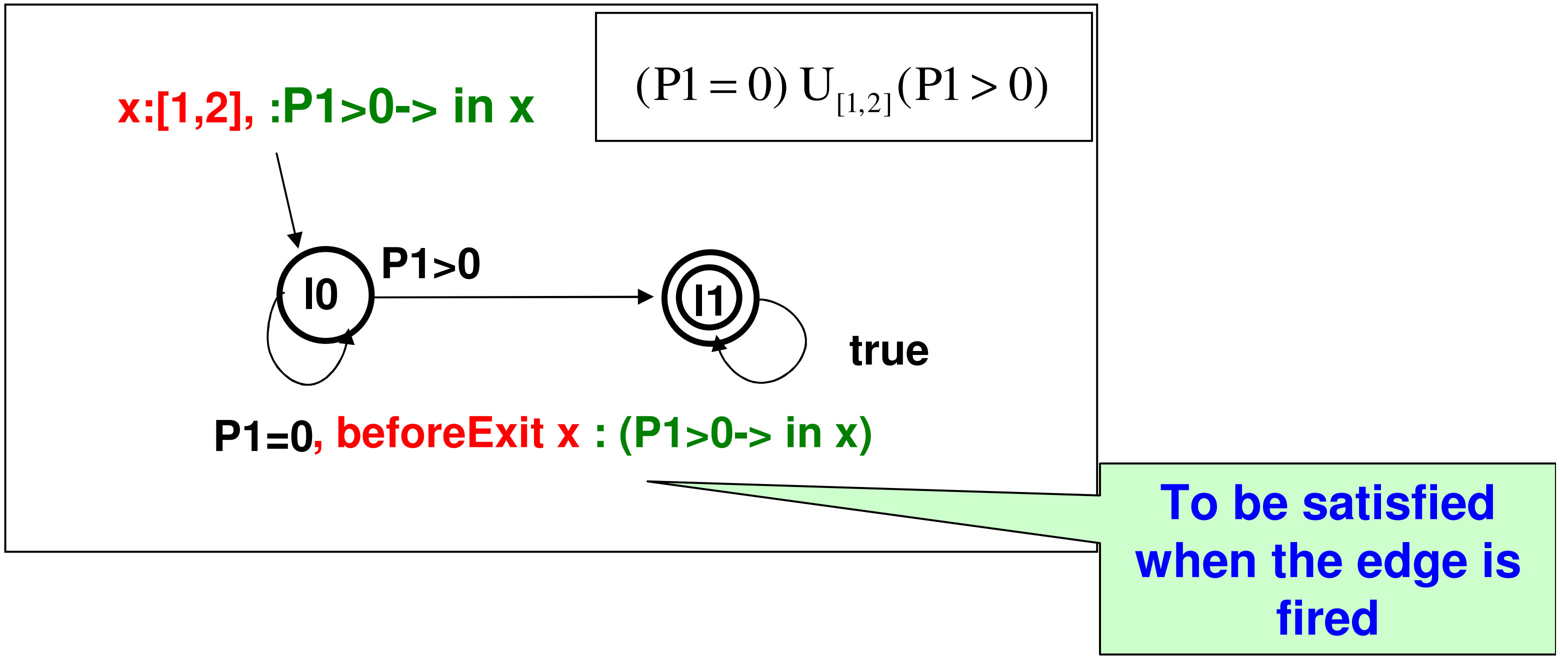
BA + **{interval delays}** **+**
{guards on delays} **+**
{**(re)setting /deactivation of delays**}

Guards on delays: **{** **before x**,
in x,
beforeExit x,
after x,
true}





Interval Timed Büchi Automata



- With each delay x is associated a dynamic interval I(x).
- I(x) can be set to an interval at the beginning or when an edge is fired.
- When I(x) is set to an interval, its bounds decrease with time until it is deactivated.

State: (l_i, A, I)

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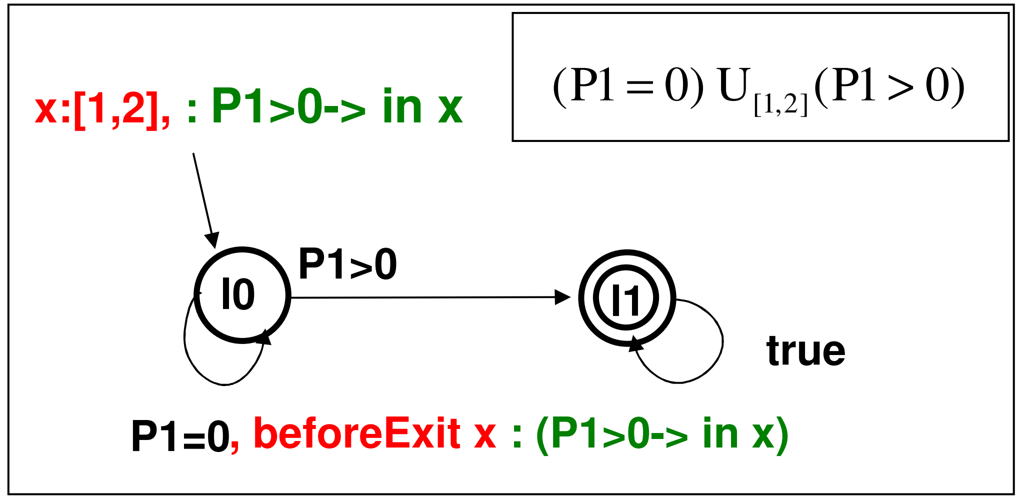
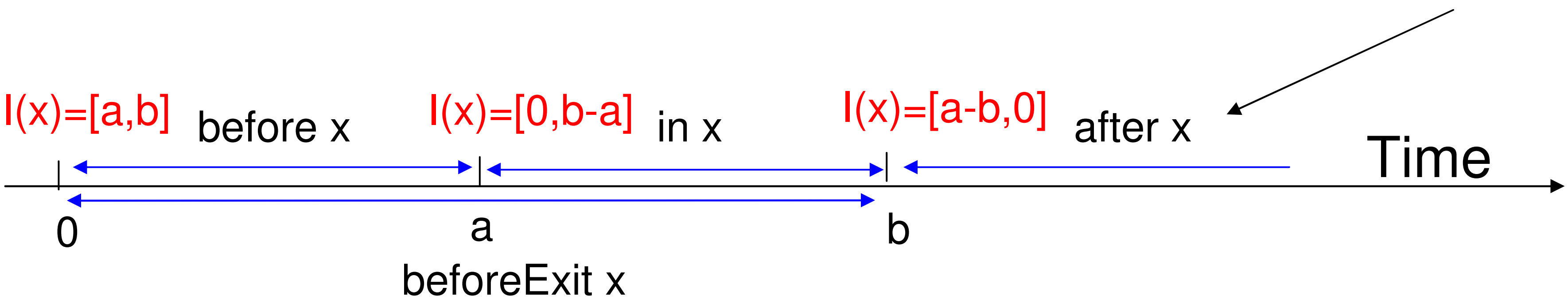
Interval Timed Büchi Automata

State: (l_j, A, I)





before x	in x	beforeExit x	after x
$\downarrow I(x) > 0$	$\downarrow I(x) \leq 0,\ \uparrow I(x) \geq 0$	$\uparrow I(x) \geq 0$	$\uparrow I(x) < 0$

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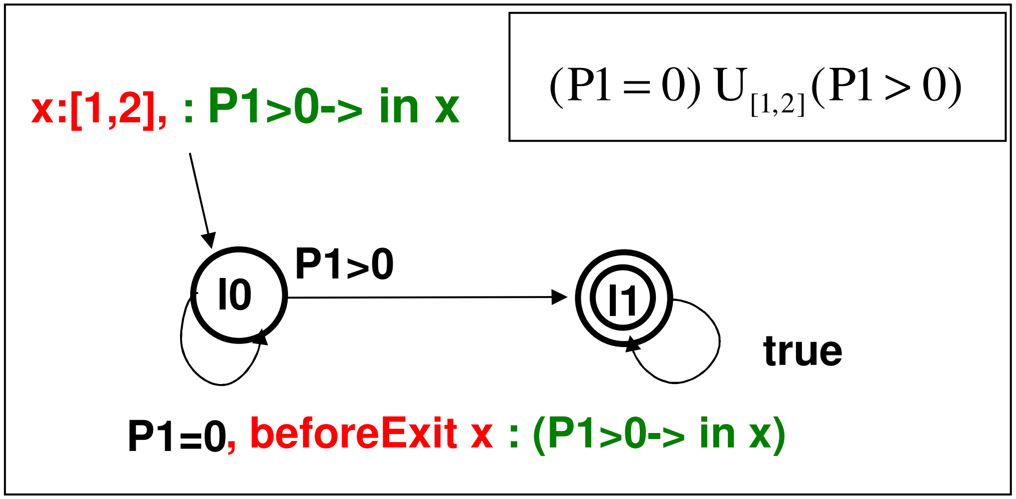
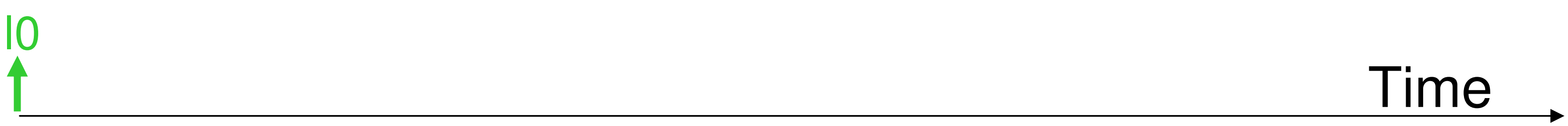
Interval Timed Büchi Automata



State q = (l0, A, I), A={x}, I(x)=[1,2]



State q = (l0, A, I), A={x}, I(x)=[1,2]

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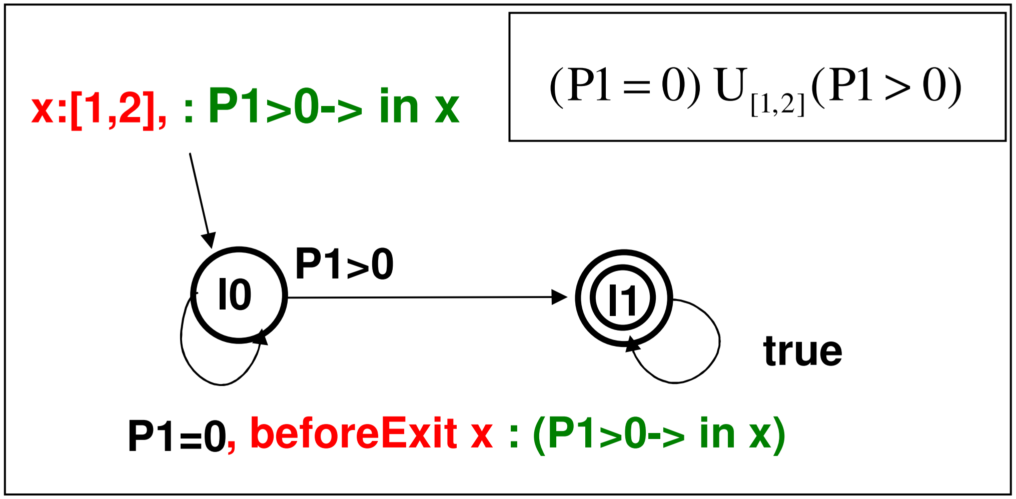
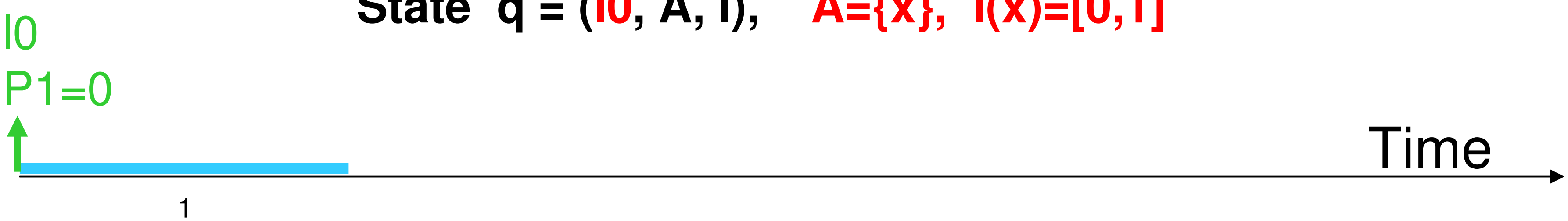
Interval Timed Büchi Automata

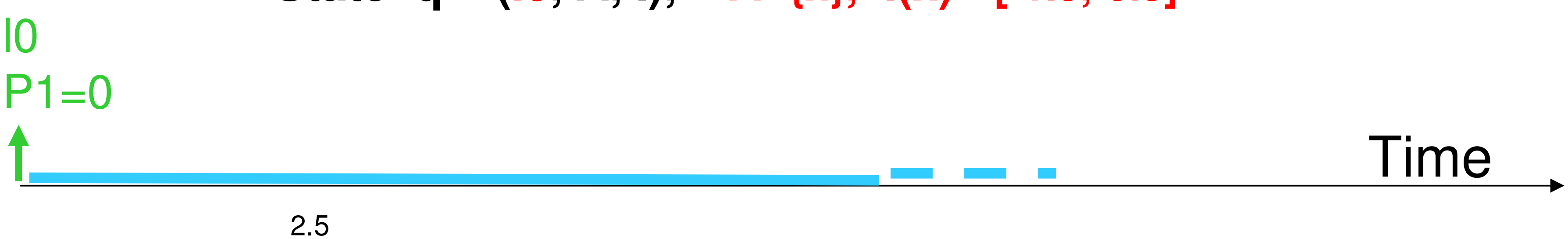


bounds of intervals decrease with time

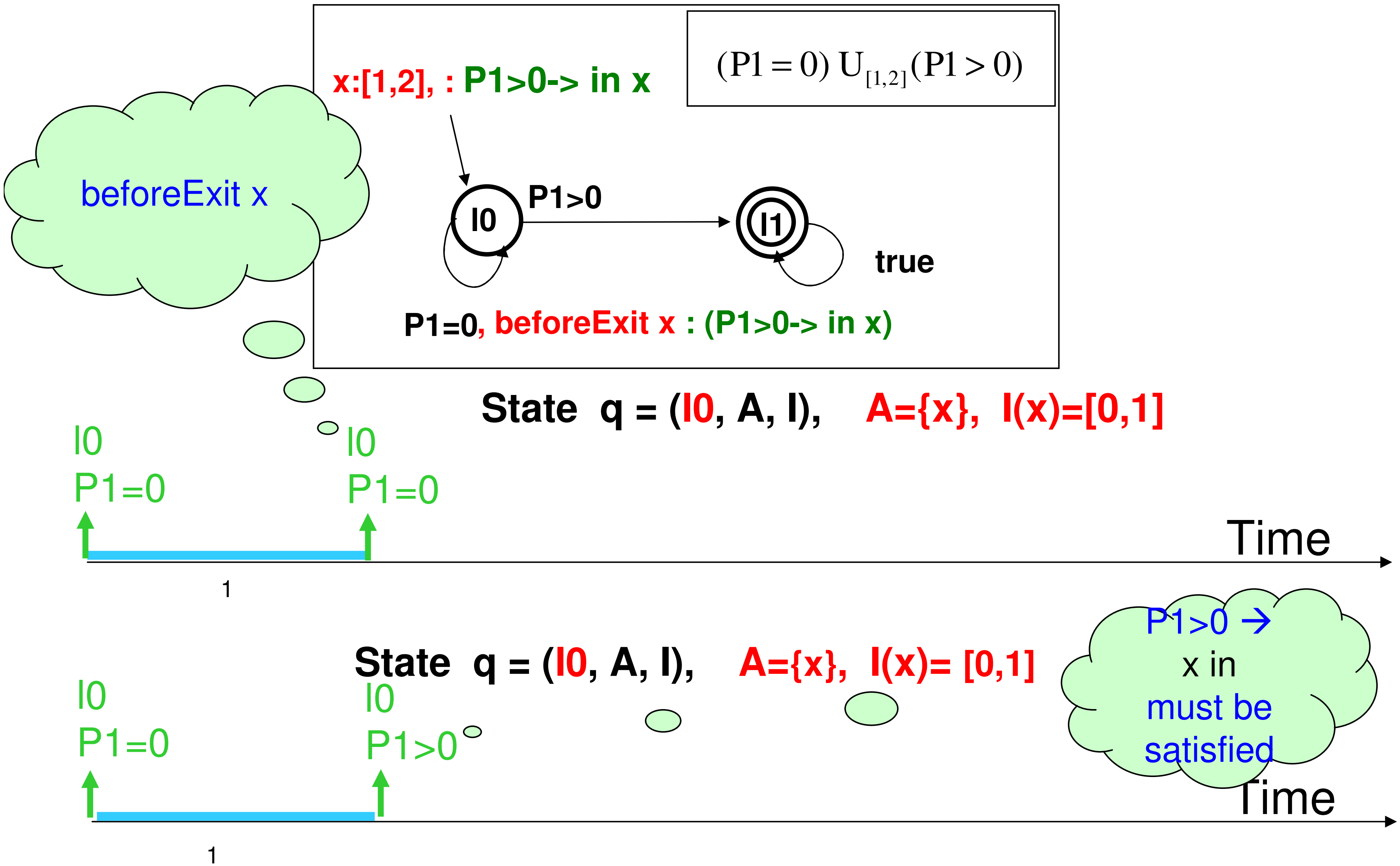
State q = (l0, A, I), A={x}, I(x)=[0,1]



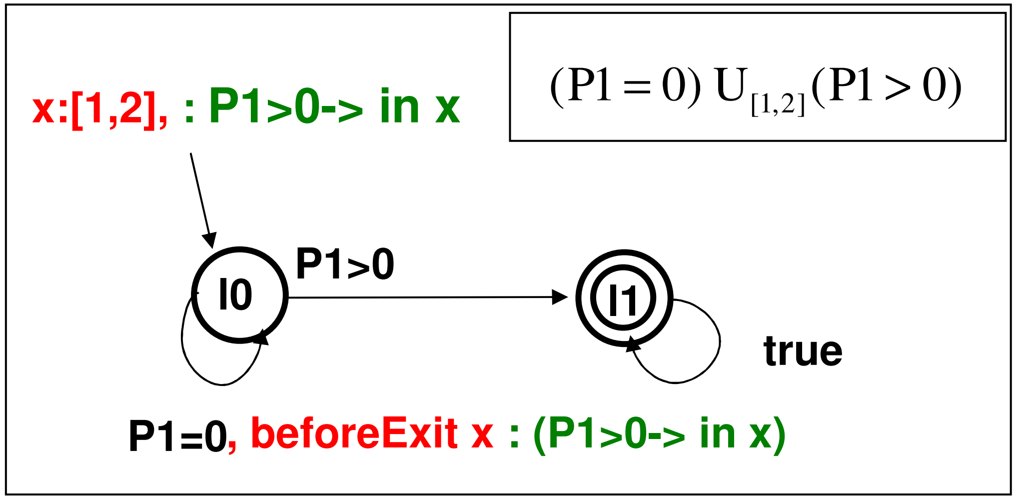
State q = (l0, A, I), A={x}, I(x)= [-1.5,-0.5]



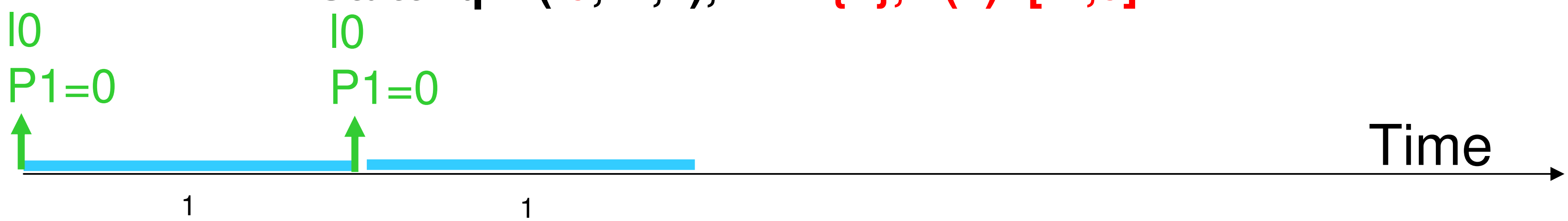
Interval Timed Büchi Automata



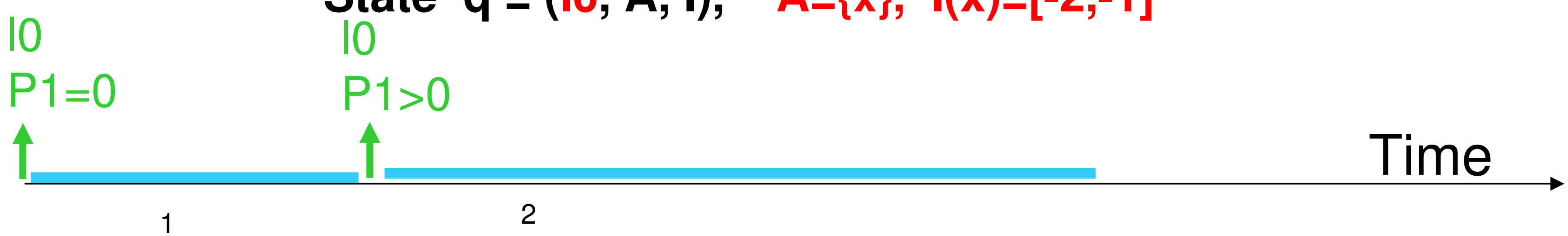
Interval Timed Büchi Automata



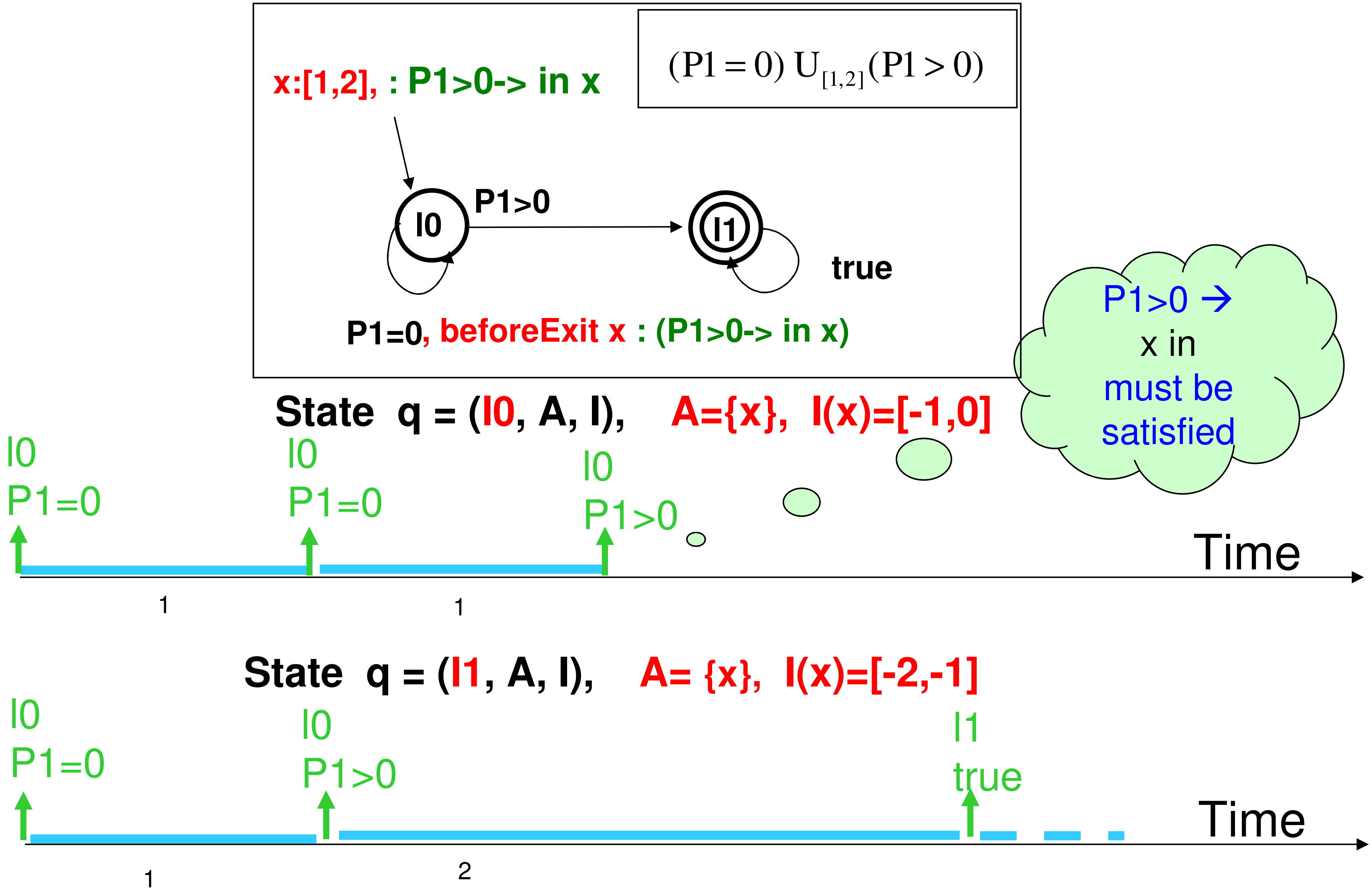
State q = (l0, A, I), A={x}, I(x)=[-1,0]



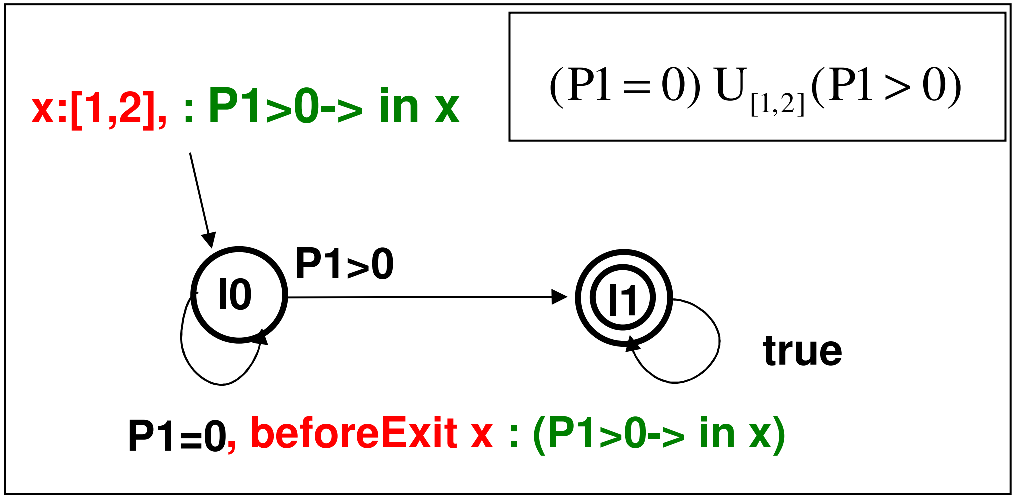
State q = (l0, A, I), A={x}, I(x)=[-2,-1]



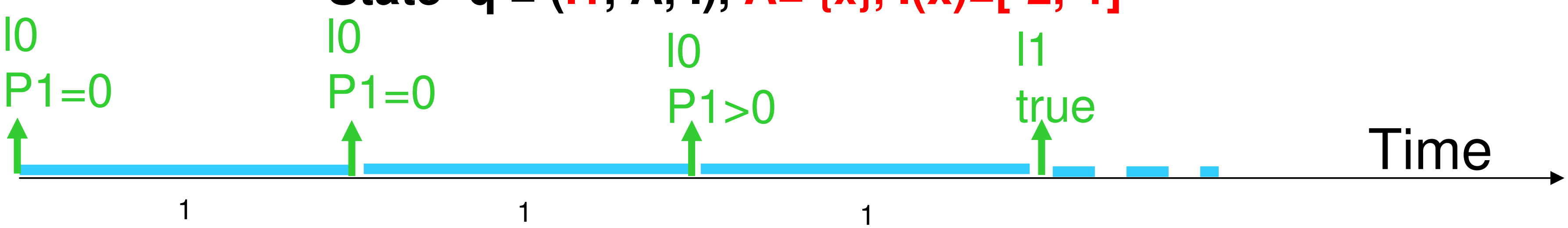
Interval Timed Büchi Automata



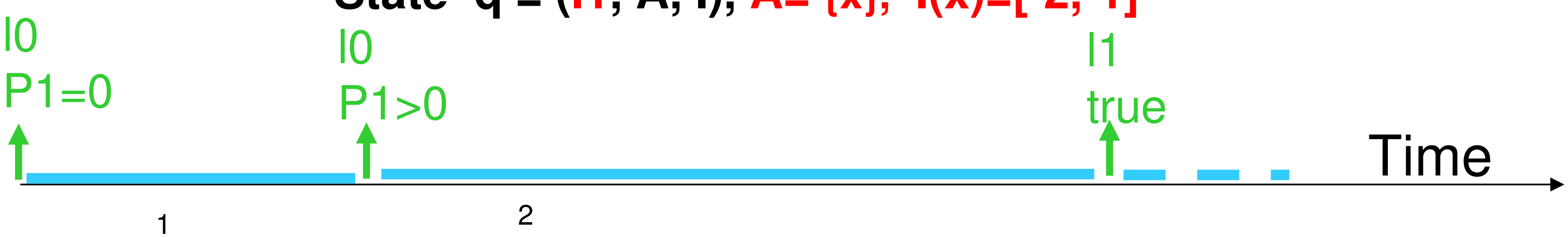
Interval Timed Büchi Automata



State q = (l1, A, I), A= {x}, I(x)=[-2,-1]



State q = (l1, A, I), A= {x}, I(x)=[-2,-1]



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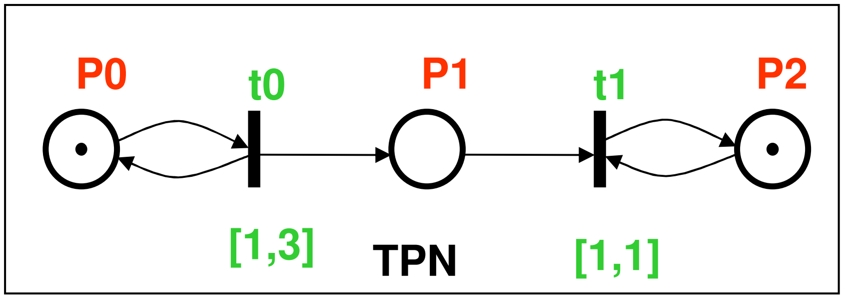
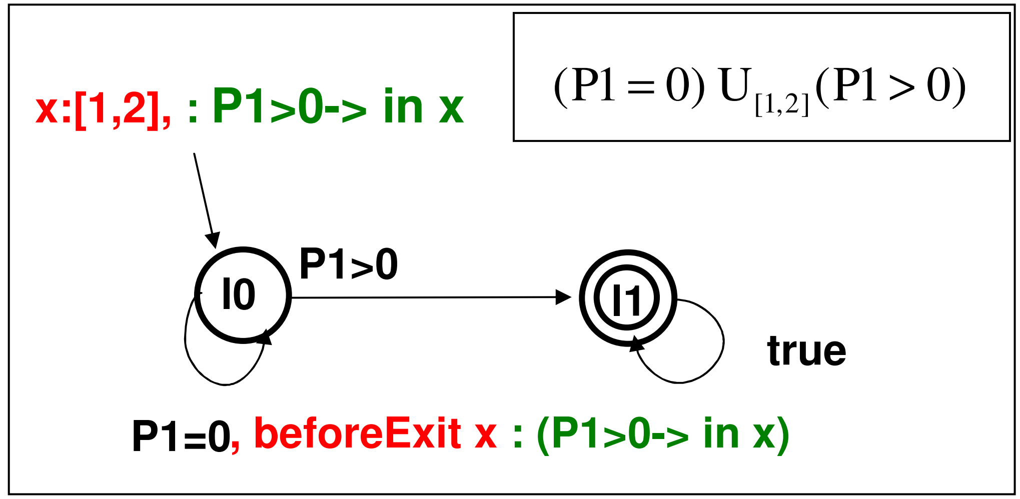
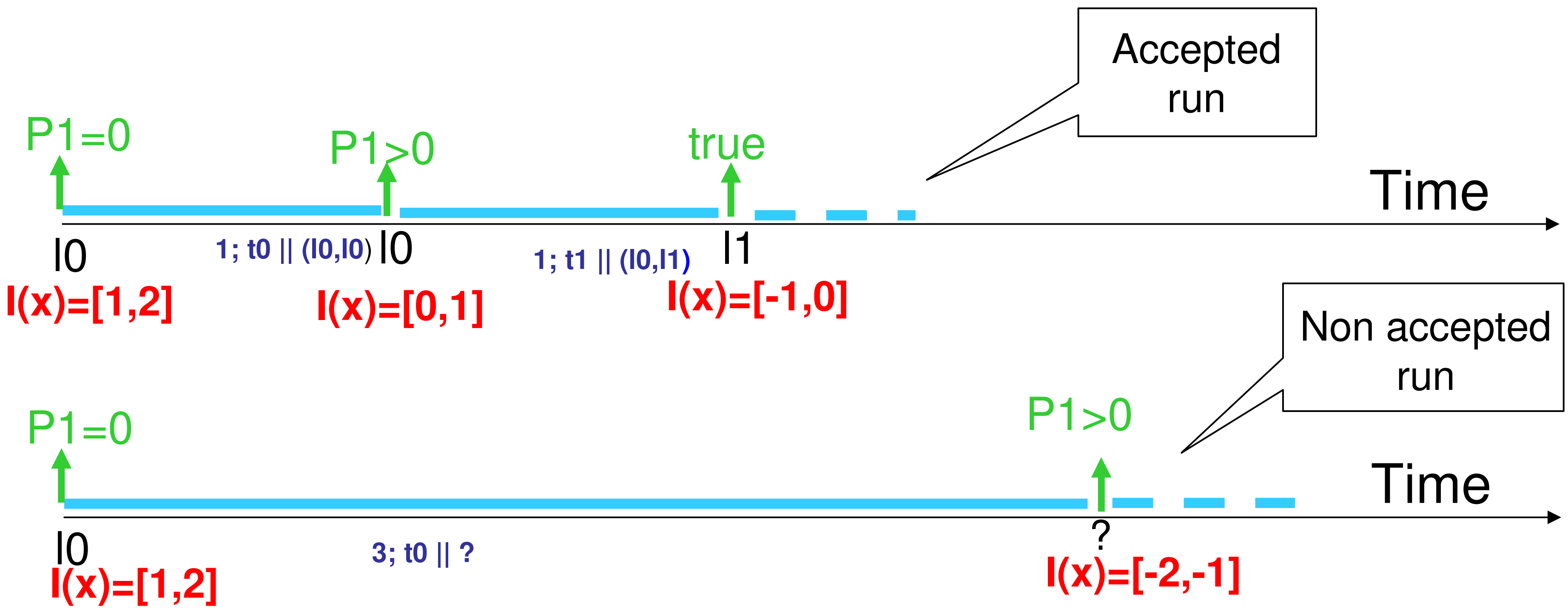
Synchronous product TPN⊗ITBA







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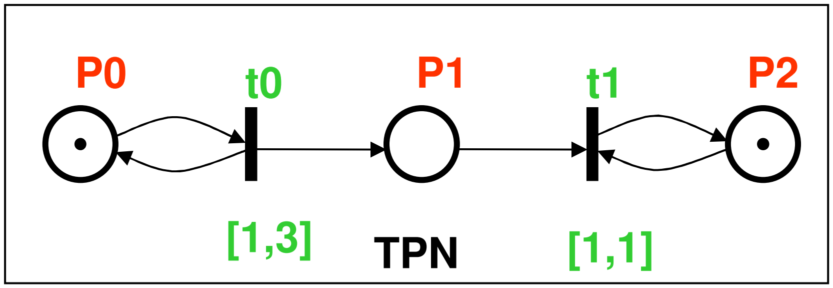
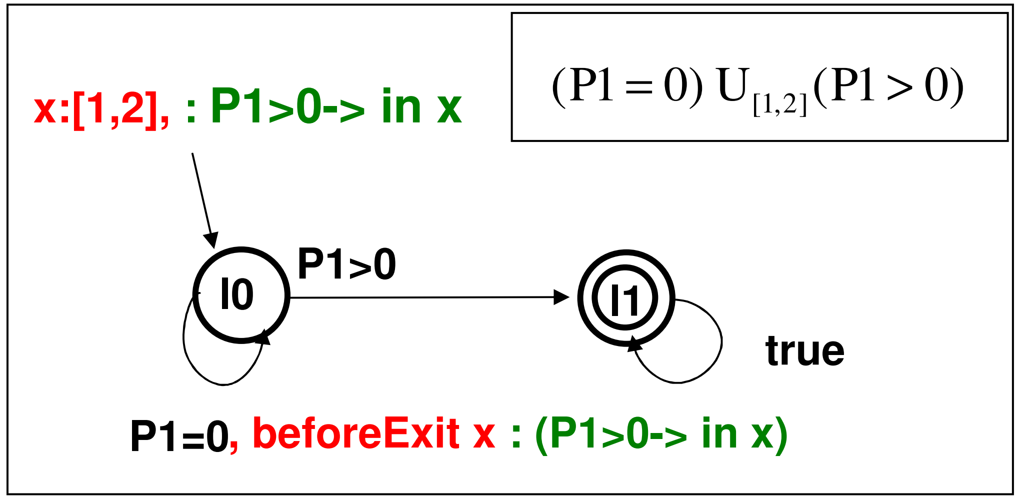
SCG / CSCG of TPN⊗ITBA





State class of TPN⊗ITBA: ***(M, I_i, A, F)***

En(M) ∪ A

Firing some transition t_f:

before x	*in x*	*beforeExit x*	*after x*
$x - t_f > 0$	$x - t_f = 0$	$x - t_f \geq 0$	$x - t_f < 0$

before x is satisfied when t_f is fired

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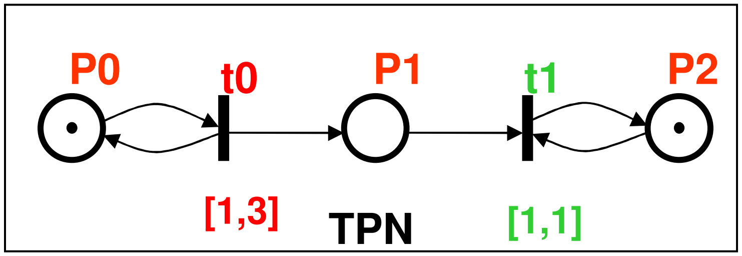
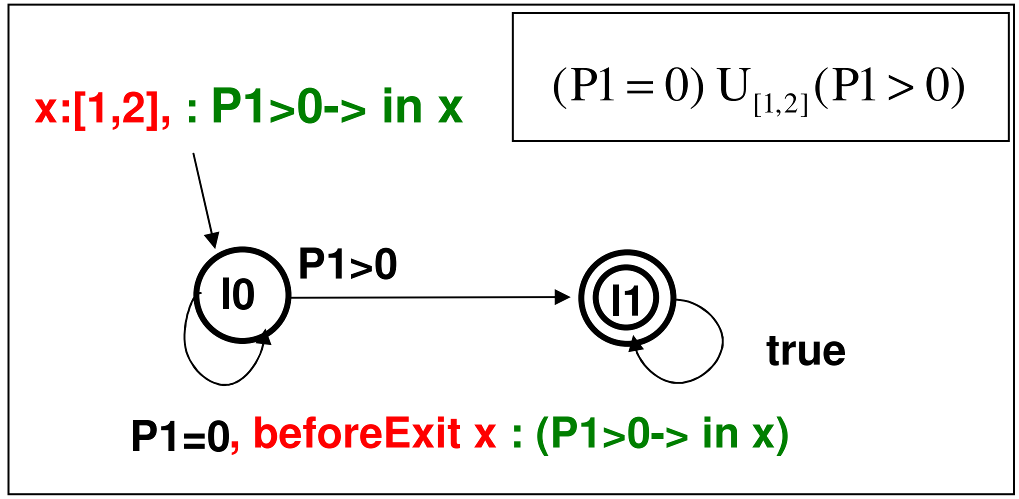
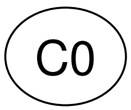
TPN⊗ITBA







$(\{P0, P2\}, l0), \{x\},$

$1 \leq x \leq 2 \wedge$

$1 \leq t0 \leq 3$

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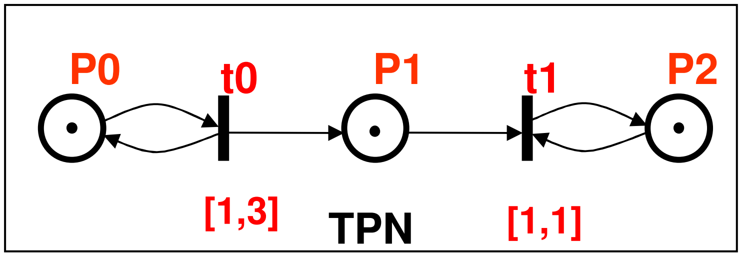
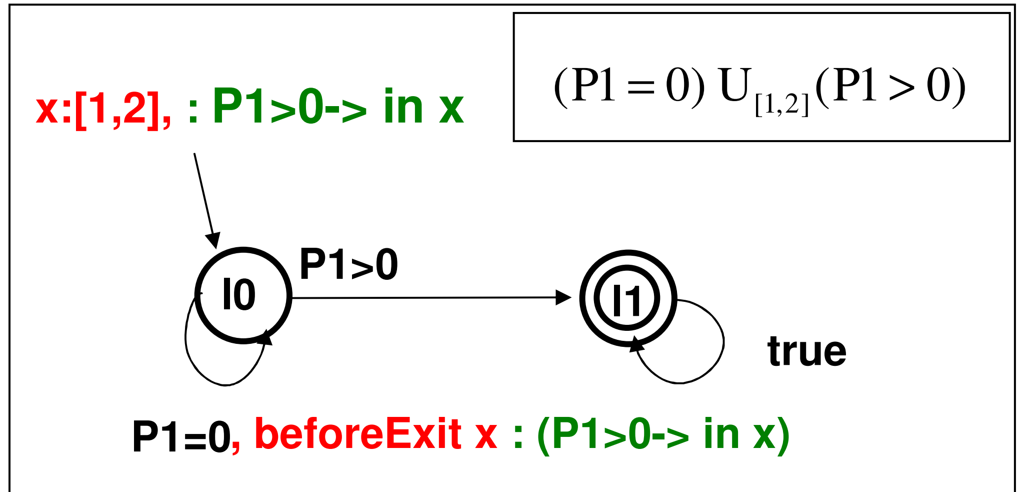
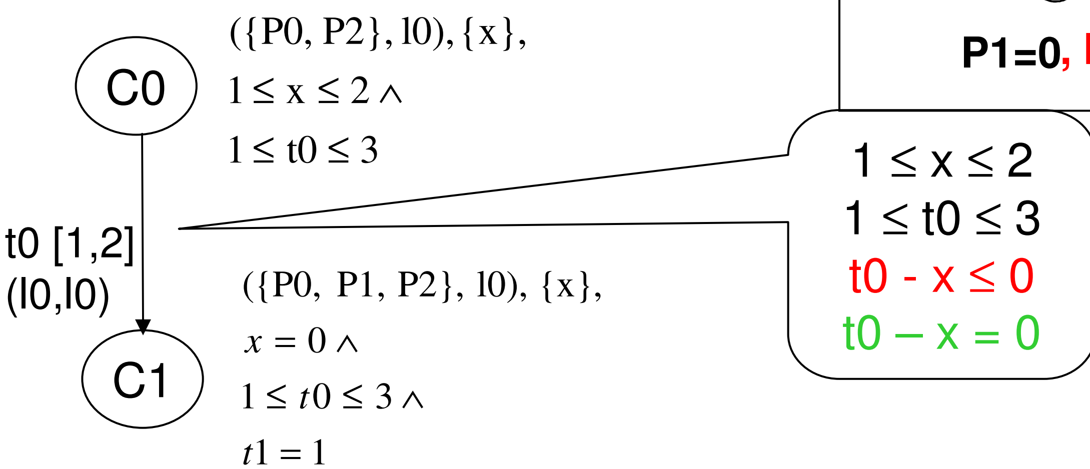
TPN⊗ITBA







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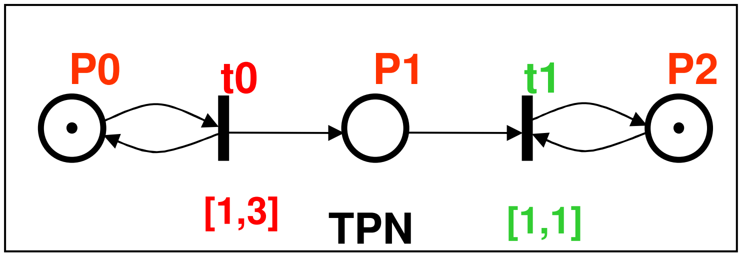

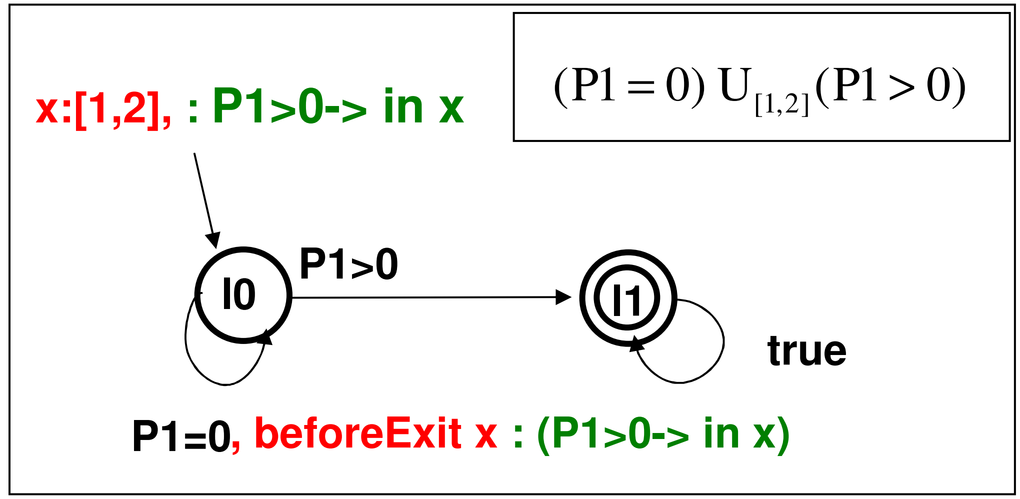

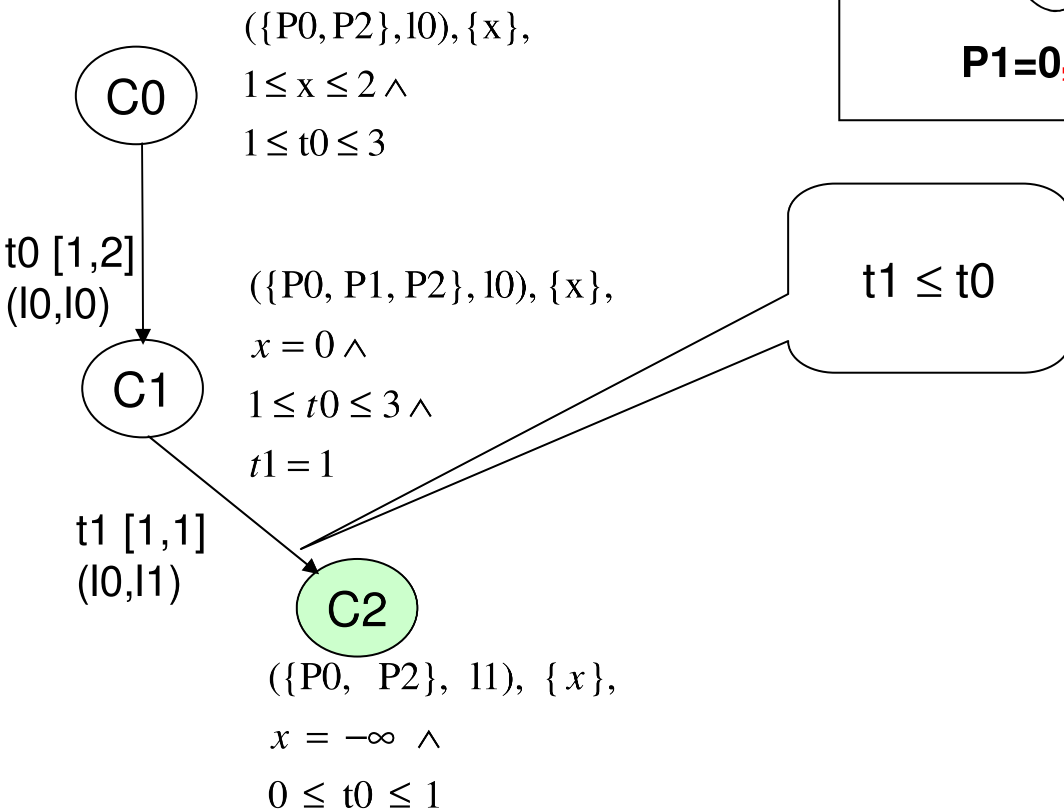

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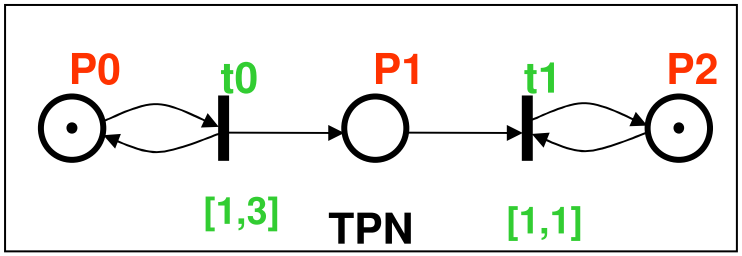

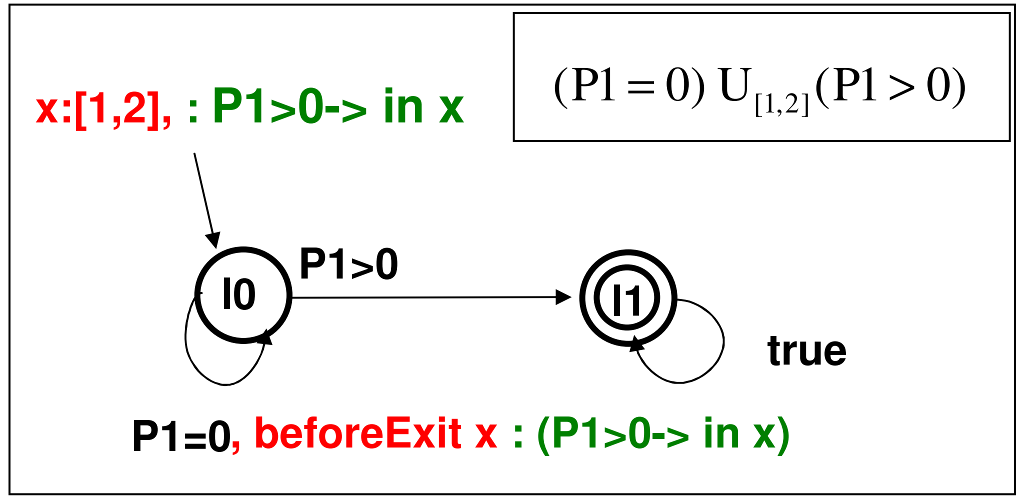

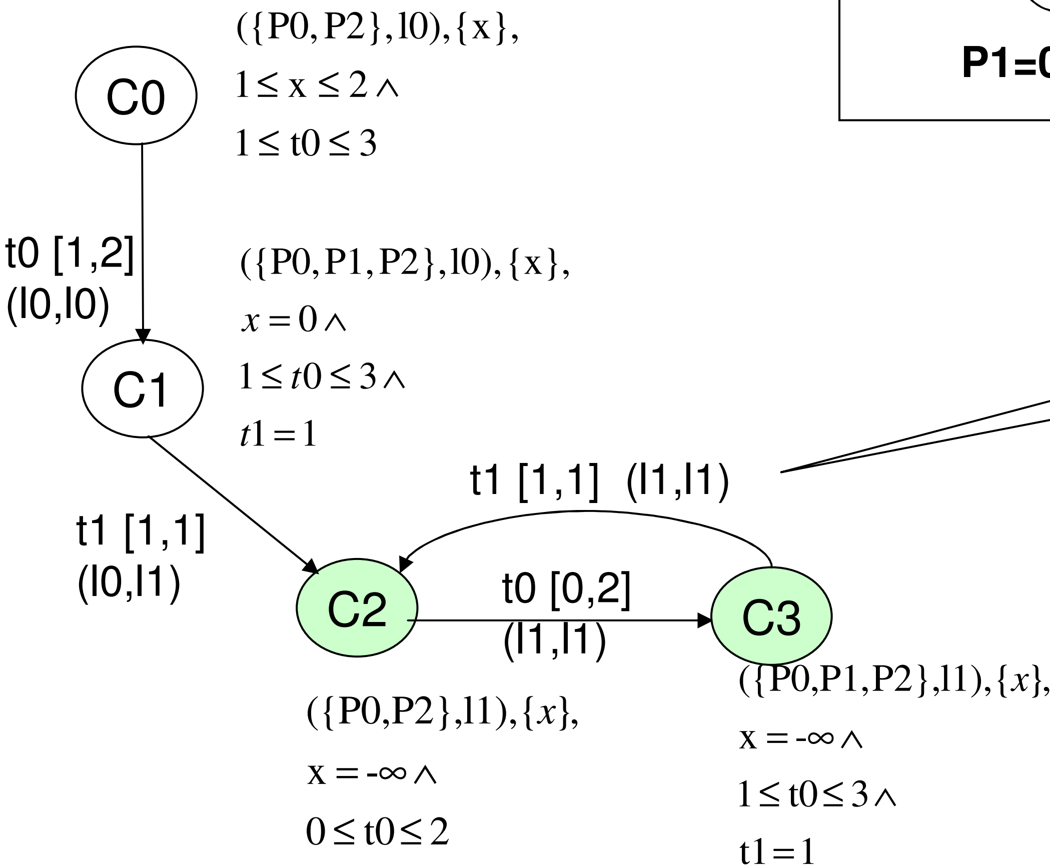

L(TPN) ∩ L(ITBA) ≠∅

Conclusion

- CSCG
- An Interval Timed Büchi Automata (ITBA)
- A verification technique using ITBA and SCG / CSCG

Merci!