Combining Widening and Acceleration in Linear Relation Analysis

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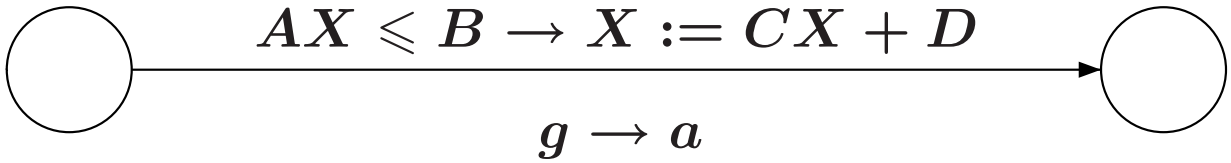
Introduction

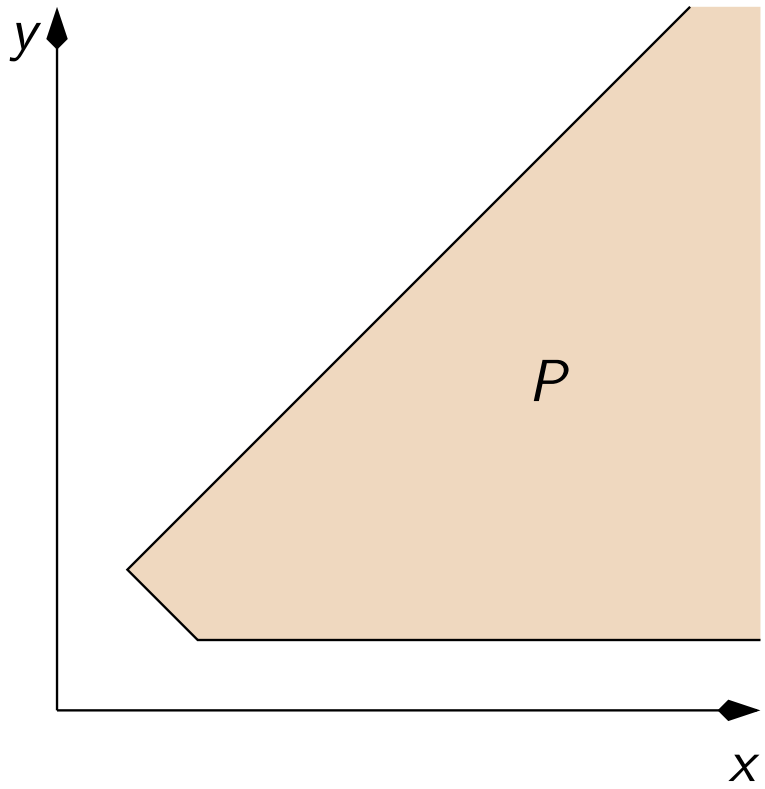
Context : Linear Relation Analysis (LRA) [Cousot&Halbwachs 78]
The analysis framework

- CFG with numerical variables and **affine** guards and actions :



- Safety/non rechability properties
- Forward and/or backward analysis to compute invariants.
- Polyhedral (over-) approximations of invariants sets. (Convex polyhedra in $\mathcal{P}(\mathbb{Q}^n)$ in **double description**).
- Possibly infinite sequences $\Rightarrow$ **widening operator**.

The polyhedral domain (1)



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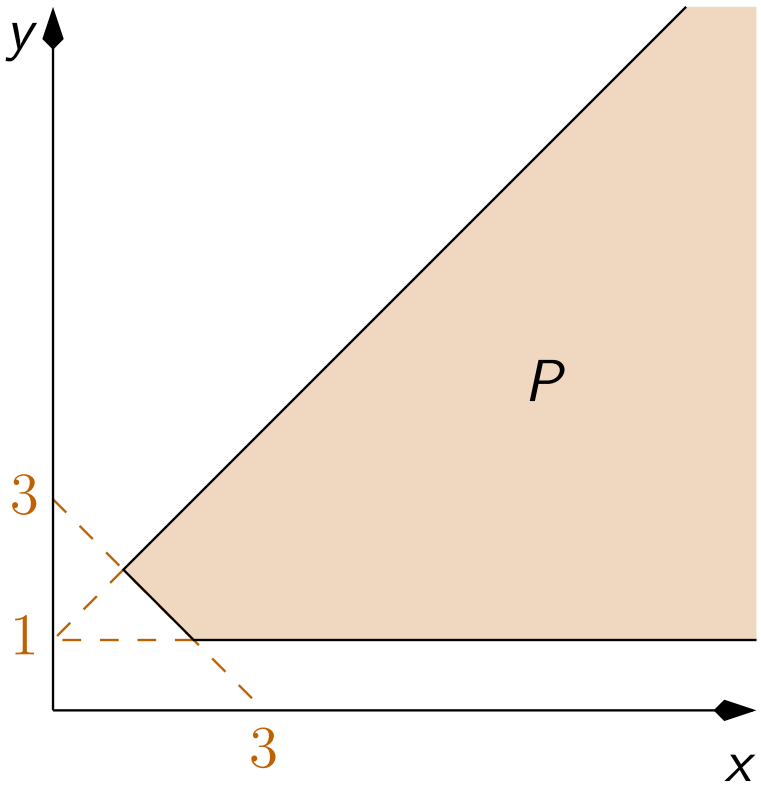

$$P = \{(x,y) \mid 1 \leq y \leq x+1 \wedge x+y \geq 3\} = cons\{AX \leq b\}$$

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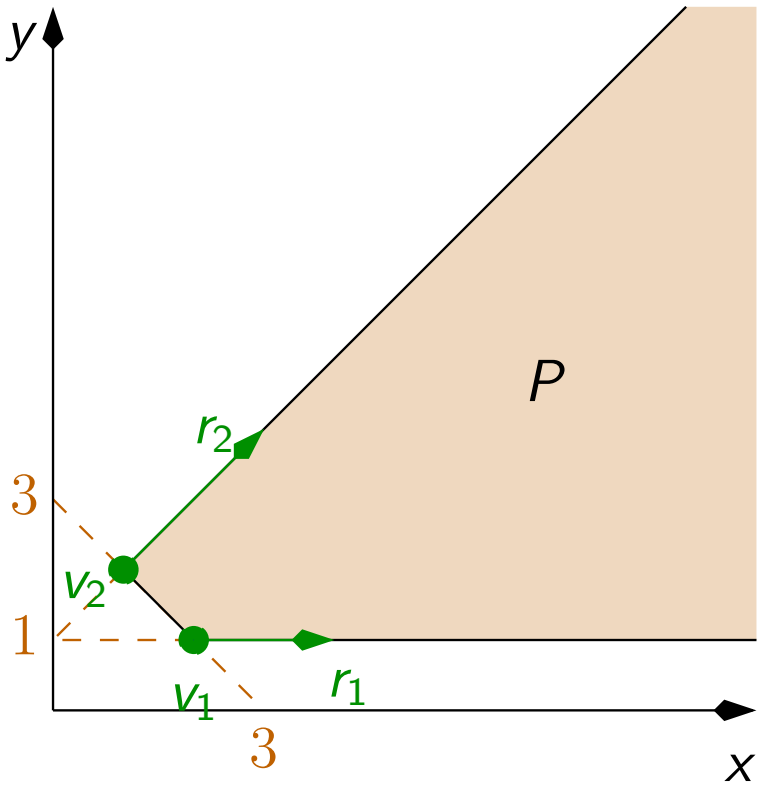
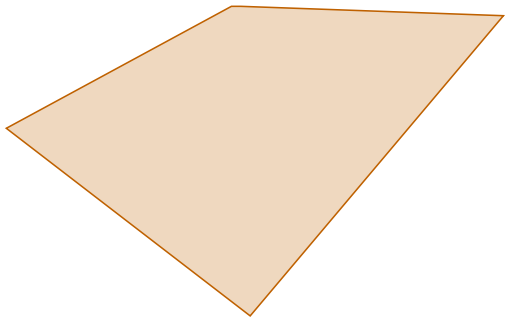


$$P = \{(x,y) \mid 1 \leq y \leq x+1 \wedge x+y \geq 3\} = cons\{AX \leq b\}$$

$$P = \{\lambda v_1 + (1-\lambda)v_2 + \mu_1 r_1 + \mu_2 r_2 \mid \lambda \in [0,1],\ \mu_1, \mu_2 \geq 0\} = gen(V,R)\}$$

The polyhedral domain (2)



- **Usual operations** : linear transformation $P' := CP + D$, intersection, union (convex hull), test for emptiness.
- Widening : $P \nabla Q =$ something.
- Adding rays : $P \nearrow R = \{x + \sum_{r_j \in R} \mu_j r_j \mid x \in P, \mu_j \in \mathbb{Q}^+\}$

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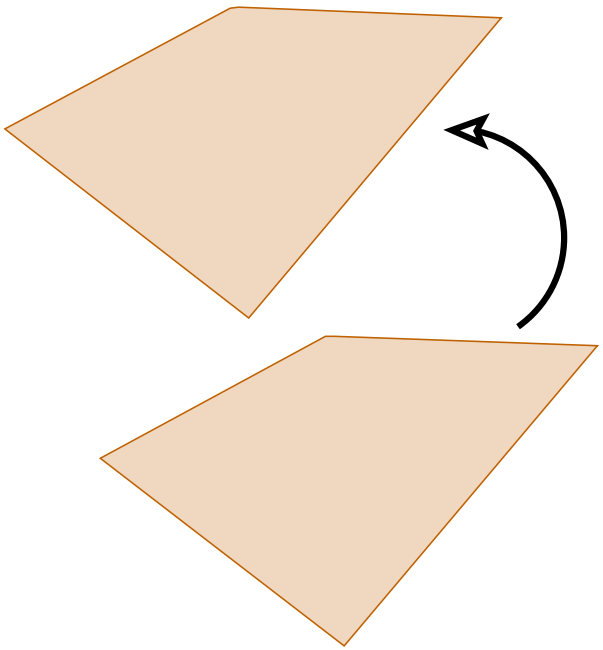

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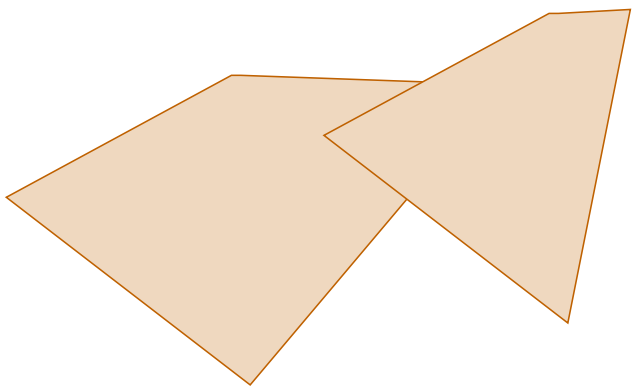

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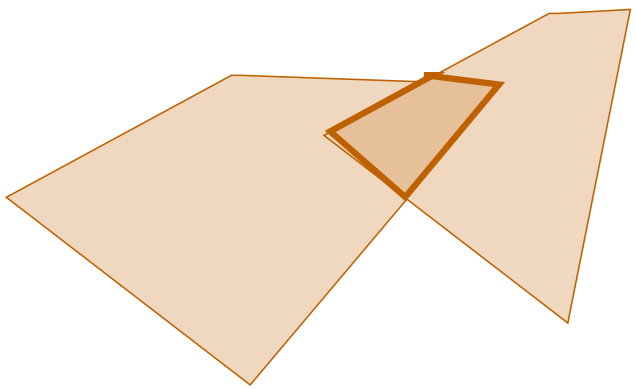

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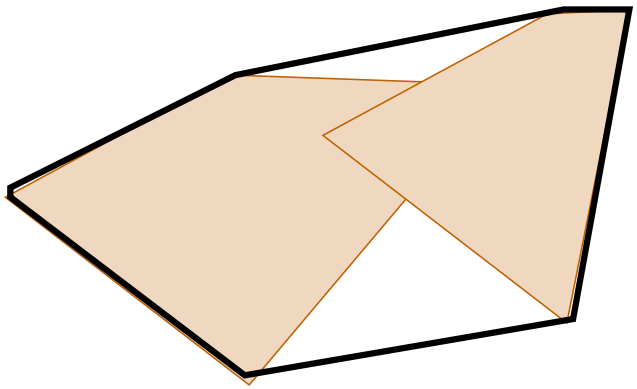

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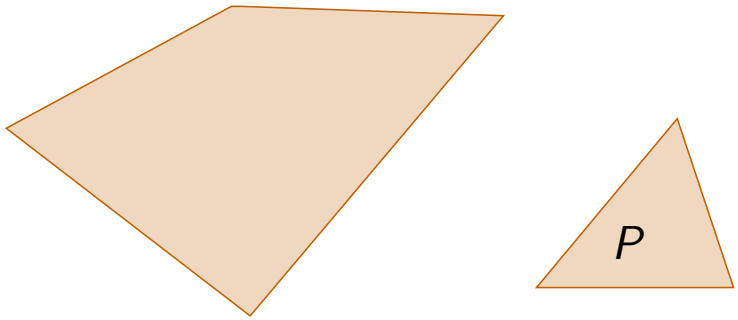

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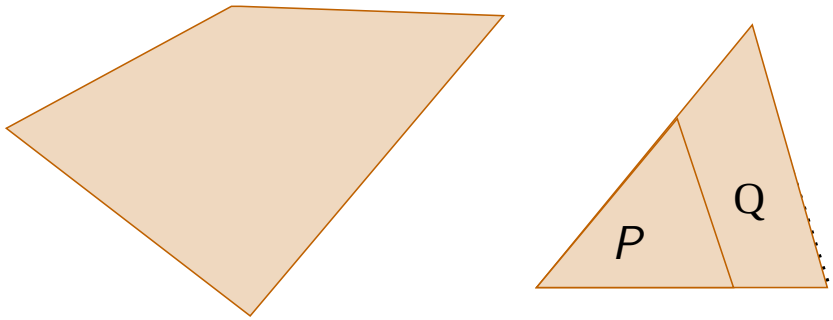

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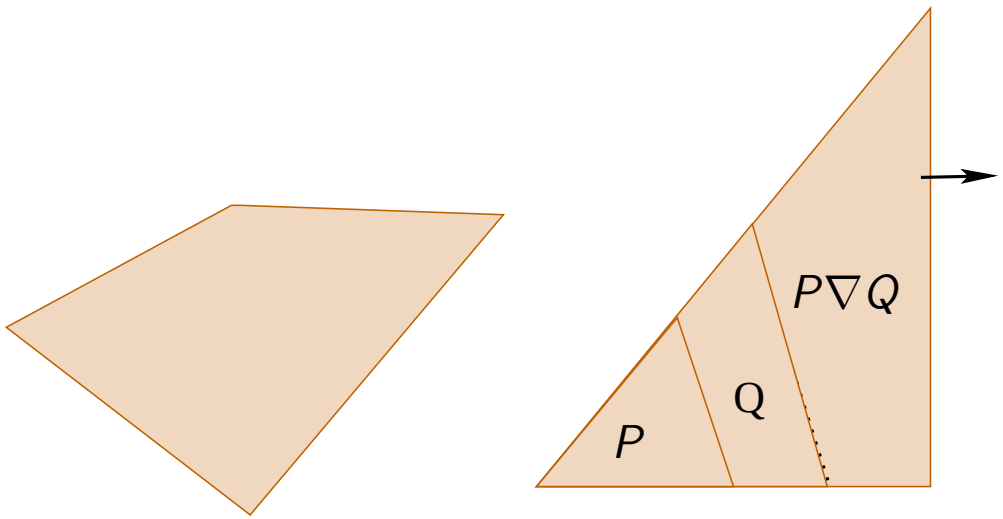

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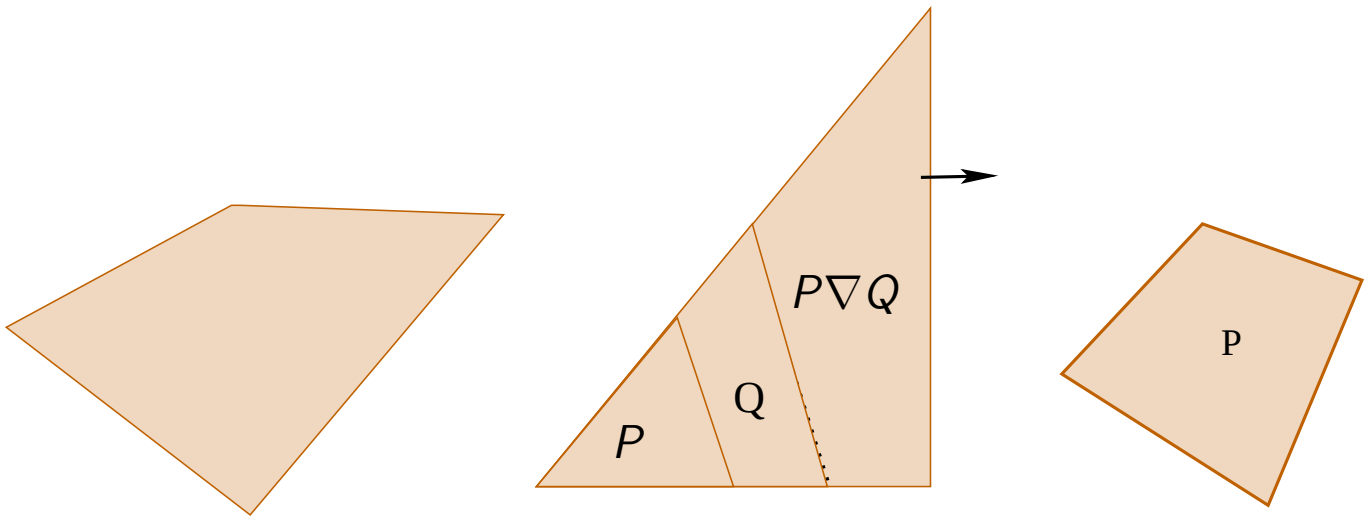

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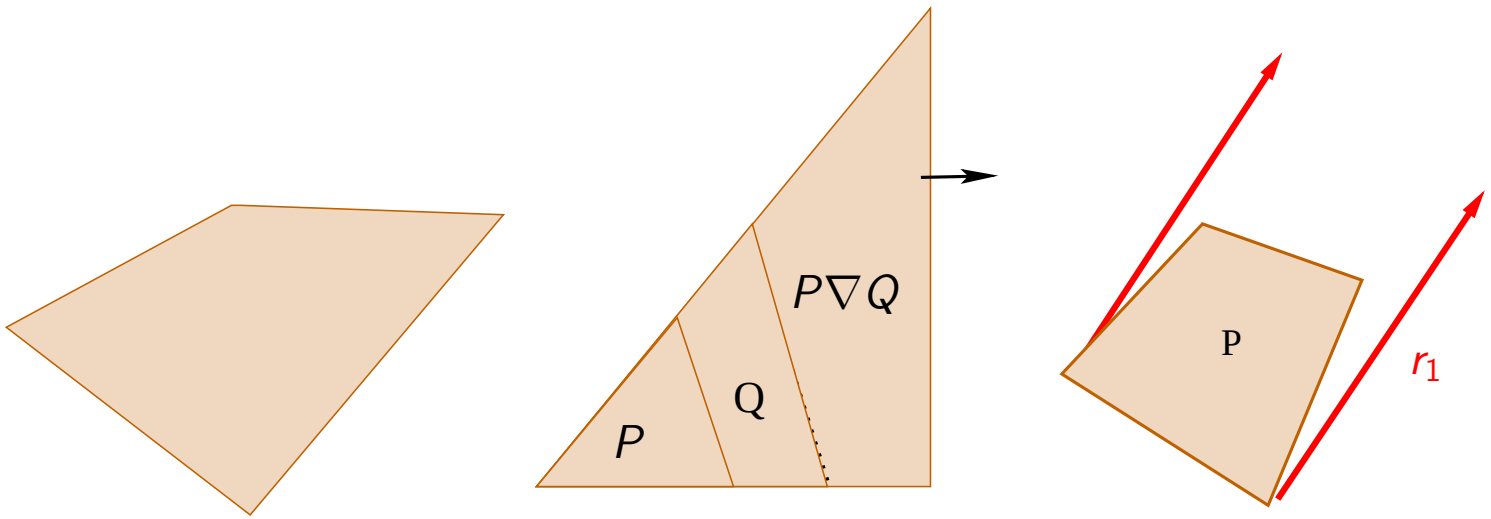

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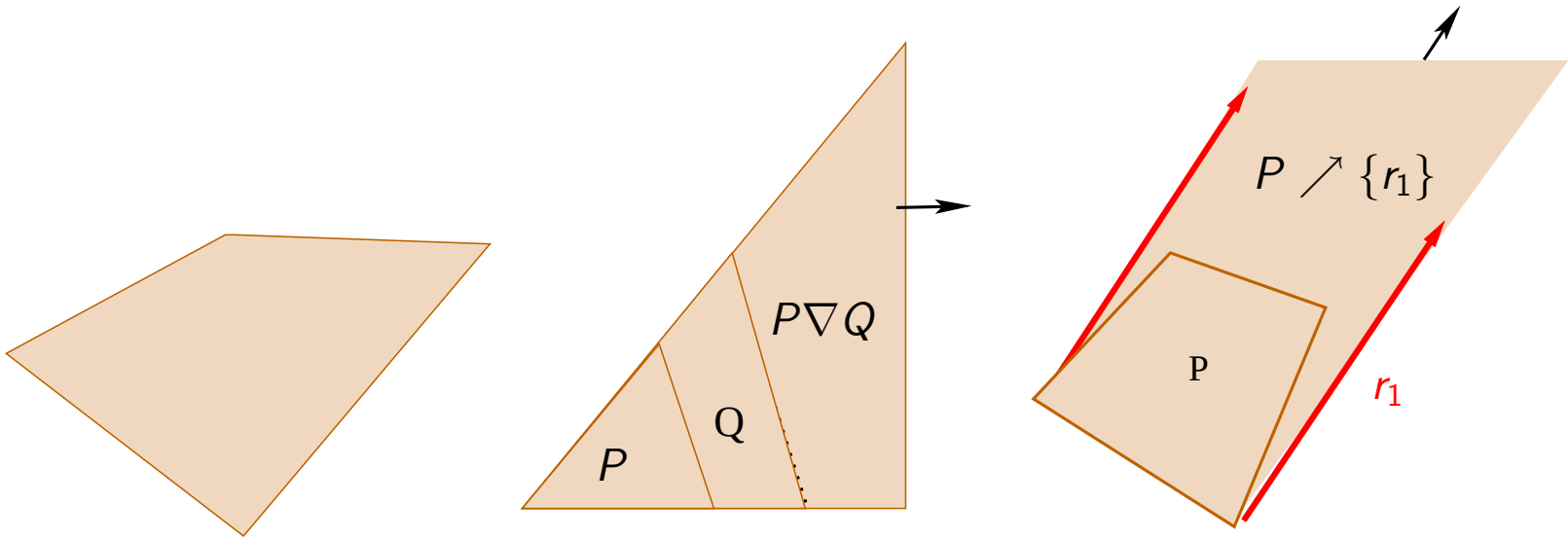

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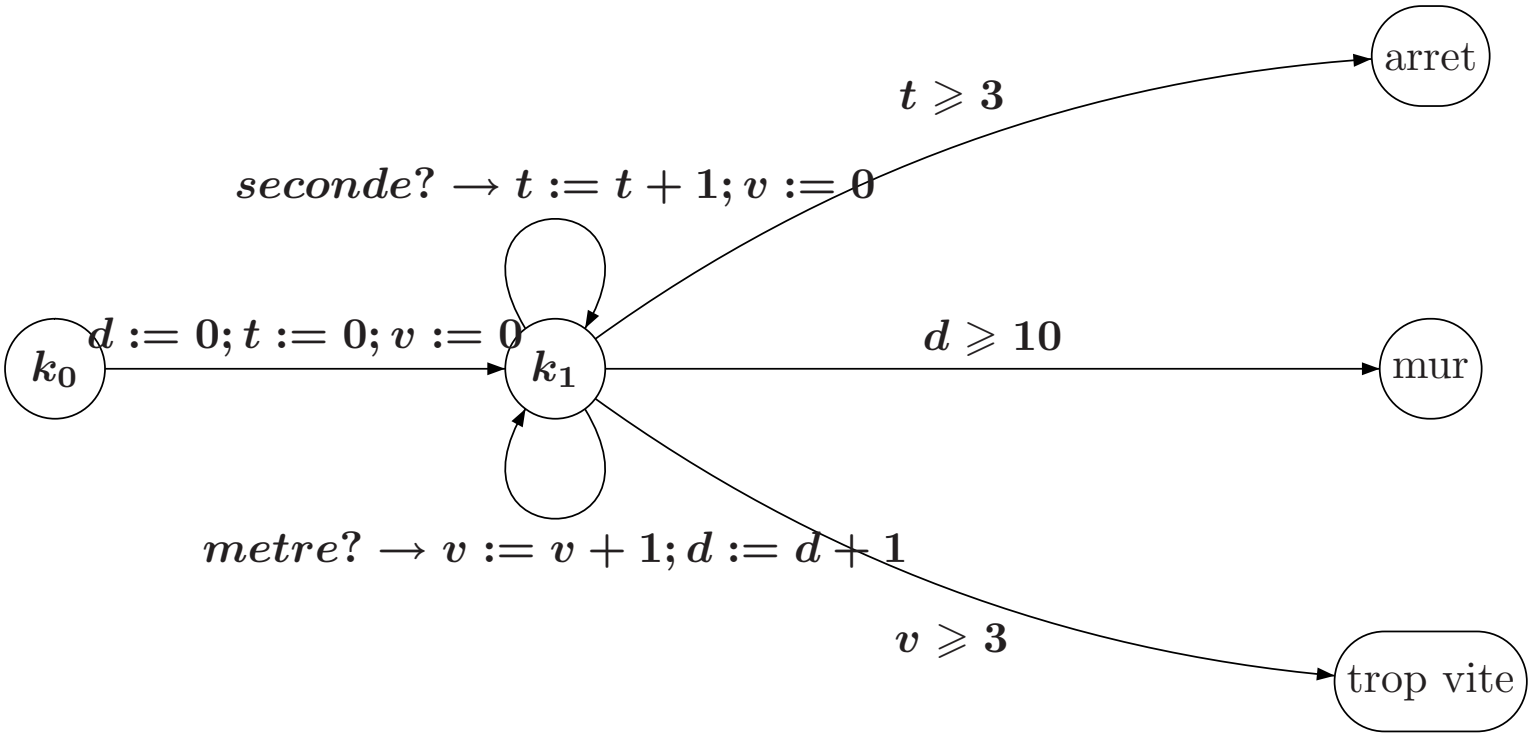
LRA : a toy example, the car (1)



- On reçoit les signaux `metre` et `seconde`.
- $d = nb(metre)$, $t = nb(seconde)$, v vitesse instantanée.

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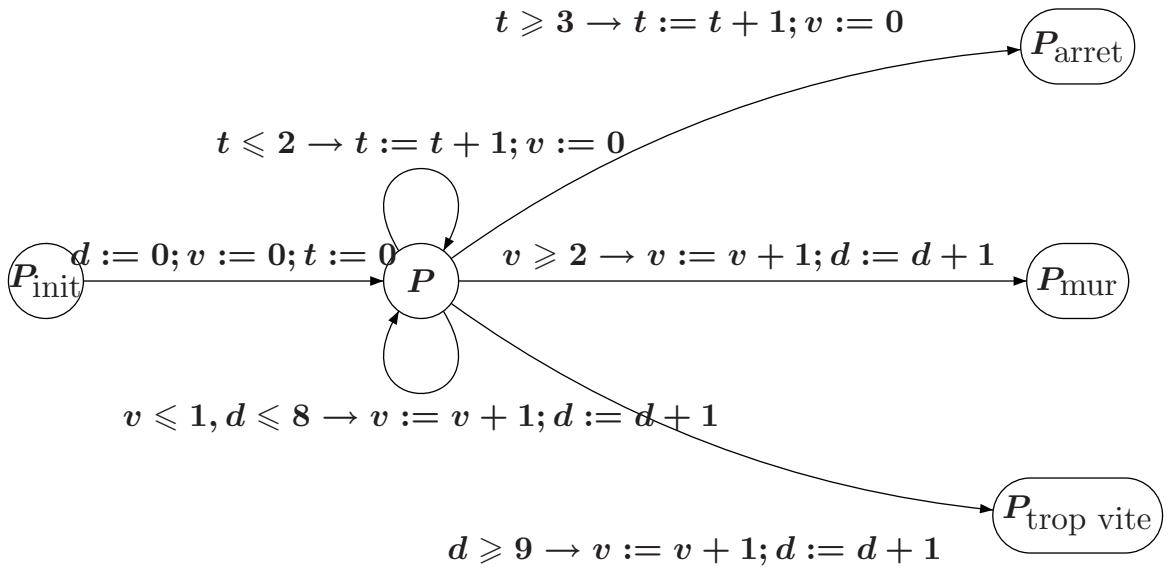
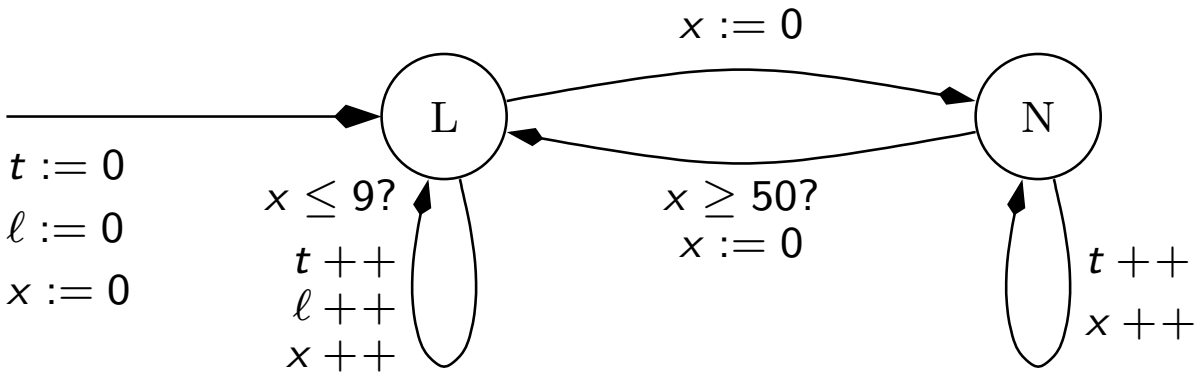
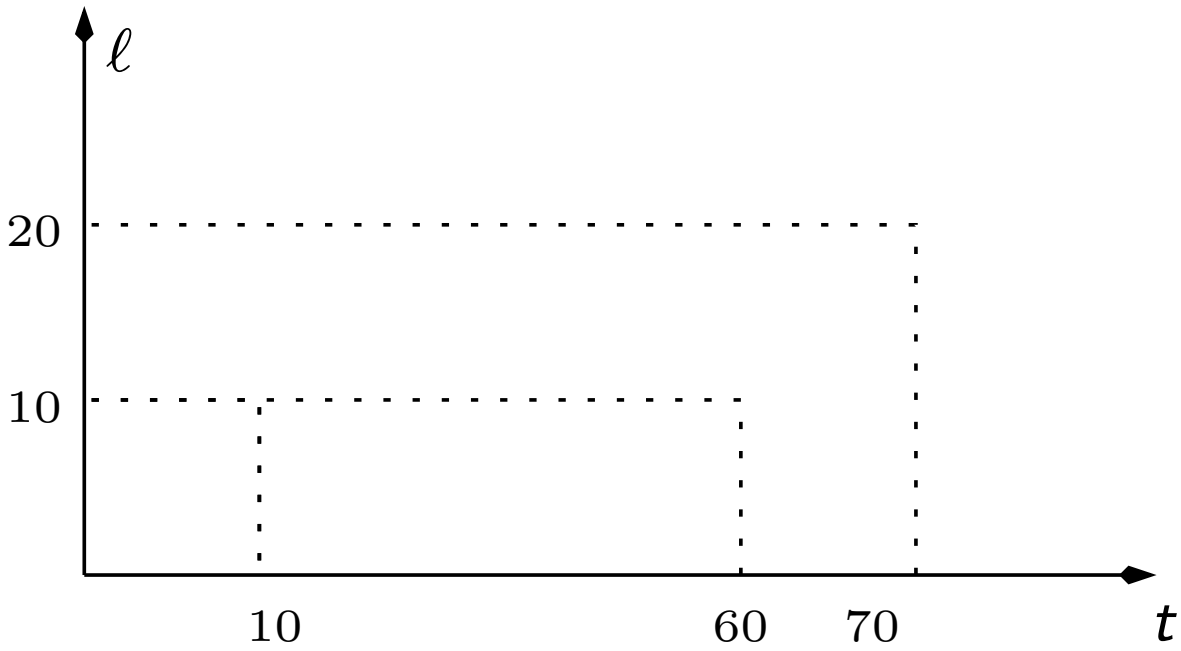


(widening upto $\mathcal{C} = \{v \leq 2, d \leq 9, t \leq 3\}$ et initialisation à $\bot$) :

$$
\begin{array}{lcl}
P^1 & = & \{d = 0; t = 0; v = 0\} \\
P^2 & = & P^1 \nabla (\{d = t = v = 0\} \sqcup \{d = v = 1; t = 0\} \sqcup \{d = v = 0; t = 1\}) \\
 & = & \{0 \leq v = d \leq 2; 0 \leq t \leq 3\} \\
P^3 & = & P^4 = \{0 \leq v \leq d \leq 2t + v; t \leq 3; v \leq 2\}
\end{array}
$$

Example - Gaz Burner - 1





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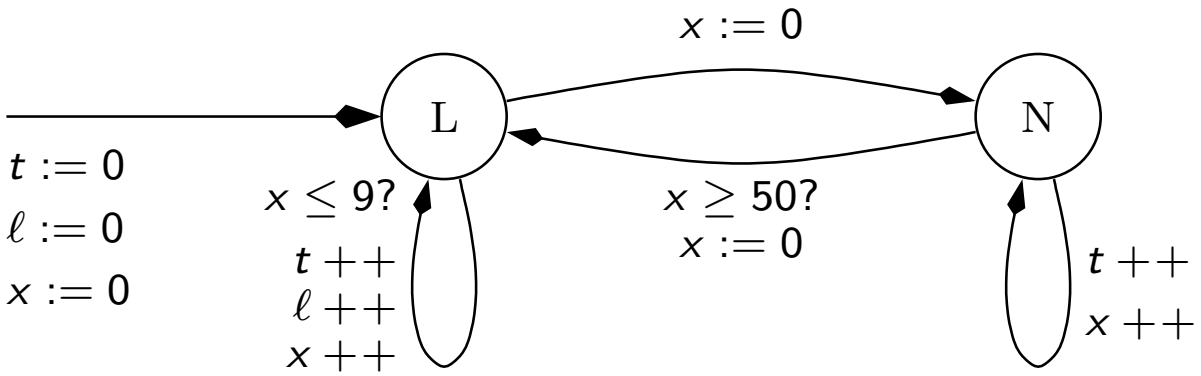

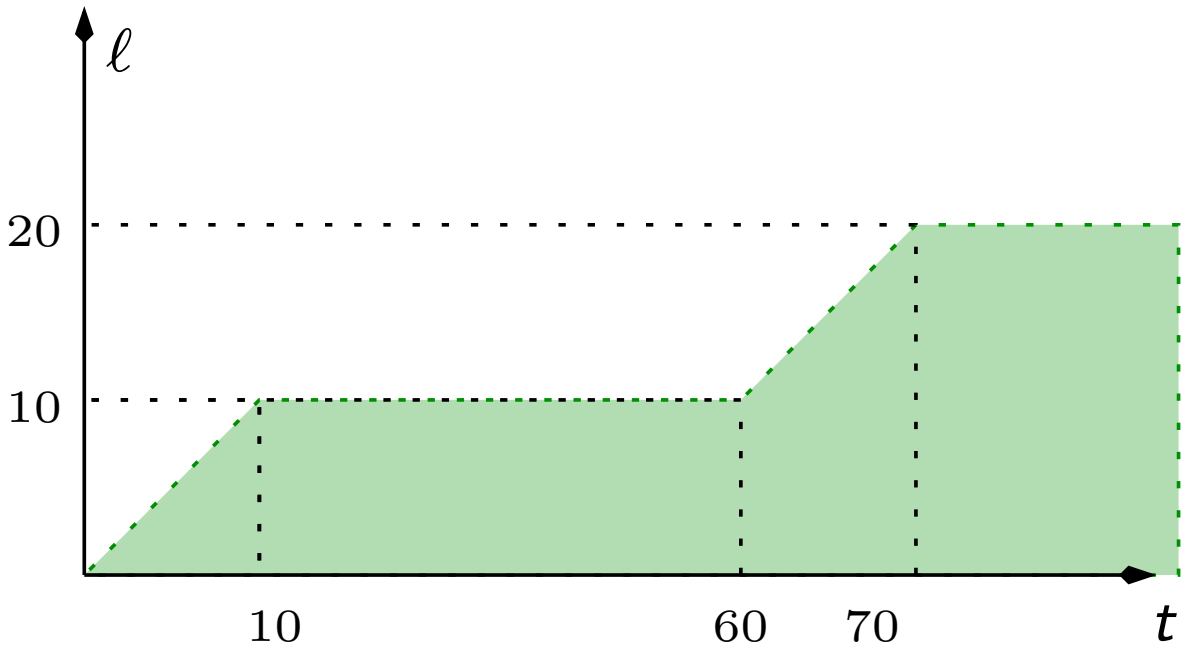

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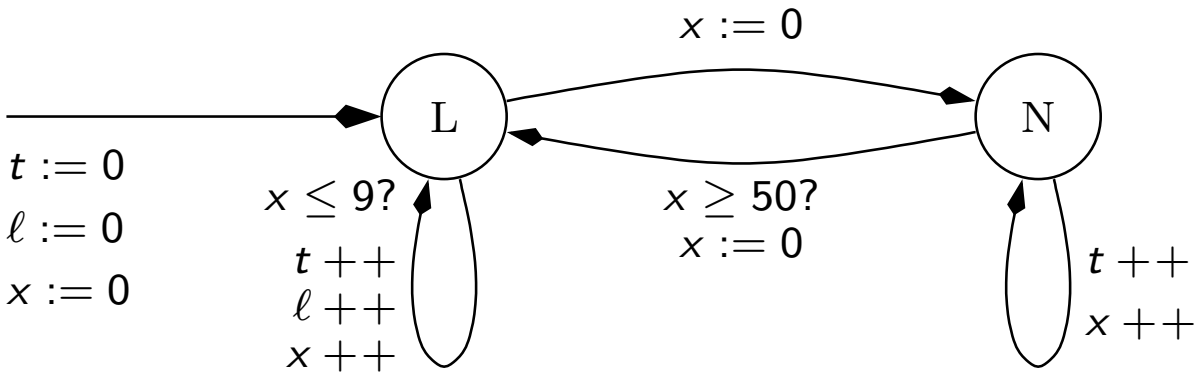
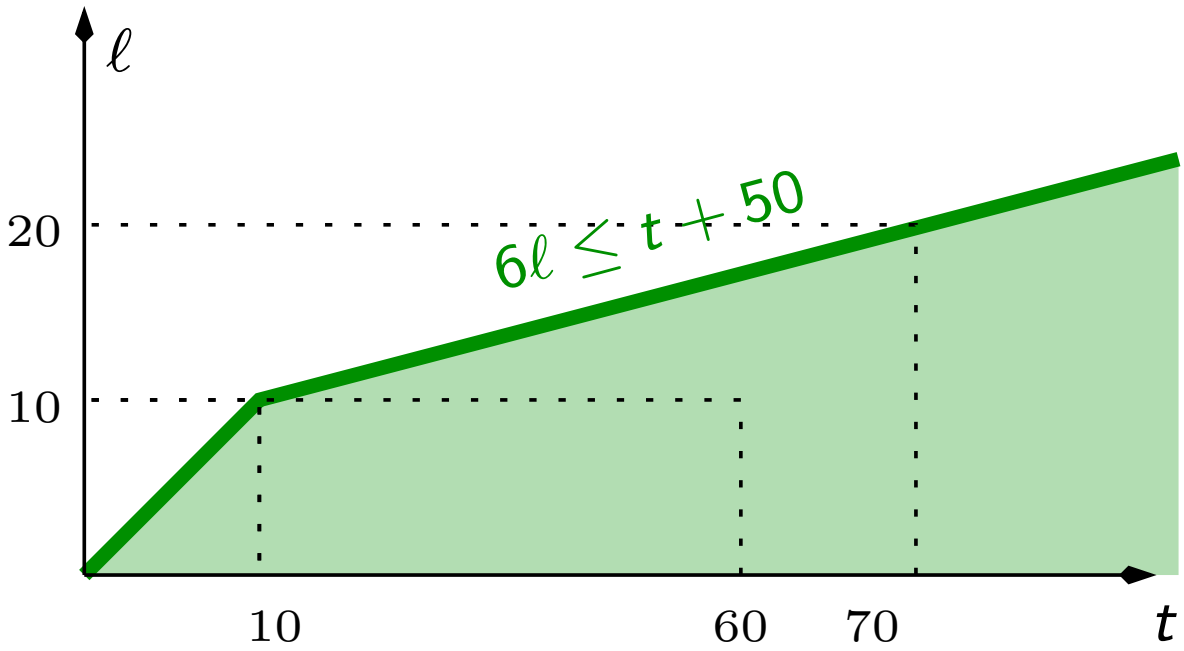
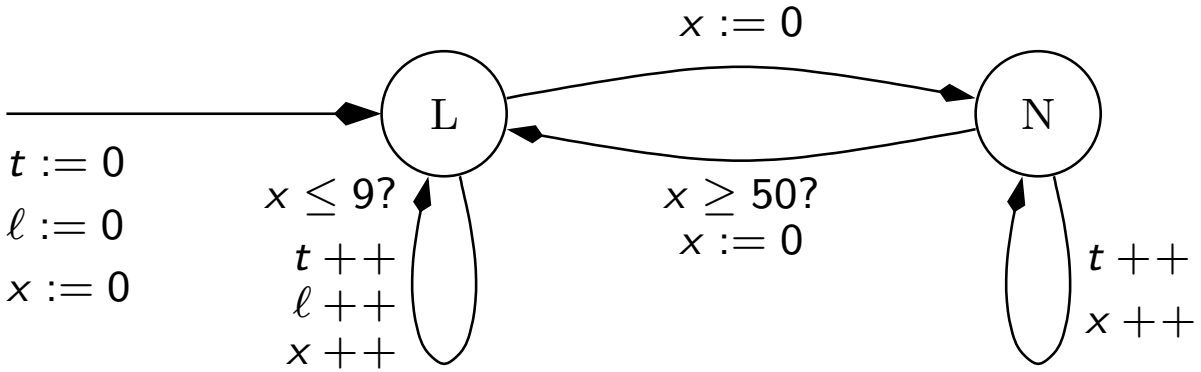
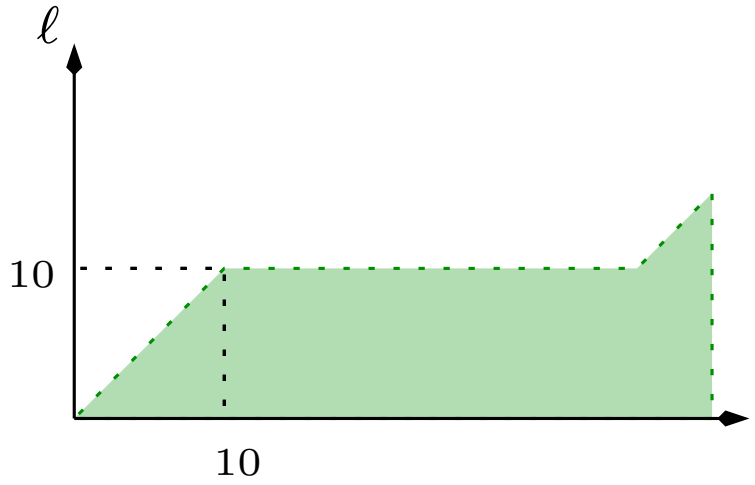




Example - Gaz Burner - 2



Standard LRA algorithm



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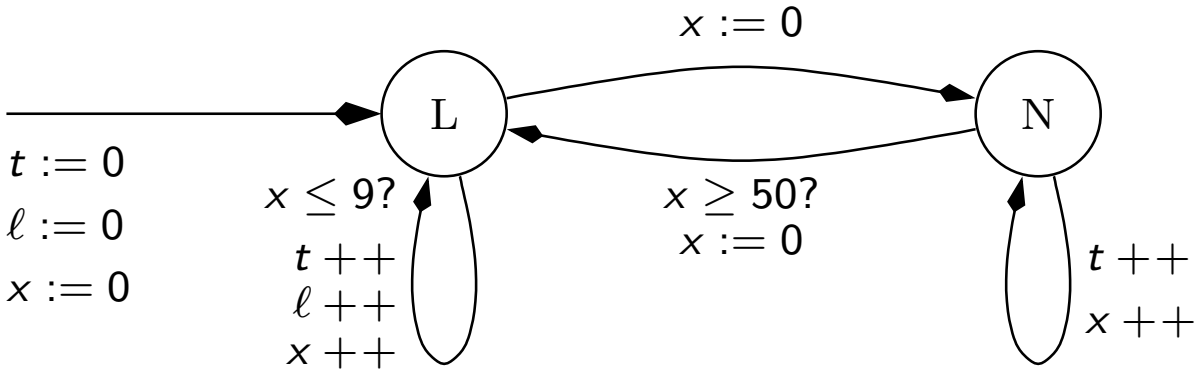

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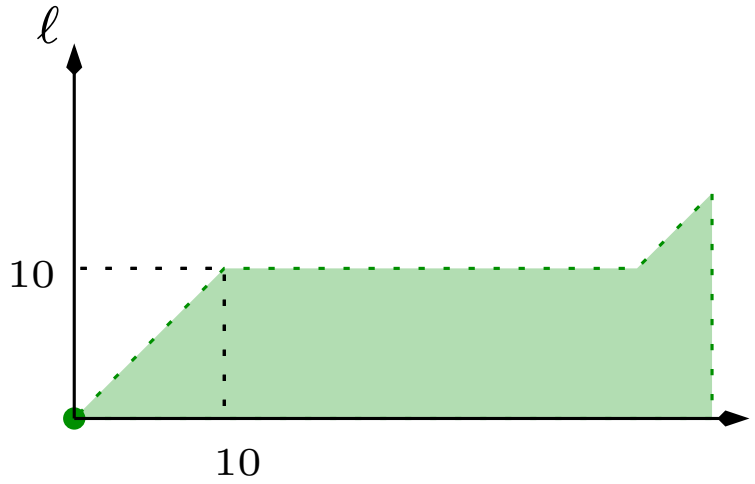

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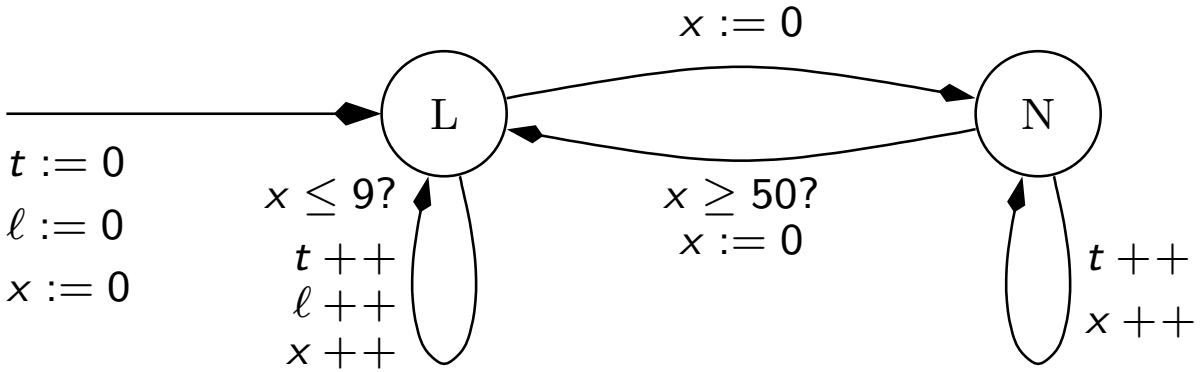

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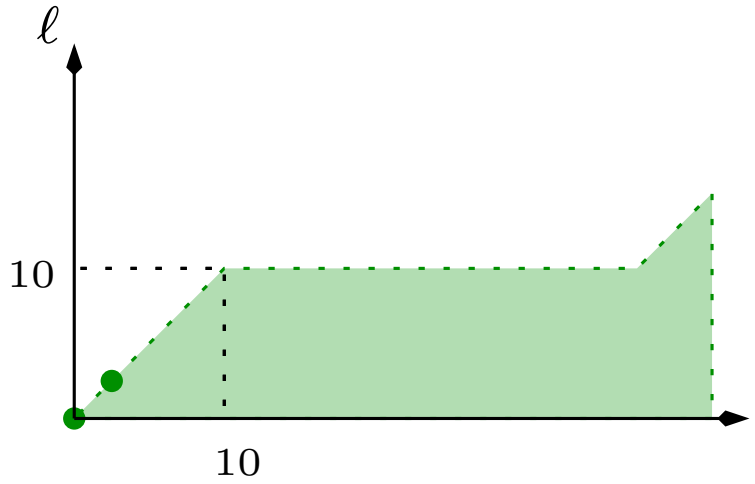

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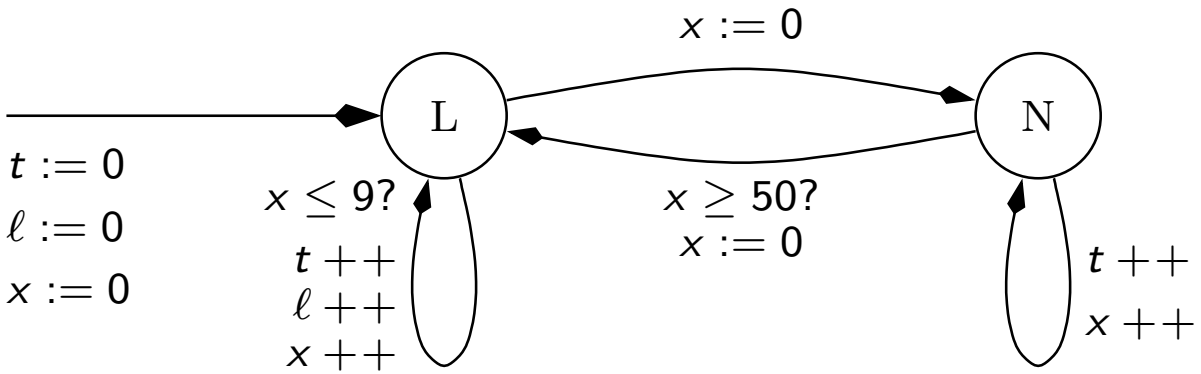

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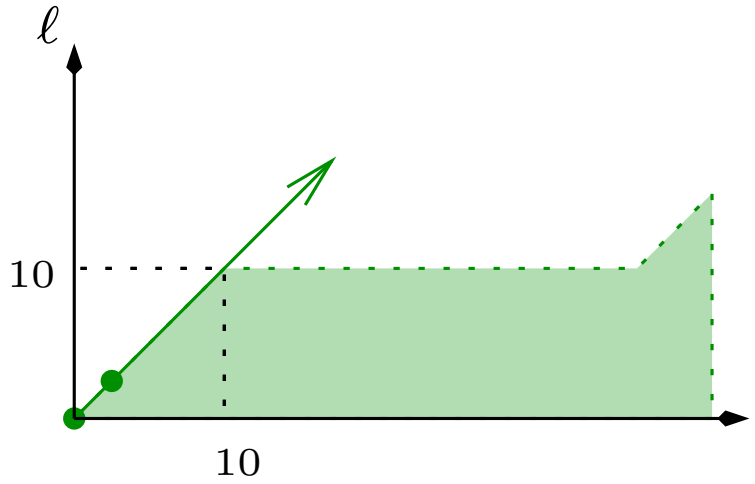

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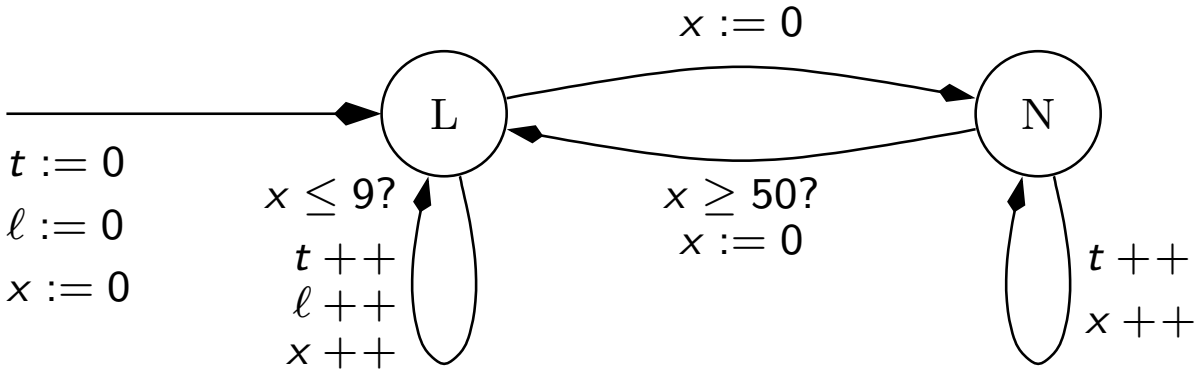

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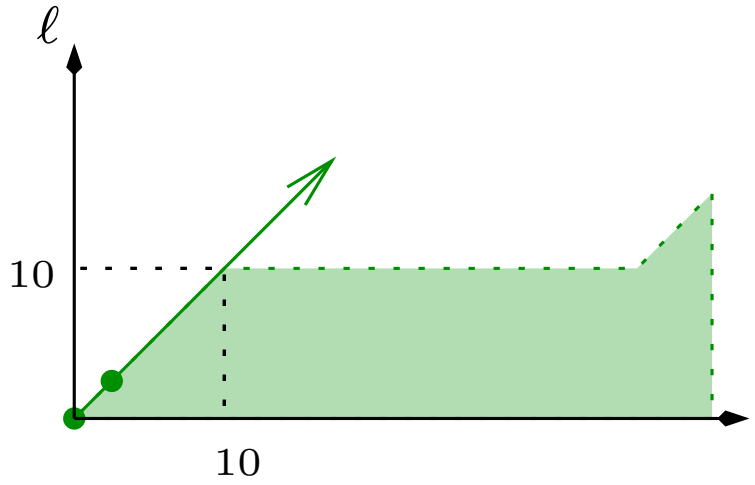

- **lack of precision** : descending sequence will not recover

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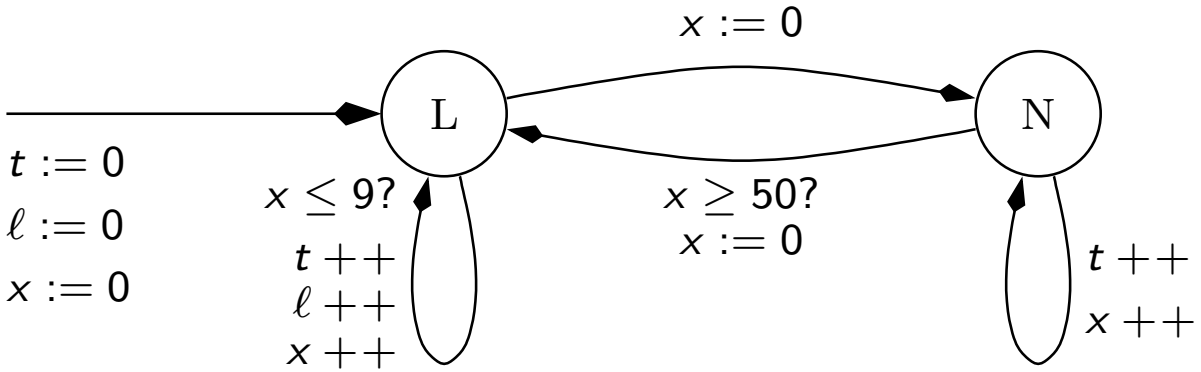

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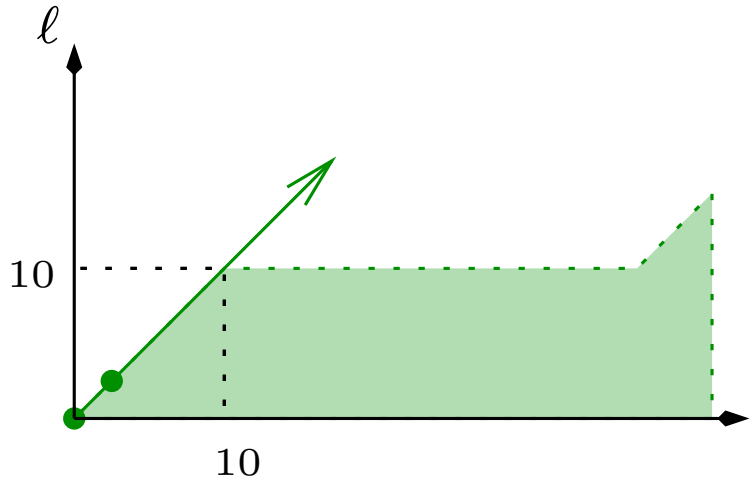

- **lack of precision** : descending sequence will not recover
- **delaying ?** 60 times !

Existing techniques (1)

Linear Relation Analysis (LRA) and Widening

- Approximate results
- Possible improvements :
  - **Delaying** the application of the widening, drawback : the cost.
  - **Changing** the operator. [Bagnara&Hill&Zafanella], drawback : no result on the global convergence.
  - Alternating widening and narrowing [Gopan&Reps : CAV 2006], drawback : the cost.

Existing techniques (2)

Acceleration

[Boigelot&Wolper, Common&Jurski, Finkel&Sutre&Leroux]

- Computing the **exact effect** of loops on integer sets.
- Encoding : Automata representing Presburger Formula
- **Drawbacks** : restricted class of programs, semi-algorithms, high complexity

▶ Our global objective : "abstract" acceleration **at low cost** for convex polyhedra combined with widening.

▶ More precisely : compute the convex hull of the exact reachable states.

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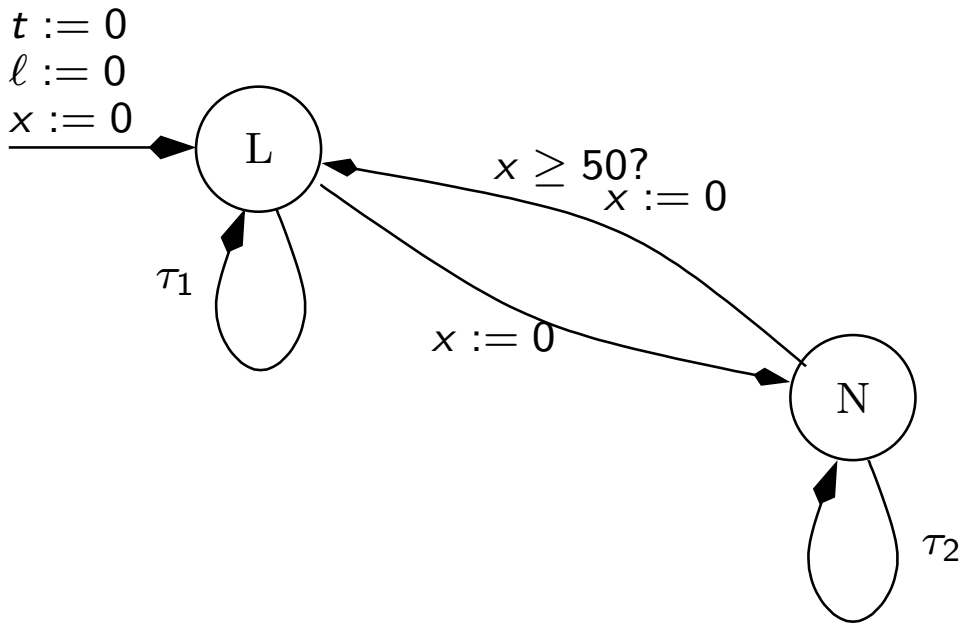
Acceleration within LRA

We want to replace the loops $(\tau_i : g_i \rightarrow a_i)$



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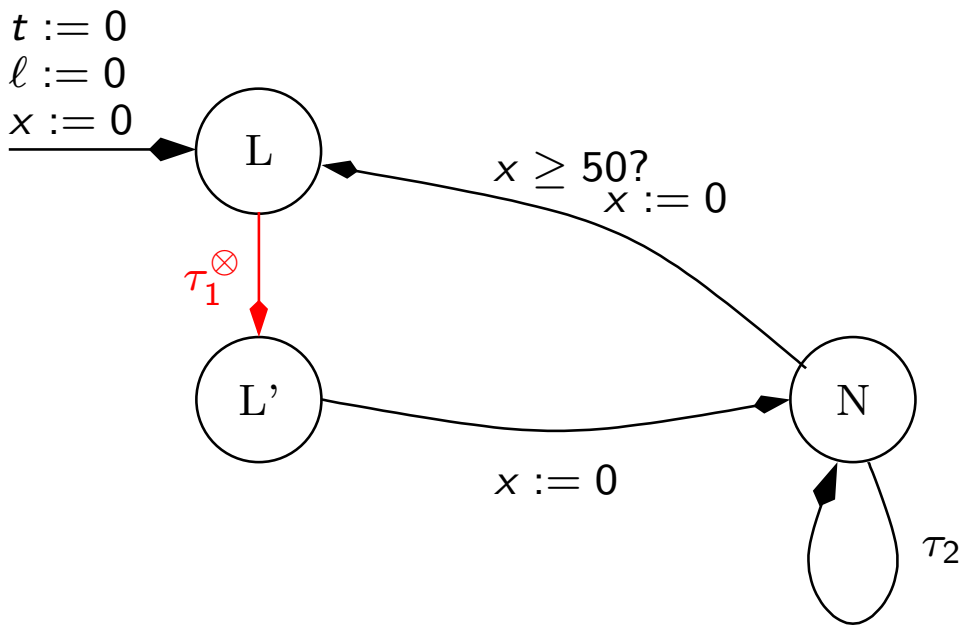

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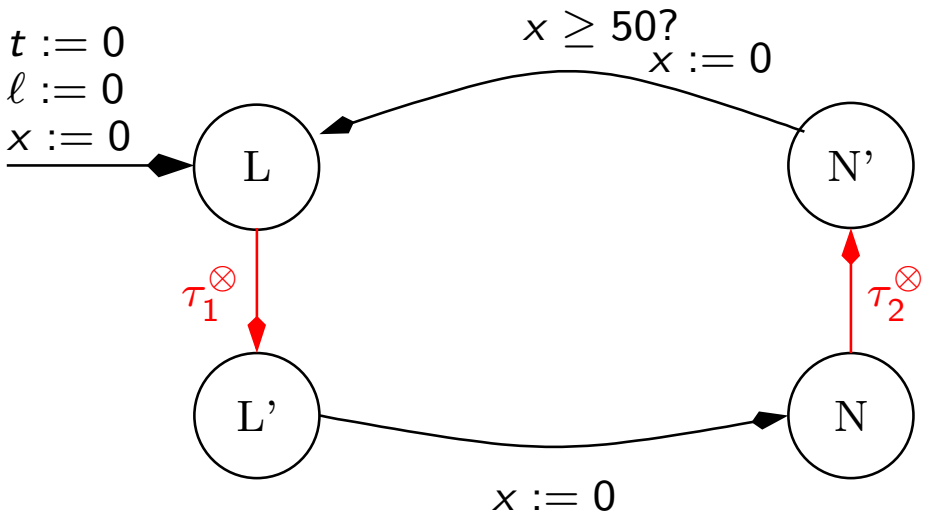

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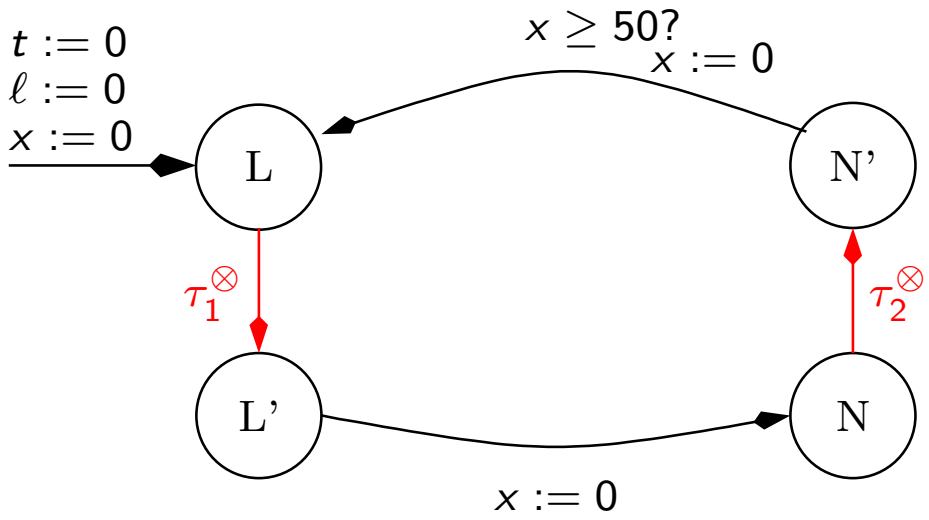

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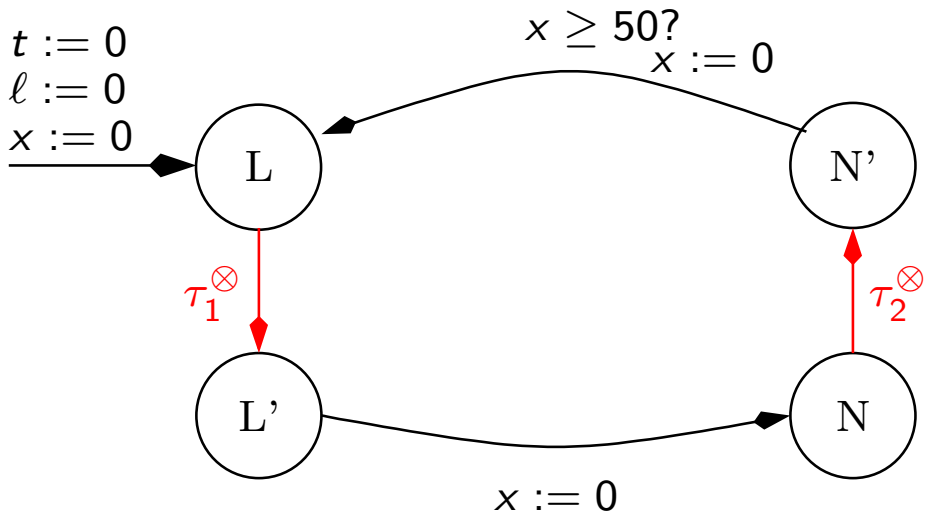
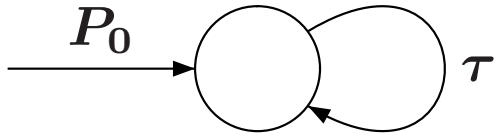


- $\tau_i^{\otimes}$ summarizes the effect of **any** number of applications of τ_i
- global loop : **accelerate** or **widen**

Simple loops

We want to **characterise** $\tau^*(P_0) = \bigcup_{i \in \mathbb{N}} \tau^i(P_0)$, with :

$\tau(x) = \text{if } Ax \leq B \text{ then } Cx + D \text{ else } x$



Previous result : [Boigelot99,Leroux02] : if $\exists p, C^{2p} = C^p$ and φ a Presburger set, then $\tau^*(\varphi)$ is a computable Presburger set.

New result (not in the SAS paper) If $\exists p, C^{2p} = C^p$, then computing $\tau^*(P_0)$ reduces itself to computing $\tau'^*(P'_0)$:

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We want to **characterise** $\tau^*(P_0) = \bigcup_{i \in \mathbb{N}} \tau^i(P_0)$, with :

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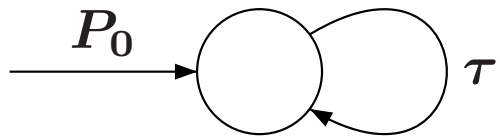

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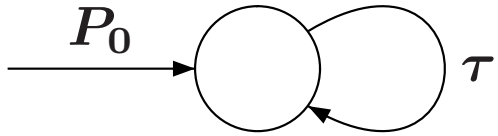

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$$\tau(x) = \text{ if } Ax \leq B \text{ then } x + D \text{ else } x$$

- (obvious) Proposition

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- Discrete vs Dense acceleration

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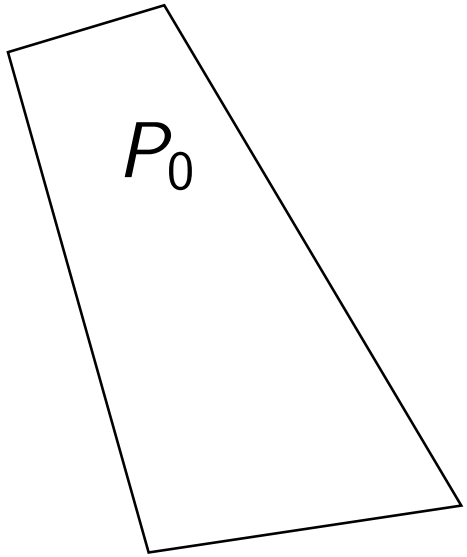

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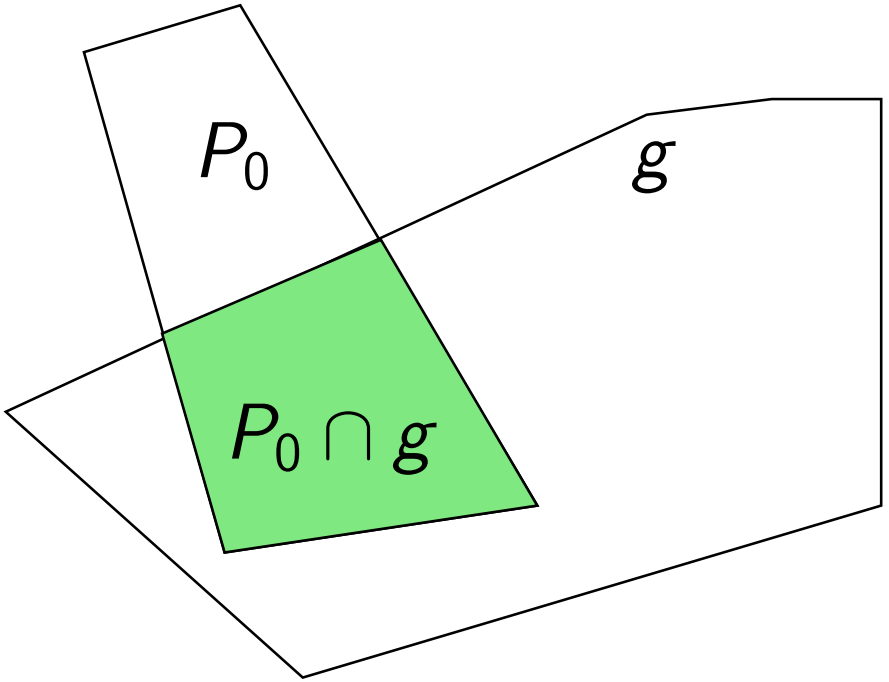

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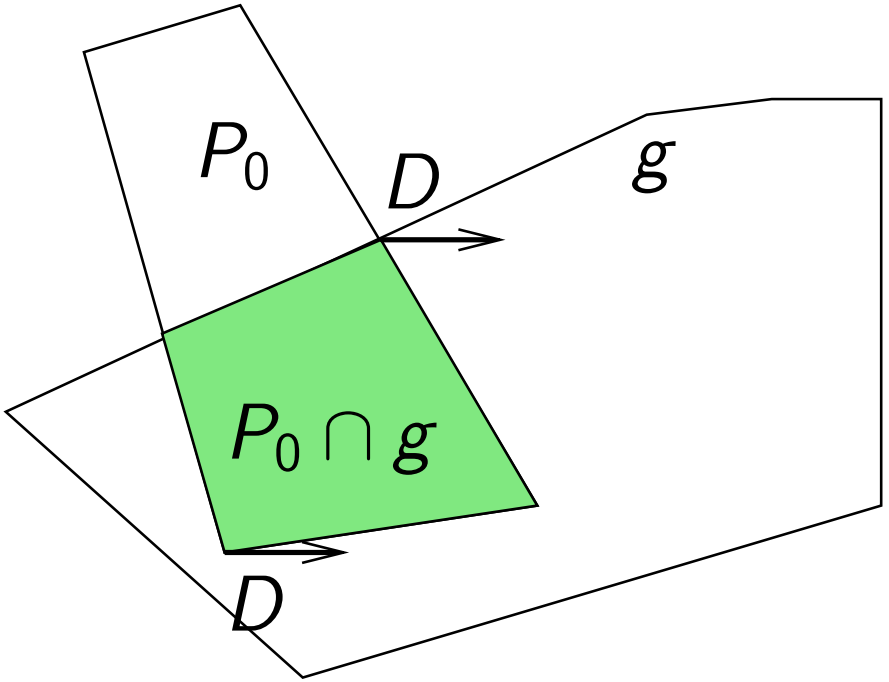

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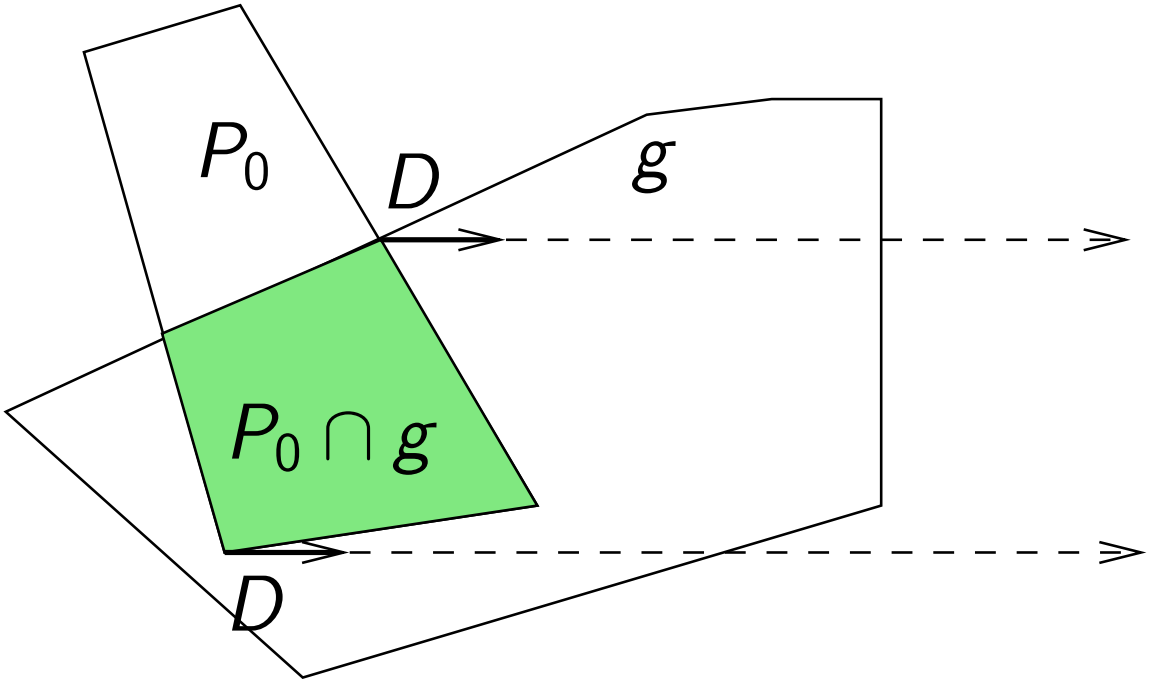

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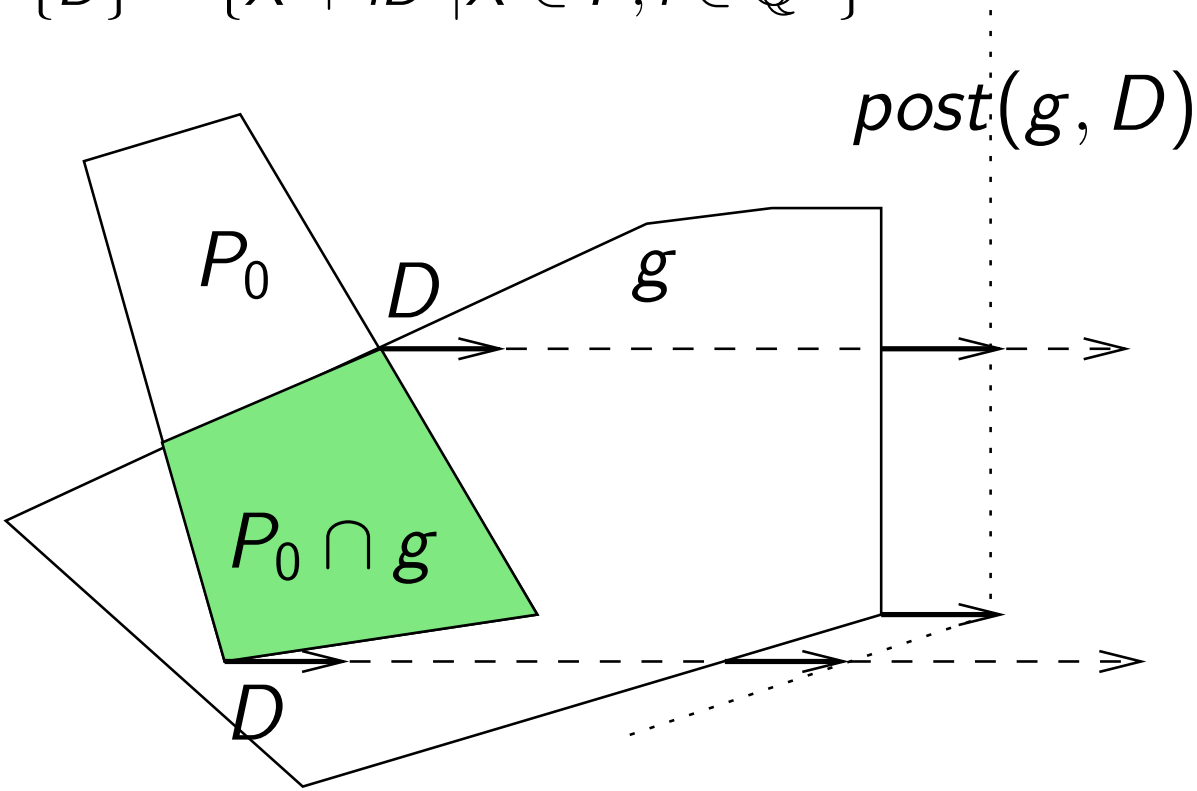

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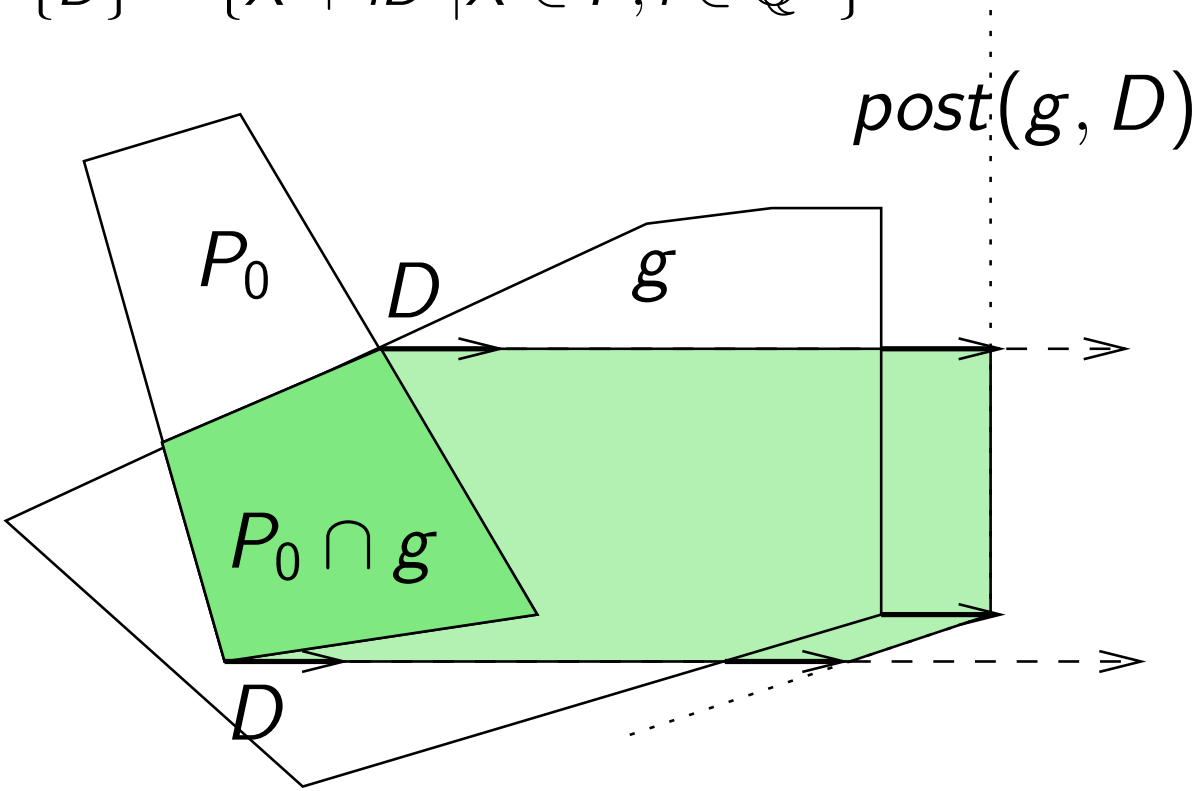

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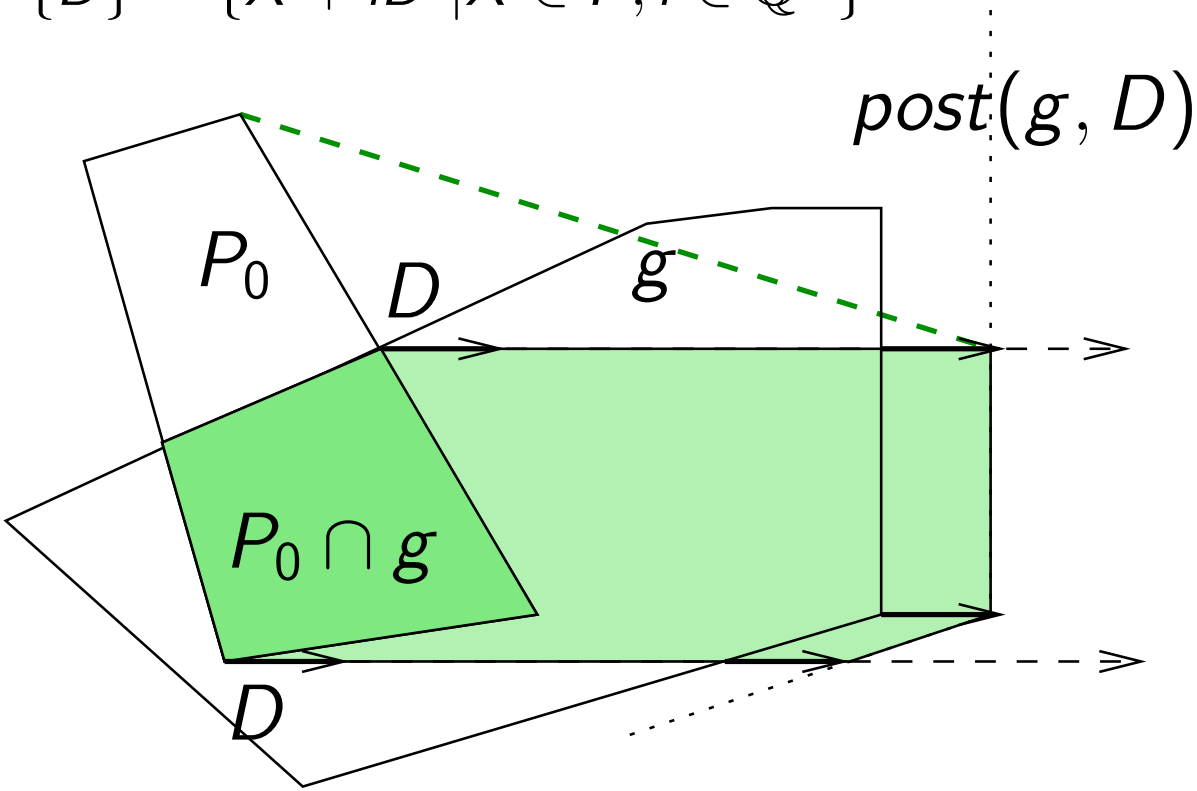

Finite Monoide simple loops

What do we lose ?

$$\tau = \begin{cases} g = (x \leq 7) \\ a = (x := x + 2) \end{cases}$$
$$P_0 = \{x = 0\}$$

$$\tau^*(P_0) = \{0 \leq x \leq 8\}$$

$$\begin{aligned} \tau^{\otimes}(P_0) &= P_0 \nearrow (1) \cap (x - 2 \leq 7) \\ &= \{0 \leq x \leq 9\} \end{aligned}$$

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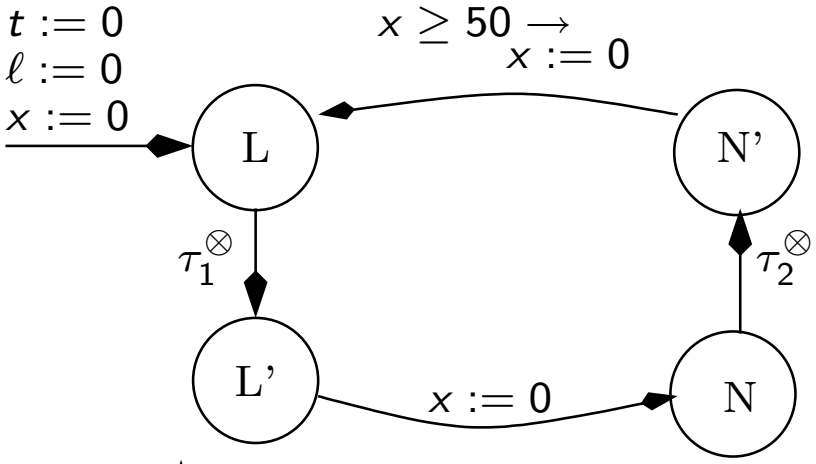

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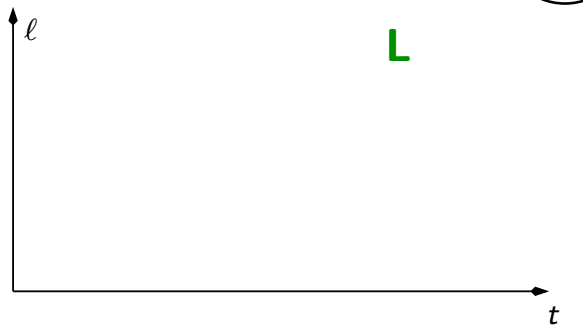

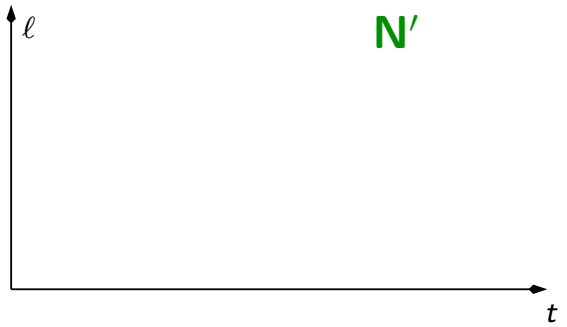

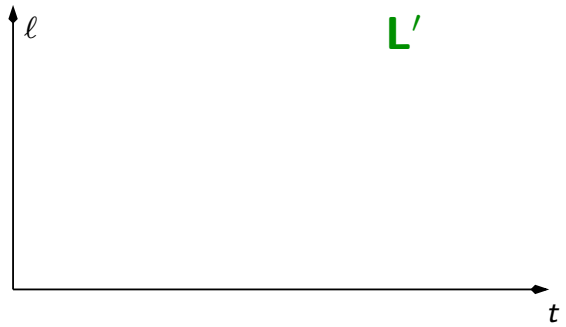

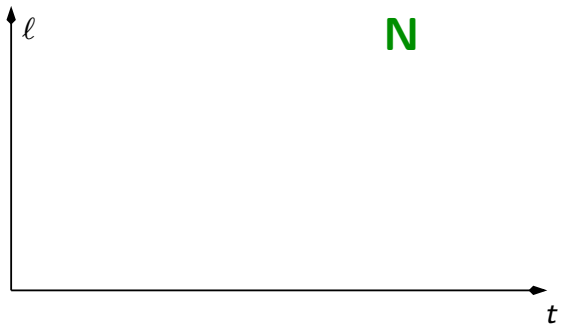

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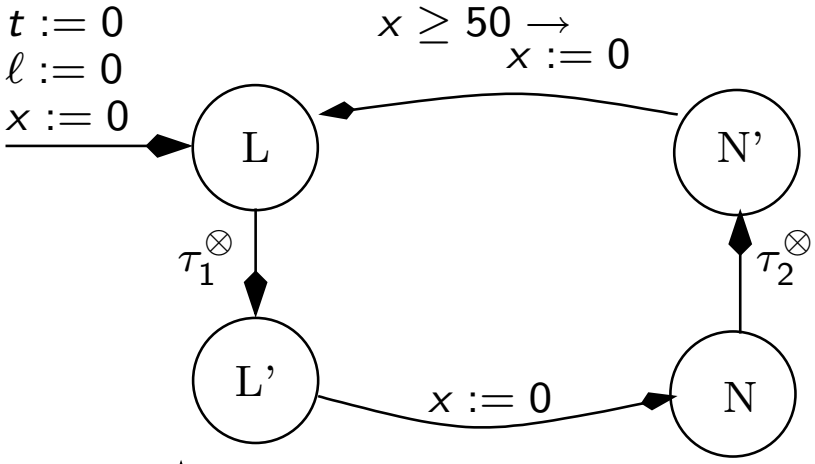

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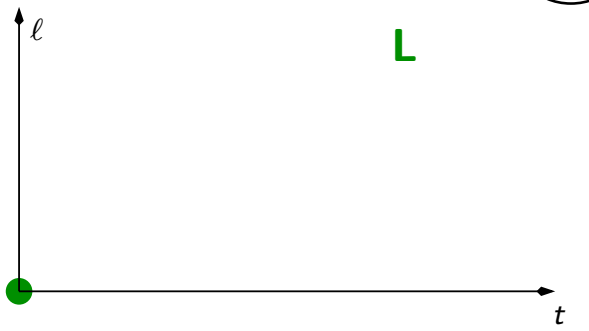

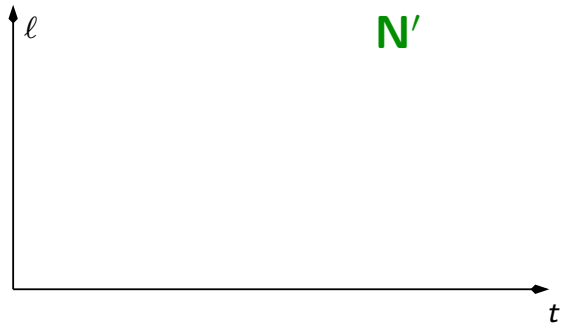

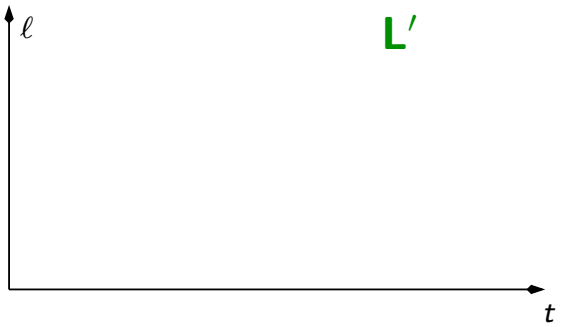

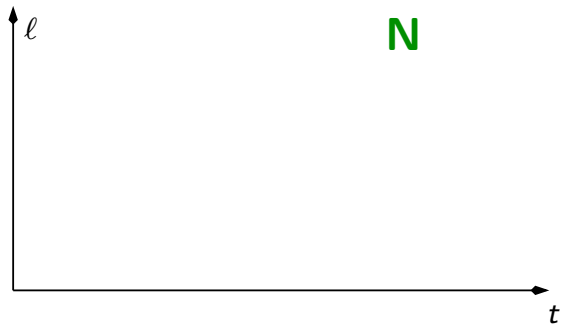

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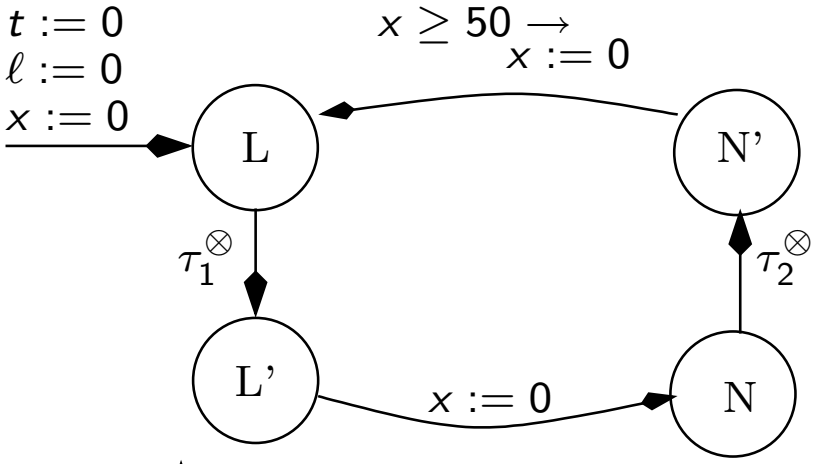

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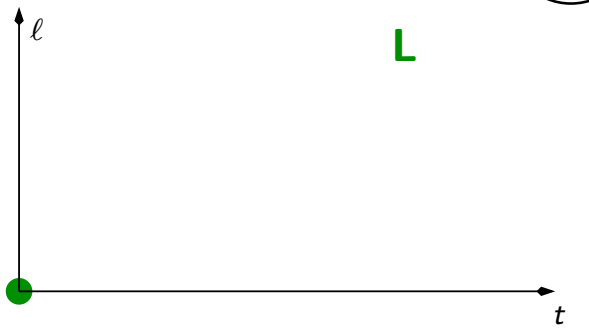

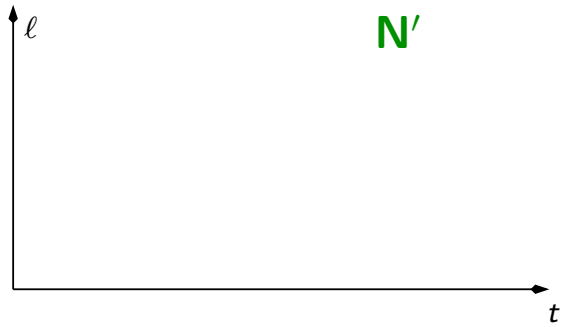

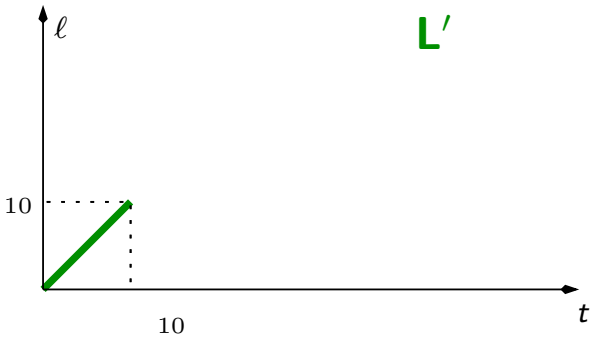

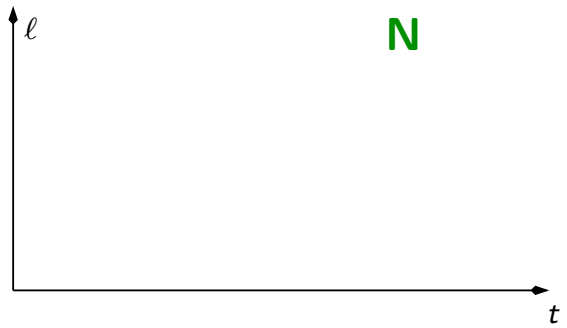

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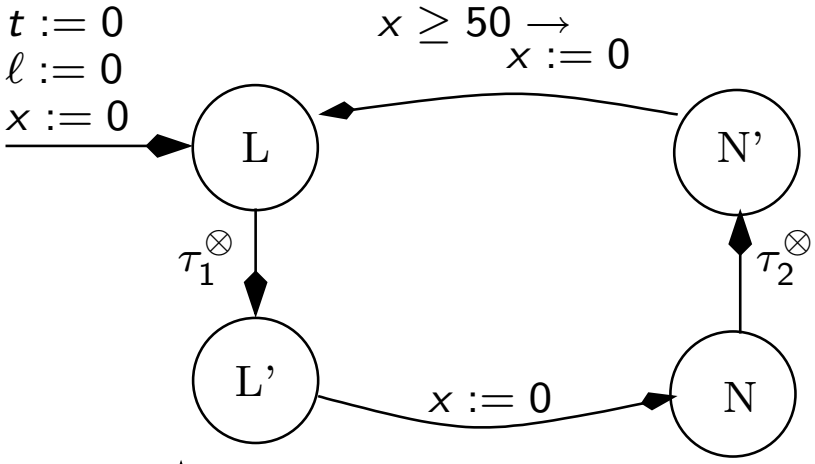

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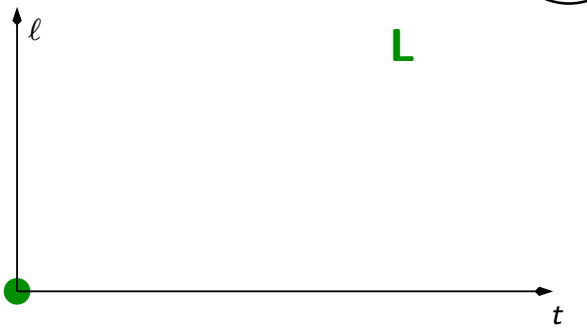

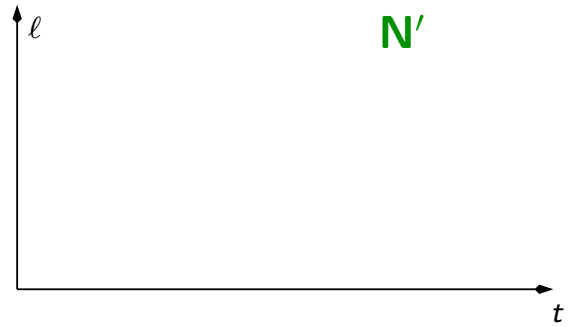

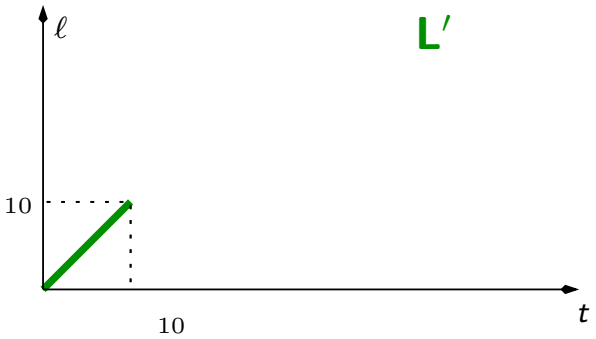

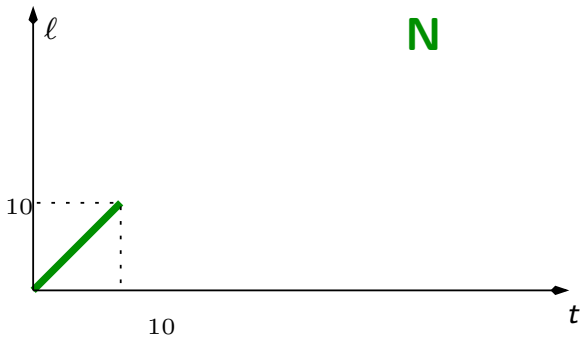

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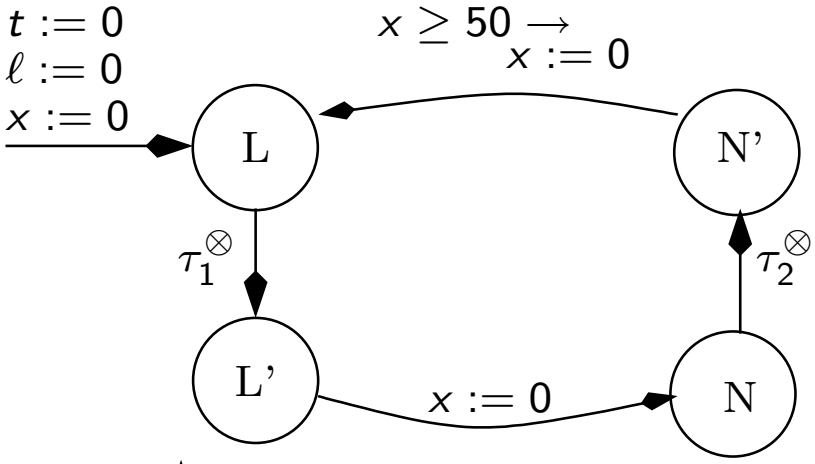

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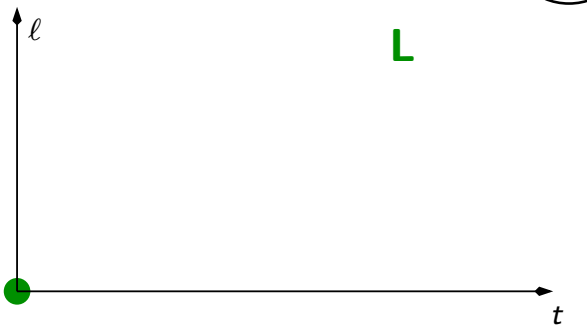

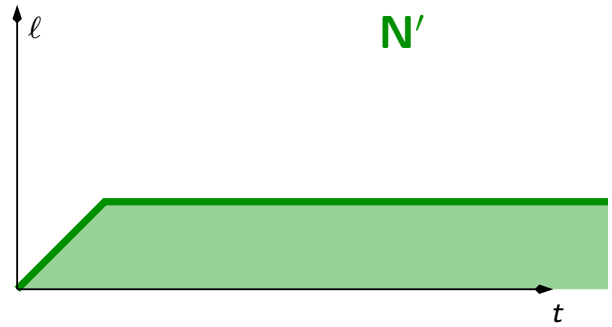

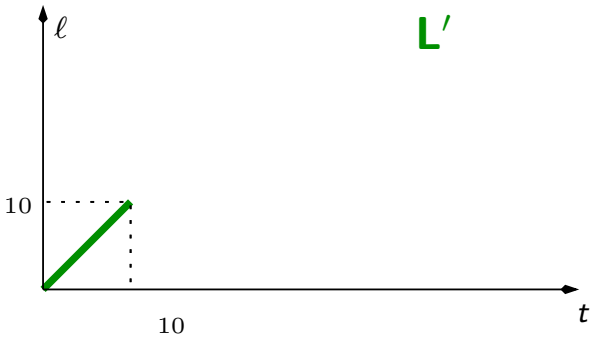

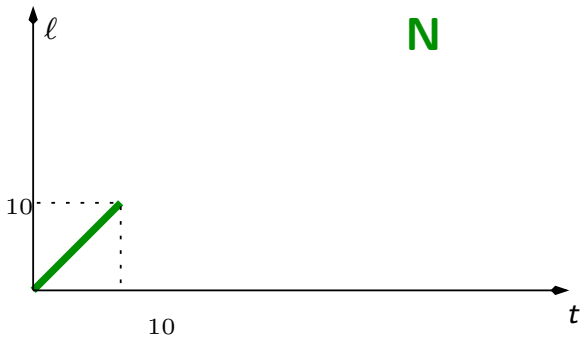

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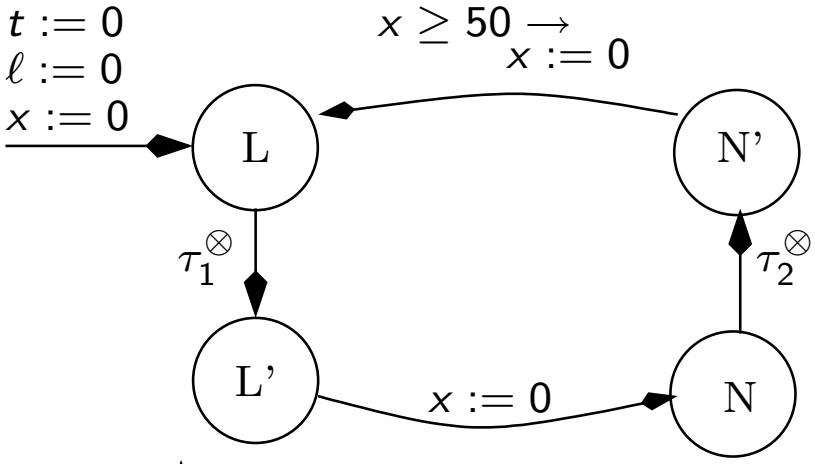

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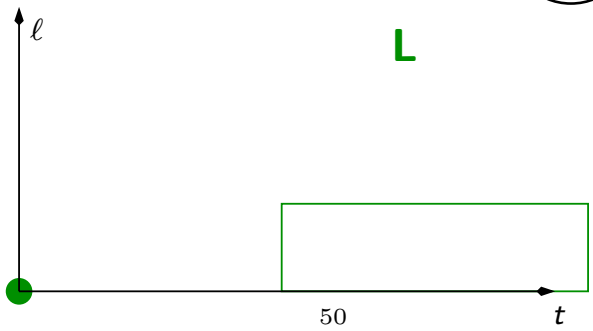

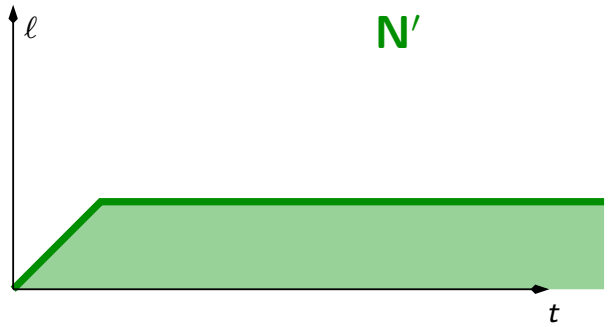

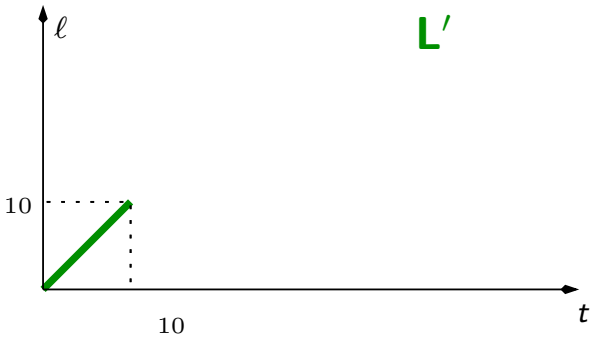

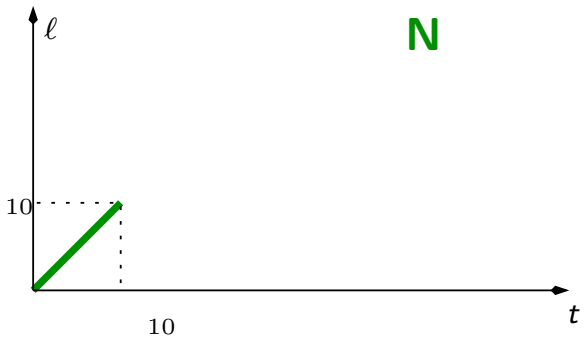

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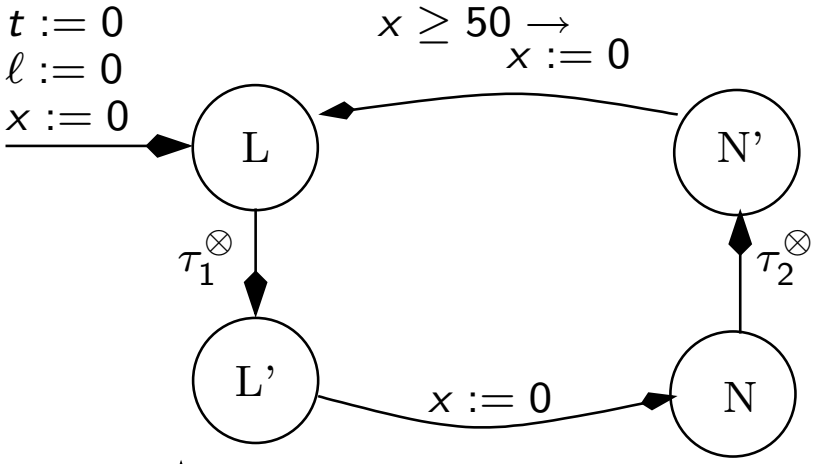

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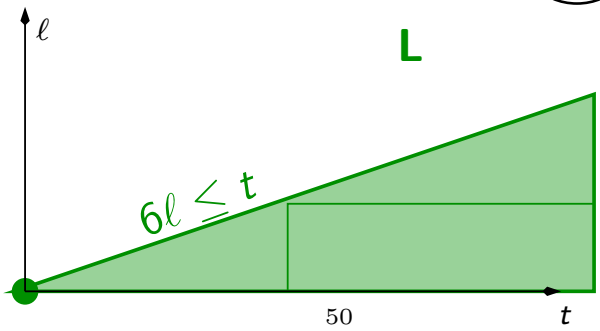
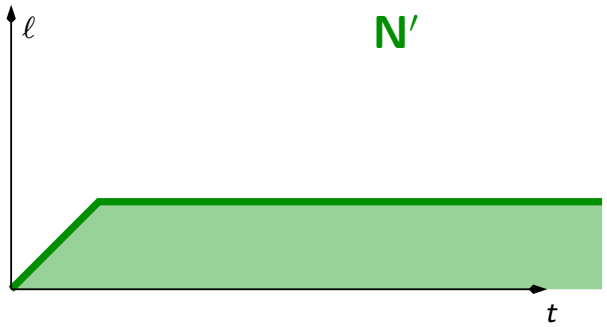
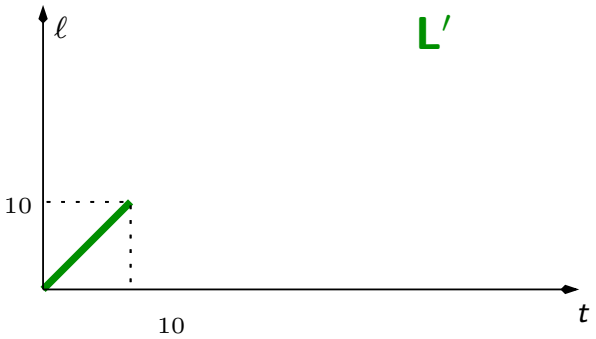
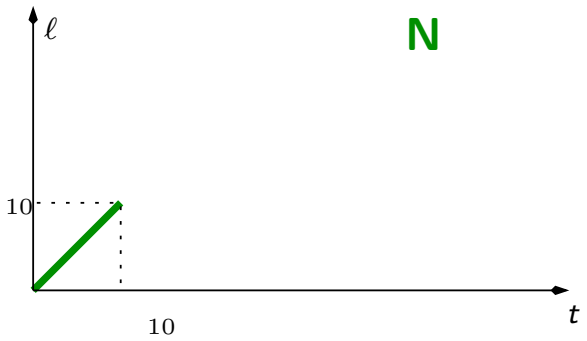
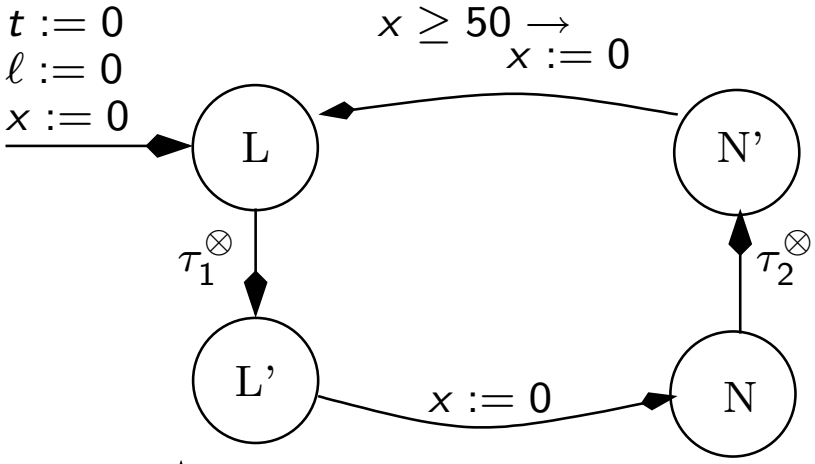








Ex. : gaz burner with acceleration



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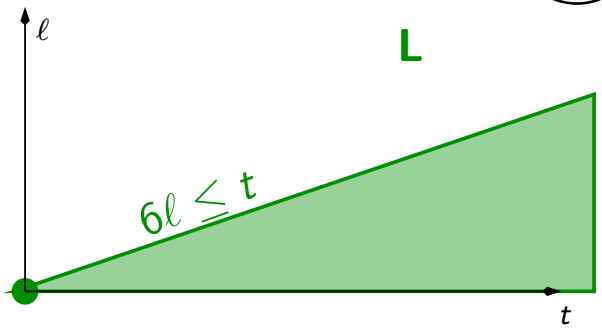

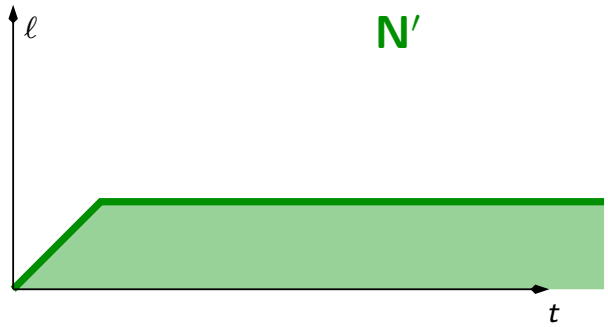

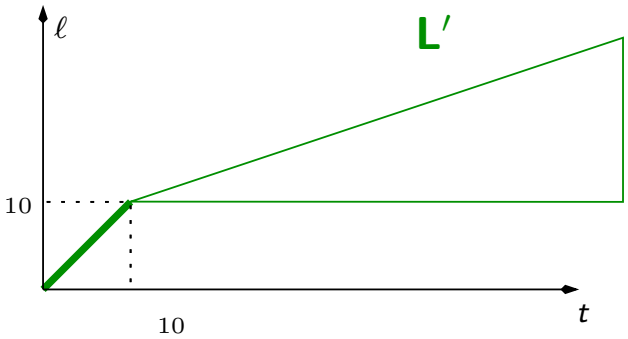

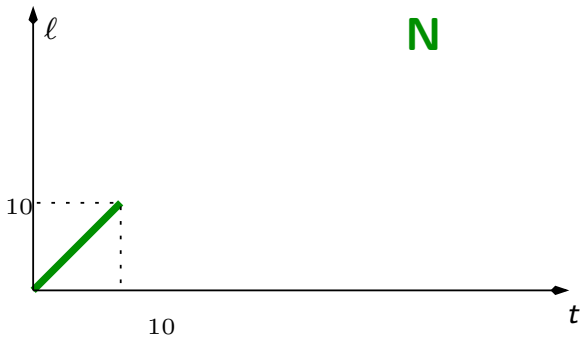

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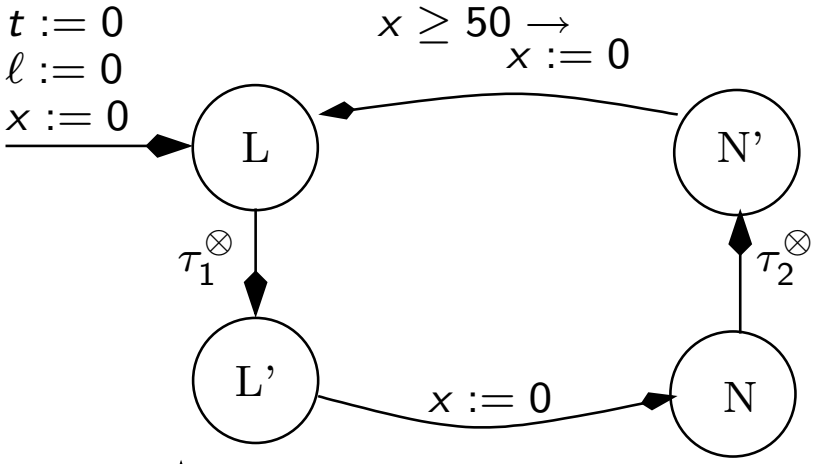

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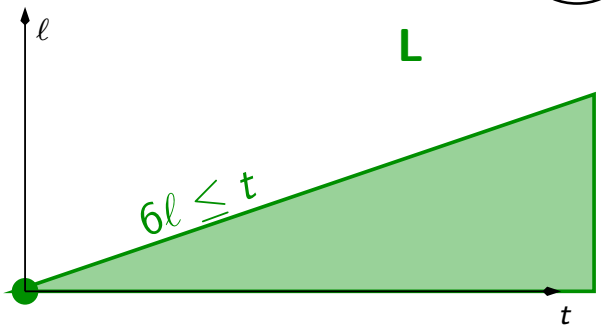

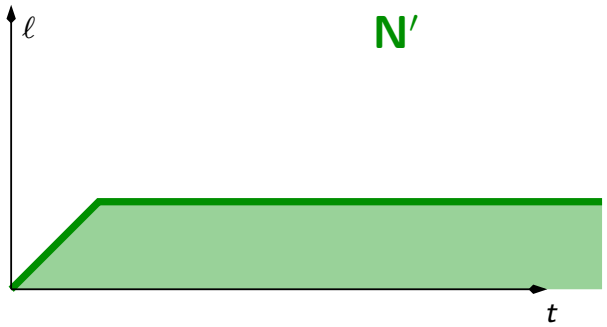

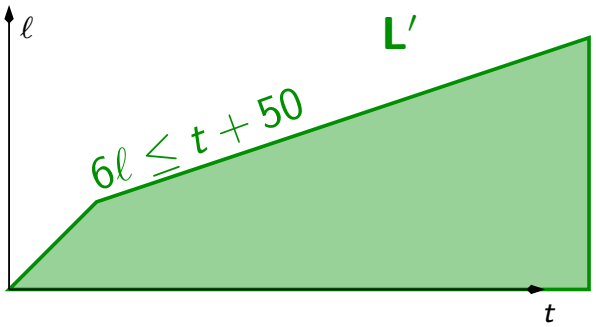

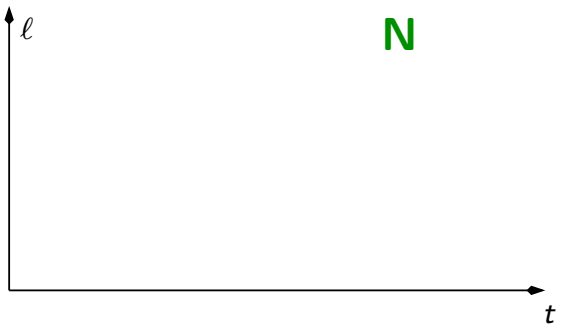

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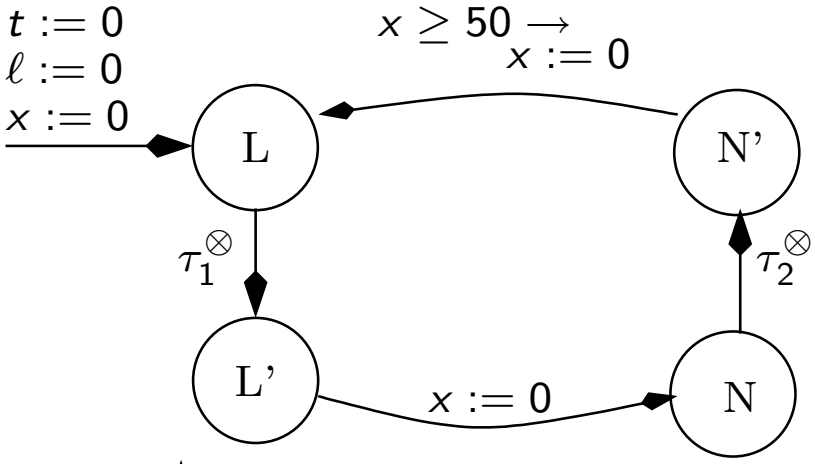

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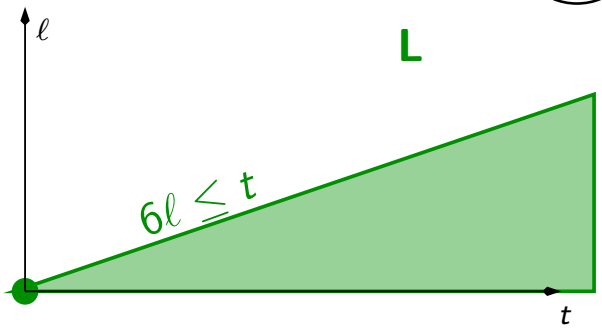

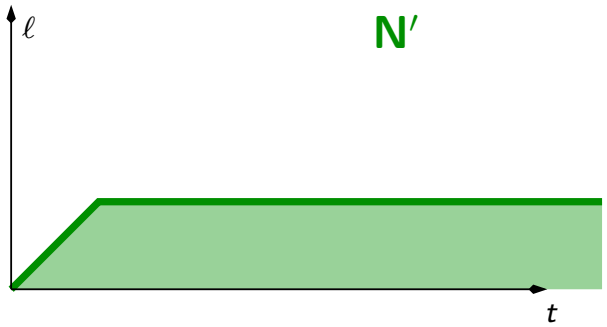

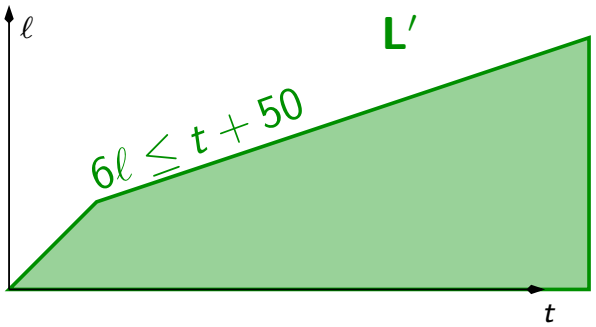

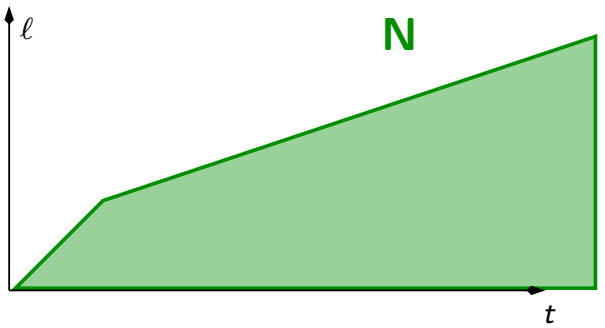

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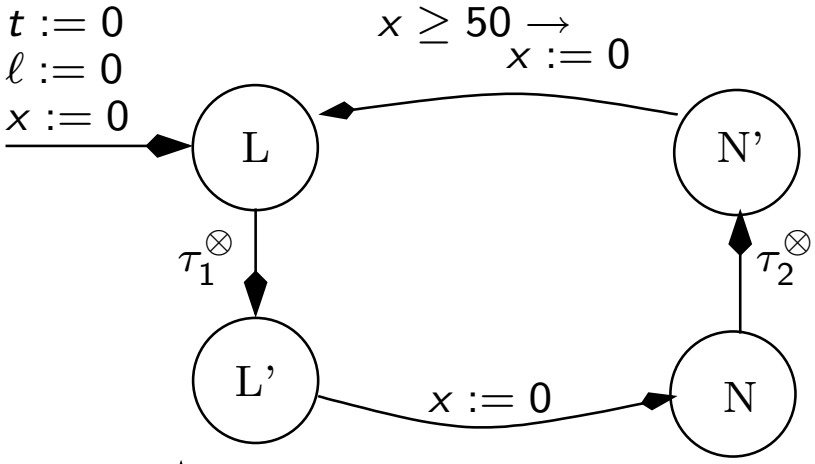

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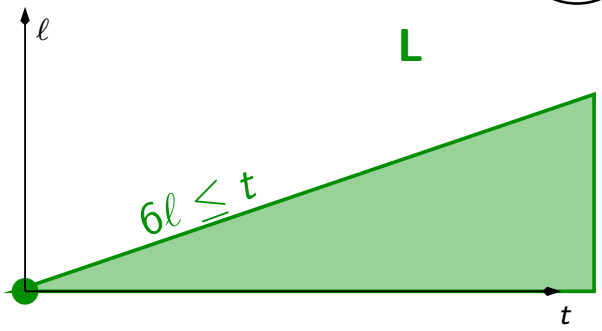
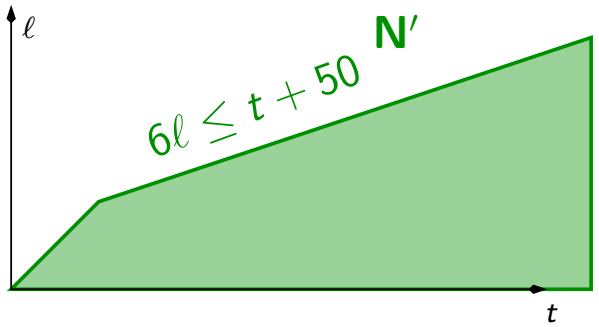
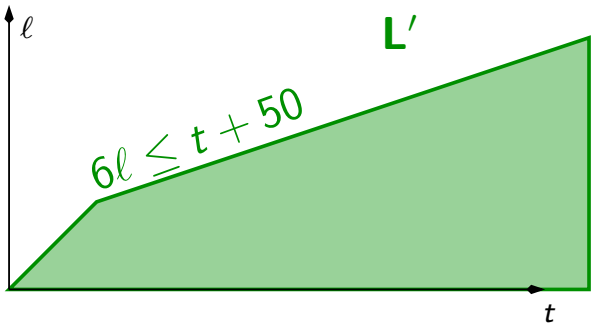
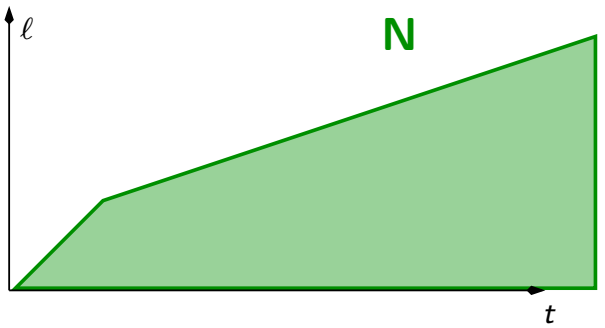


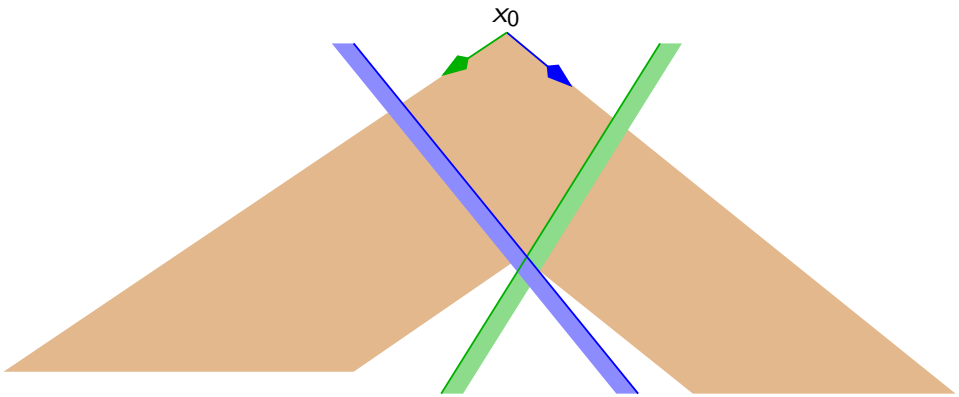






Two loops - First remarks

$(\tau_1 + \tau_2)^*(P_0)$ is not necessarily **convex** :



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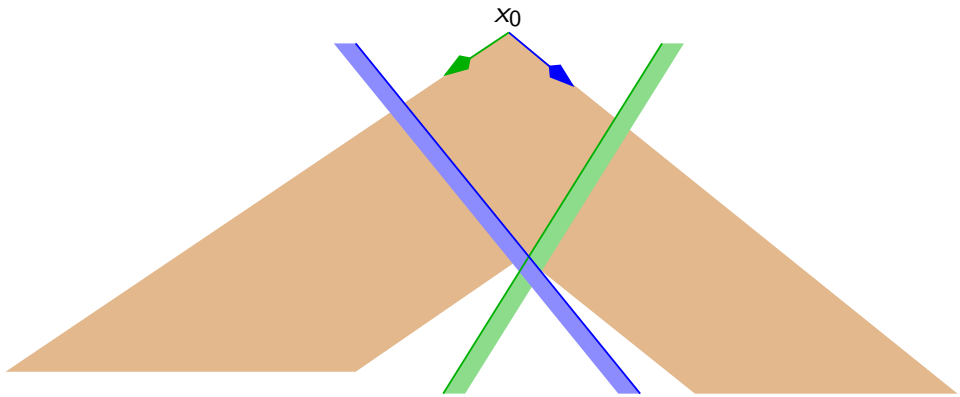
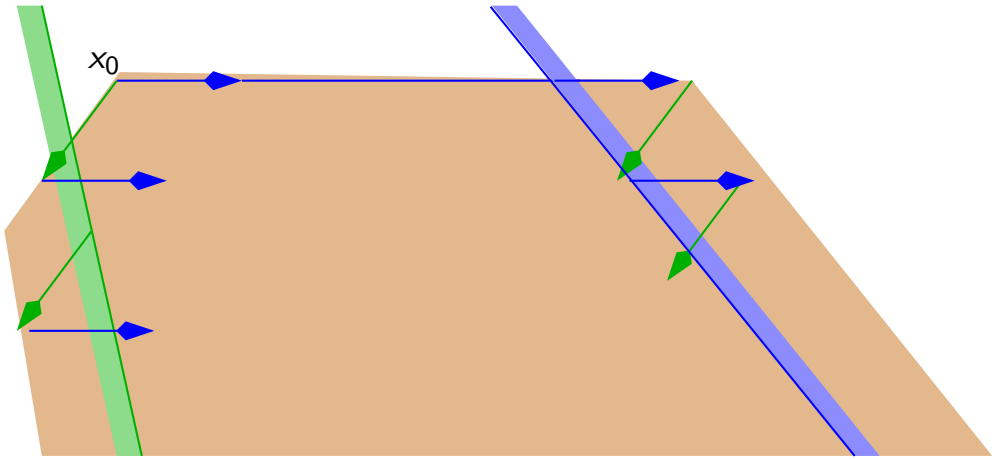
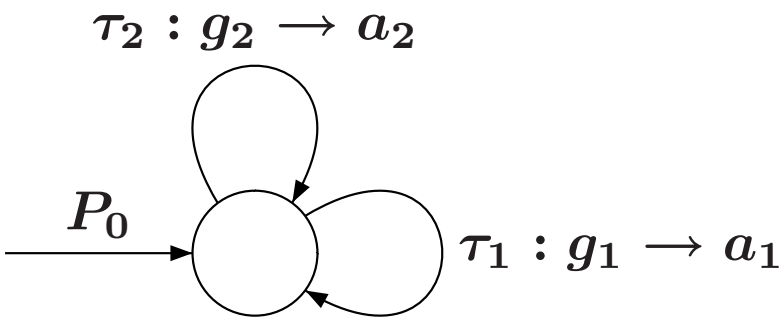


There can be quite complex **oscillations**



Two simple translation loops – new results



- New result for $g_i = G_i X_i \leq c_i$: an algorithm to compute an over-approximation of $(\tau_1 + \tau_2)^*(P_0)$ (convex polyhedron).
- In other cases, add a new loop computing P_1 :

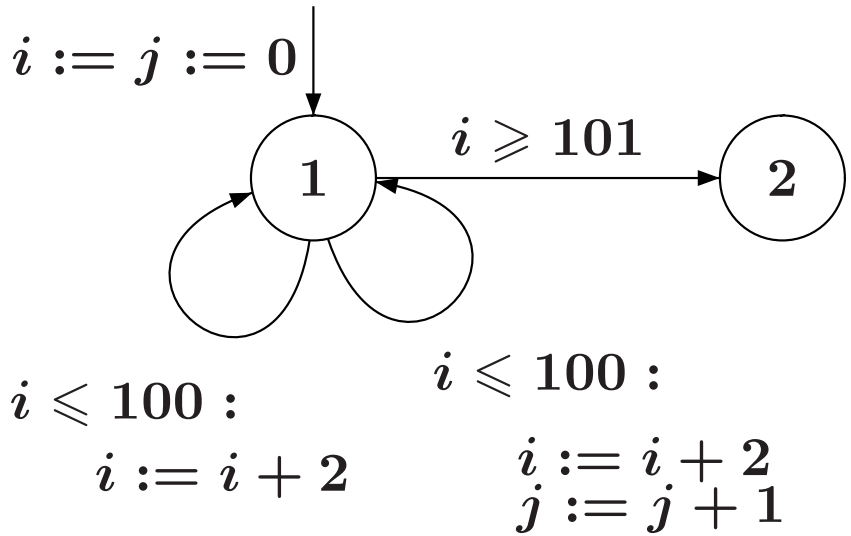
$$P_1 = P_0 \sqcup \tau_1^{\otimes}(P') \sqcup \tau_2^{\otimes}(P')$$

where :

$$P' = (P_0 \cap g_1 \cap g_2 \nearrow \{D_1, D_2\}) \cap g_1 \cap g_2$$

Old Cousot&Halbwachs78 example

```
  i :=0 ;
  j :=0 ;
  while i<= 100 do
1       if ? then i :=i+2
        else i :=i+2 ; j :=j+1
        fi
  od
2
```



Immediate result at control point 1

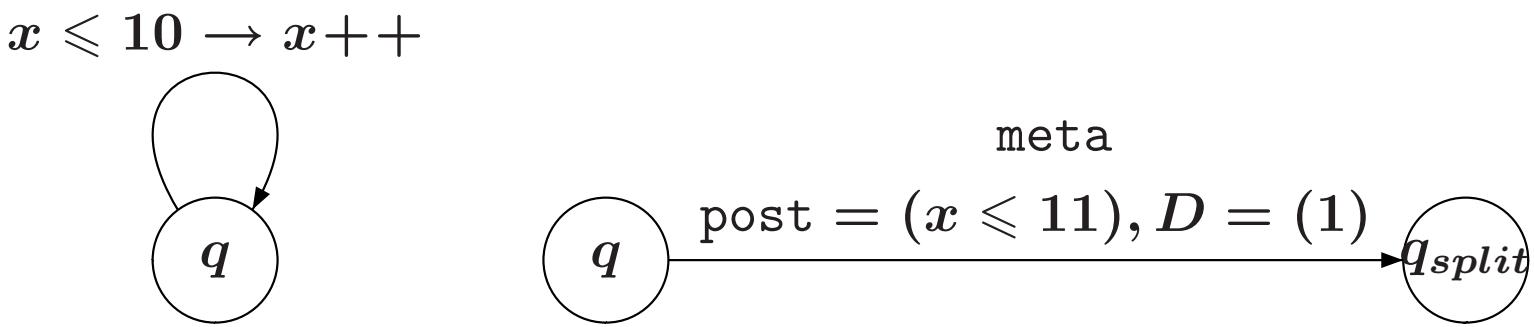
$$(0,0) \nearrow \{(2,0),(2,1)\} \cap (i \leq 100)$$
$$= 0 \leq 2j \leq i \leq 100$$

Loops loops with reset (or constant assignments)

Some kind of loops can be accelerated alltogether.

Overview of ASPIC

- A Fixpoint engine for the polyhedral lattice [B. Jeannet]
- Creation of **meta-transitions** if possible :



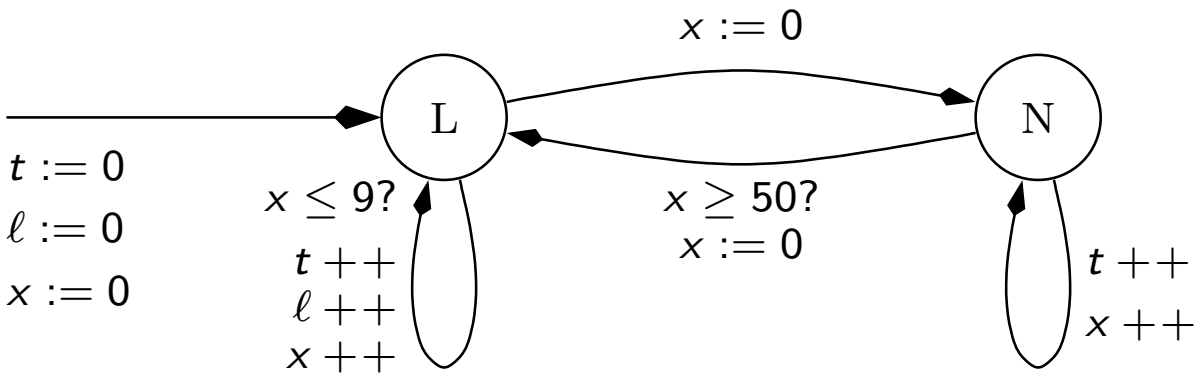
- Classical LRA with forward computation, widening and **meta-transitions**.
- A compilation chain from Lustre, a synchronous functional language designed in Verimag.

Aspic demo

ASPIC : Accelerated Symbolic Polyhedral Invariant Computation

`http://www-verimag.imag.fr/~gonnord/aspic/aspic.html`

demo.



Currently working on

- More general cases of loops.
- Sets of benchmarks coming from :
  - Sensor networks : consumption properties (Maraninchi/Samper)
  - "Programs with list are counter automata" (CAV 06, Iosif/Bozga/Bouajjani/Habermehl/Moro/Vojnar)
  - ...
- My PHD (!)

Future work

- More general cases of loops.
- Compare/Combine with "Lookahead widening" (CAV 06, Gopan/Reps) Implemented !
- Implement in NBAC tool [B.Jeannet]