Formal Methods
Module II: Model Checking
Ch. 09: **Timed and Hybrid Systems**

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M.S. in Computer Science, Mathematics, & Artificial Intelligence Systems
Academic year 2020-2021

last update: Thursday 27th May, 2021, 13:26

Outline

1. Motivations
2. Timed systems: Modeling and Semantics
   - Timed automata
3. Symbolic Reachability for Timed Systems
   - Making the state space finite
   - Region automata
   - Zone automata
4. Hybrid Systems: Modeling and Semantics
   - Hybrid automata
5. Symbolic Reachability for Hybrid Systems
   - Multi-Rate and Rectangular Hybrid Automata
   - Linear Hybrid Automata
6. Exercises

Outline

Acknowledgments

Thanks for providing material to:

- Rajeev Alur & colleagues (Penn University)
- Paritosh Pandya (IIT Bombay)
- Andrea Mattioli, Yusi Ramadian (Univ. Trento)
- Marco Di Natale (Scuola Superiore S.Anna, Italy)

Disclaimer

- very introductory
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- mostly computer-science centric

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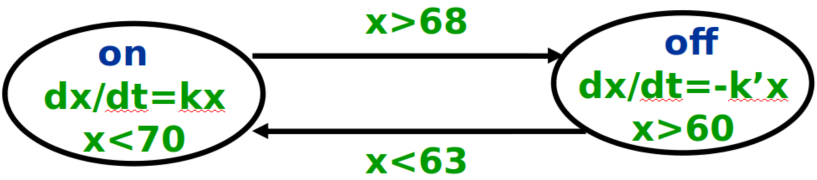
Hybrid Modeling

Hybrid machines = State machines + Dynamic Systems



Hybrid Modeling: Examples

- Automotive Applications
- Vehicle Coordination Protocols
- Interacting Autonomous Robots
- Bio-molecular Regulatory Networks

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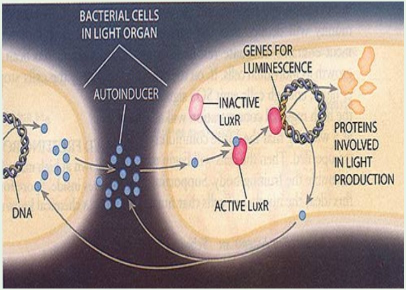

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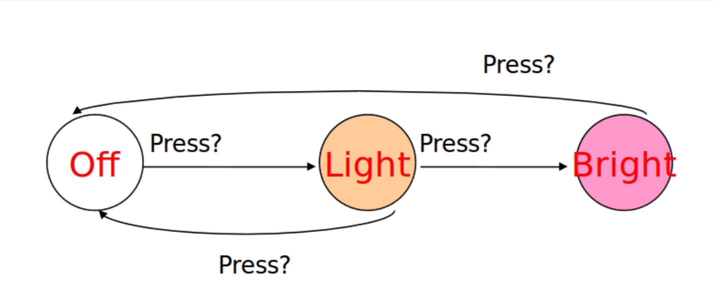
Timed Automata

Example: Simple light control

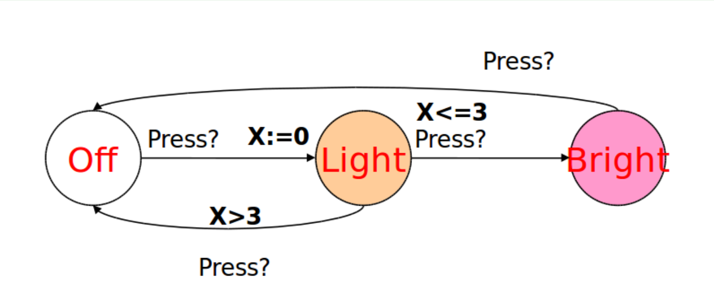


Requirement:

- if Off and press is issued once, then the light switches on;
- if Off and press is issued twice quickly, then the light gets brighter;
- if Light/Bright and press is issued once, then the light switches off;

$\Longrightarrow$ Cannot be achieved with standard automata

Example: Simple light control

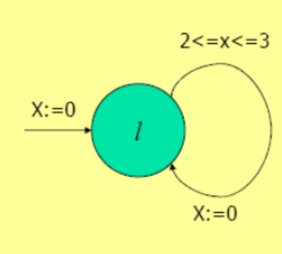


Solution: add real-valued clock x

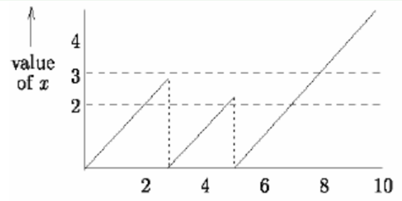
- x reset at first press
- if next press before x reaches 3 time units, then the light will get brighter;
- otherwise the light is turned off

Modeling: timing constraints

Finite graph + finite set of (real-valued) clocks



- Vertexes are locations
  - Time can elapse there
  - Constraints (invariants)
- Edges are switches
  - Subject to constraints
  - Reset clocks



Meaning of clock value: time elapsed since the last time it was reset.

Timed Automata

- Locations $l_1, l_2, \ldots$ (like in standard automata)
  - discrete part of the state
  - may be implemented by discrete variables
- Switches (discrete transitions like in standard aut.)
- Labels, aka events, actions,... (like in standard aut.)
  - used for synchronization
- Clocks: x, y,... $\in \mathbb{Q}^+$
  - value: time elapsed since the last time it was reset
- Guards: $(x \bowtie C)$ s.t. $\bowtie \in \{\leq, <, \geq, >\}$, $C \in \mathbb{N}$
  - set of clock comparisons against integers bounds
  - constrain the execution of the switch
- Resets $(x := 0)$
  - set of clock assignments to 0
- Invariants: $(x \bowtie C)$ s.t. $\bowtie \in \{\leq, <, \geq, >\}$, $C \in \mathbb{N}$
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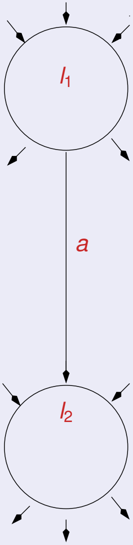

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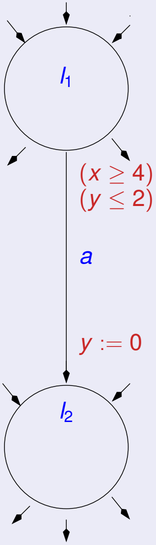

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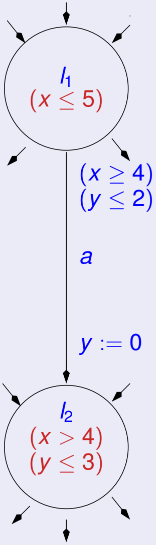
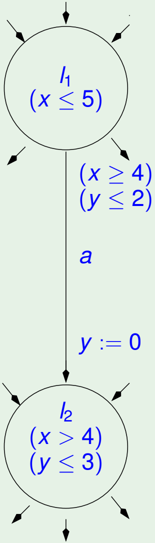


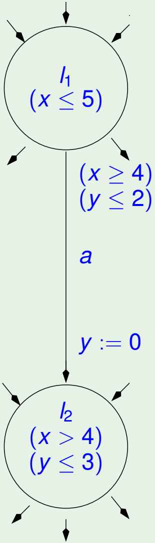
Timed Automata: States and Transitions

- State: $\langle l_i, x, y \rangle$



Timed Automata: States and Transitions

- State: $\langle l_i, x, y \rangle$
  - $\langle l_1, 4, 7 \rangle$:



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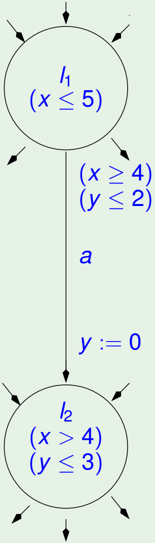

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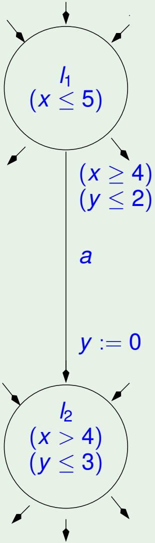

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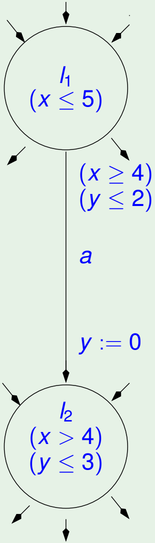

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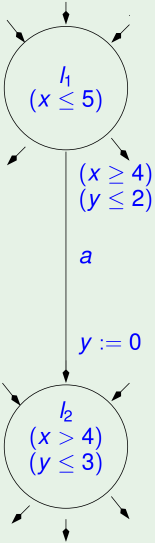

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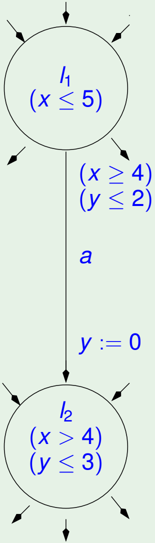

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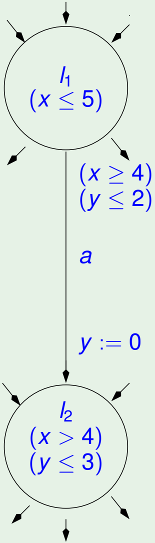

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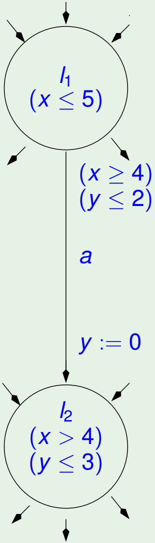

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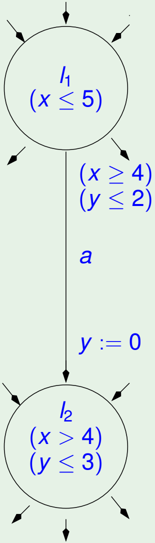

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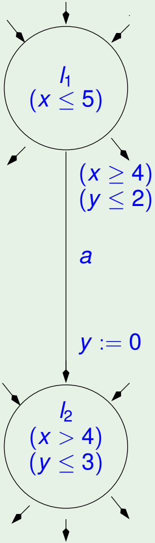

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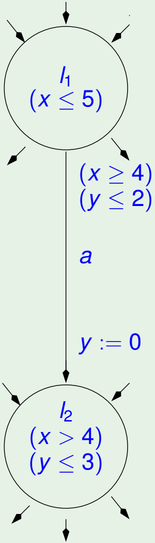

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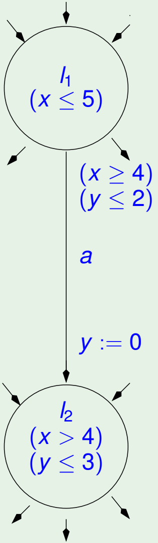

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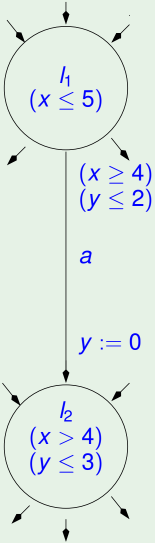

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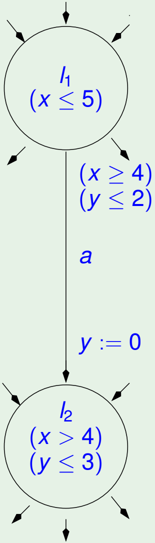

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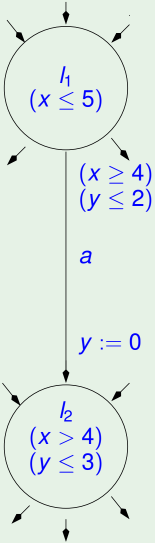

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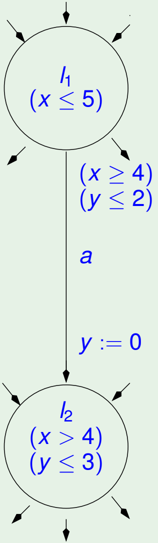
  - $\langle l_1, 4, 2\rangle \xrightarrow{a} \langle l_2, 4, 0\rangle$: not OK! (violates invar. in l_2)
- Wait (time elapse): $\langle l_i, x, y\rangle \xrightarrow{\delta} \langle l_i, x+\delta, y+\delta\rangle$



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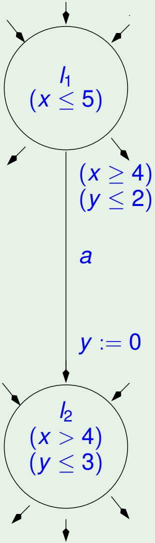
- Wait (time elapse): $\langle l_i, x, y\rangle \xrightarrow{\delta} \langle l_i, x+\delta, y+\delta\rangle$
  - $\langle l_1, 3, 0\rangle \xrightarrow{2} \langle l_1, 5, 2\rangle$:



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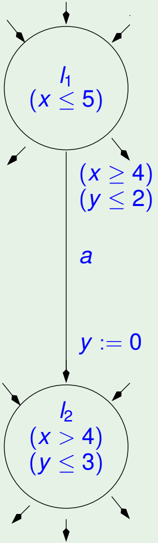
  - $\langle l_1, 4.5, 2 \rangle \xrightarrow{a} \langle l_2, 4.5, 2 \rangle$: not OK! (violates reset)
  - $\langle l_1, 4, 2 \rangle \xrightarrow{a} \langle l_2, 4, 0 \rangle$: not OK! (violates invar. in l_2)
- Wait (time elapse): $\langle l_i, x, y \rangle \xrightarrow{\delta} \langle l_i, x + \delta, y + \delta \rangle$
  - $\langle l_1, 3, 0 \rangle \xrightarrow{2} \langle l_1, 5, 2 \rangle$: OK!



Timed Automata: States and Transitions

- State: $\langle l_i, x, y \rangle$
  - $\langle l_1, 4, 7 \rangle$: OK!
  - $\langle l_2, 2, 4 \rangle$: not OK! (violates invariant in l_2)
- Switch: $\langle l_i, x, y \rangle \xrightarrow{a} \langle l_j, x', y' \rangle$
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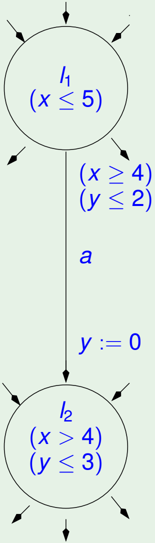
  - $\langle l_1, 3, 0 \rangle \xrightarrow{3} \langle l_1, 6, 3 \rangle$:



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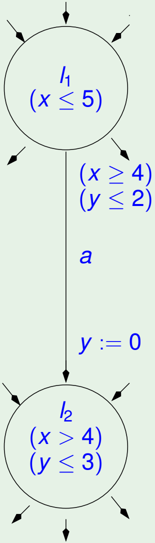

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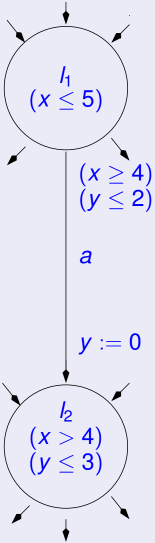

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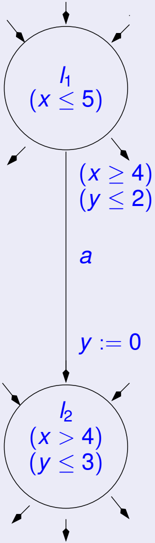

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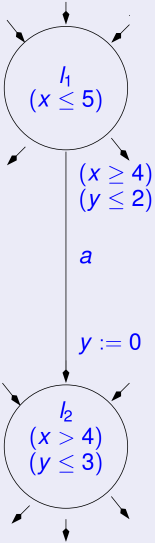

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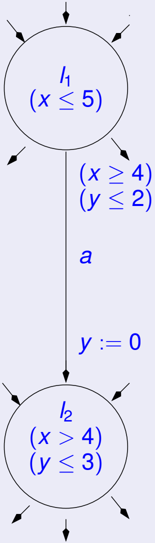

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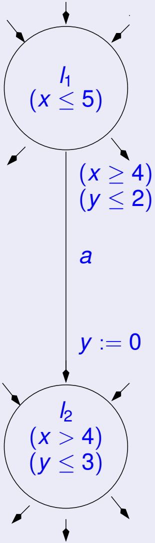

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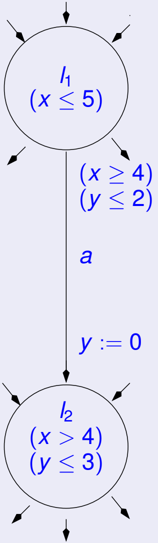

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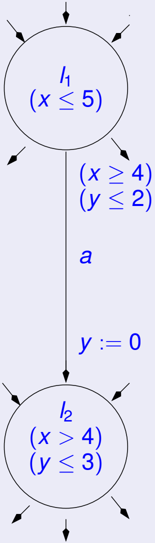

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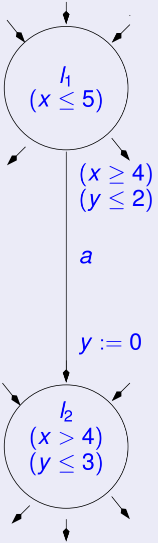

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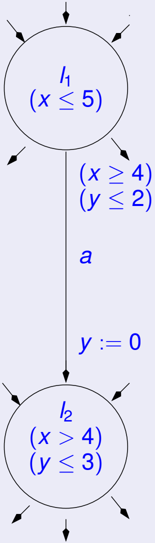

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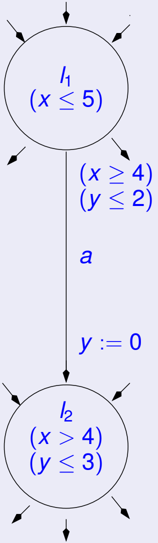

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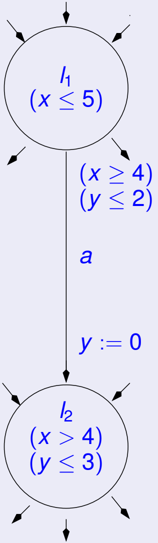


Clock constraints and clock interpretations

- Grammar of clock constraints:

$$\varphi ::= x \leq C \mid x < C \mid x \geq C \mid x > C \mid \varphi \wedge \varphi$$

  s.t. C positive integer values.
  $\Longrightarrow$ allow only comparison of a clock with a constant

- clock interpretation: ν

$$X = \langle x, y, z \rangle, \quad \nu = \langle 1.0, 1.5, 0 \rangle$$

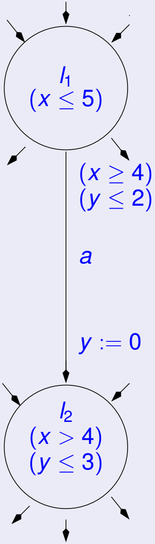
- clock interpretation ν after δ time: $\nu + \delta$

$$\delta = 0.2, \quad \nu + \delta = \langle 1.2, 1.7, 0.2 \rangle$$

- clock interpretation ν after reset λ: $\nu[\lambda]$

$$\lambda = \{y\}, \quad \nu[y := 0] = \langle 1.0, 0, 0 \rangle$$

A state for a timed automaton is a pair $\langle l, \nu \rangle$, where l is a location and ν is a clock interpretation



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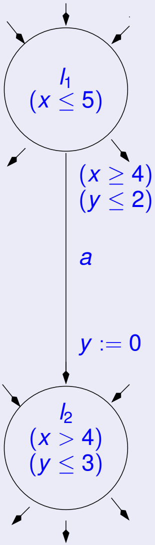

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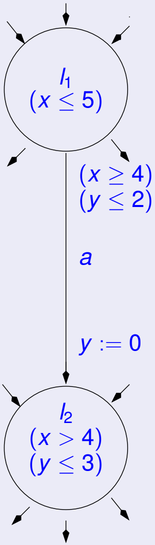

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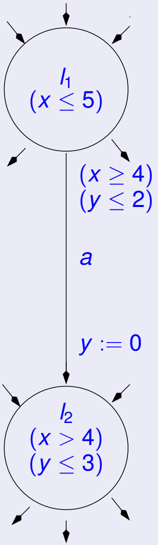

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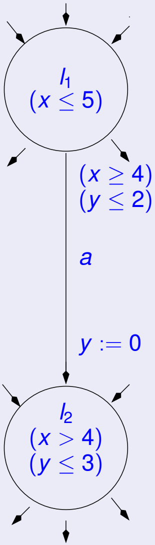
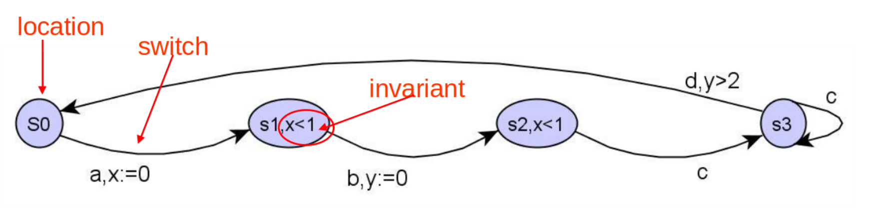


Remark: why integer constants in clock constraints?

The constant in clock constraints are assumed to be integer w.l.o.g.:

- if rationals, multiply them for their greatest common denominator, and change the time unit accordingly
- in practice, multiply by 10^k (resp 2^k), k being the number of precision digits (resp. bits), and change the time unit accordingly
  Ex: 1.345, 0.78, 102.32 seconds
  $\Longrightarrow 1,345,\ 780,\ 102,320$ milliseconds

Example



- clocks $\{x, y\}$ can be set/reset independently
- x is reset to 0 from s_0 to s_1 on a
- switches b and c happen within 1 time-unit from a because of constraints in s_1 and s_2
- delay between b and the following d is > 2
- no explicit bounds on time difference between event $c - d$

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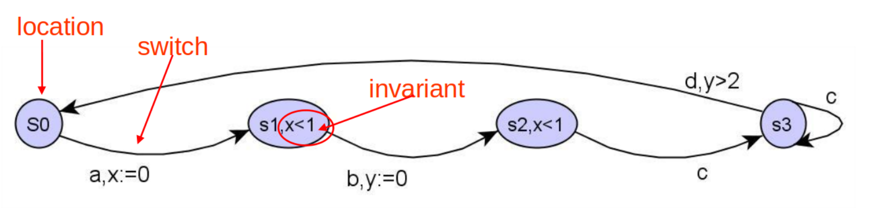

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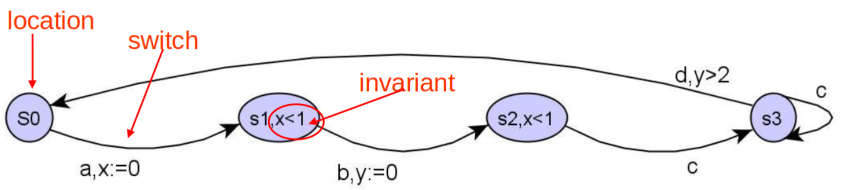

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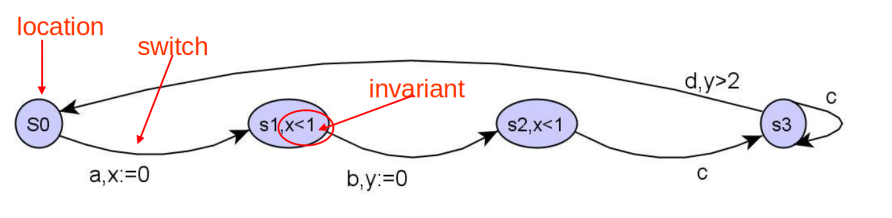

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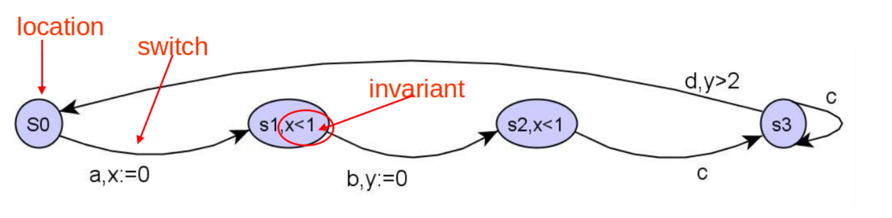

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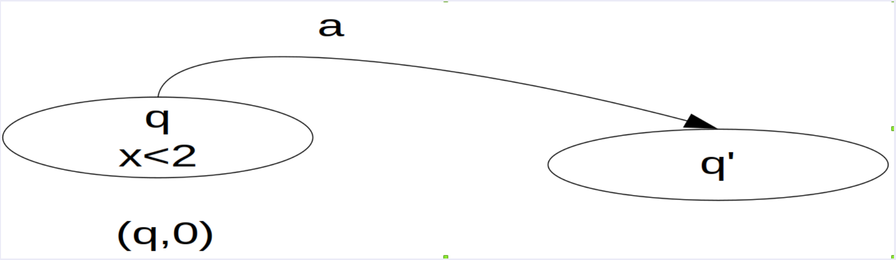
Timed Automata: Semantics

Semantics of A defined in terms of a (infinite) transition system

$$S_A \stackrel{\text{def}}{=} \langle Q, Q^0, \rightarrow, \Sigma \rangle$$

- Q: $\{\langle l, \nu \rangle\}$ s.t. l location and ν clock evaluation
- Q^0: $\{\langle l, \nu \rangle\}$ s.t. $l \in L^0$ location and $\nu(X) = 0$
- $\rightarrow$:
  - state change due to location switch
  - state change due to time elapse
- Σ: set of labels of $\Sigma \cup \mathbb{Q}^+$

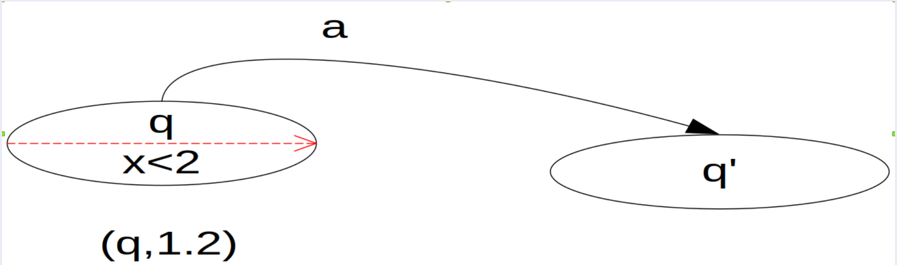
State change in transition system



Initial State

- $\langle q, 0 \rangle$
- Initial state

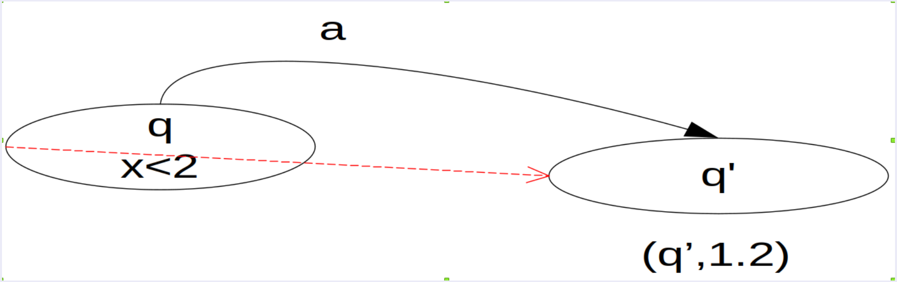
State change in transition system



Time elapse

- $\langle q, 0 \rangle \xrightarrow{1.2} \langle q, 1.2 \rangle$
- state change due to elapse of time

State change in transition system

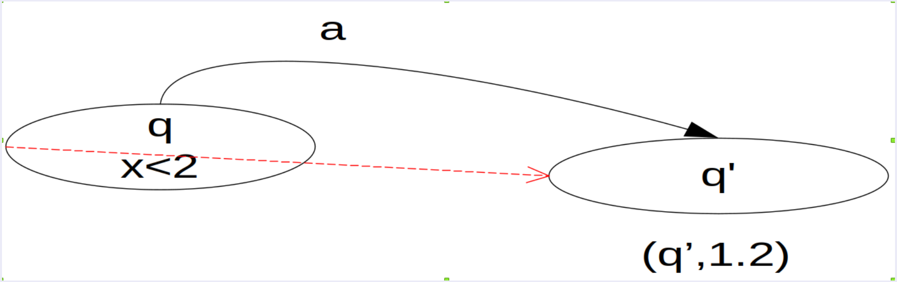


Time Elapse, Switch and their Concatenation

- $\langle q, 0\rangle \xrightarrow{1.2} \langle q, 1.2\rangle \xrightarrow{a} \langle q', 1.2\rangle$ "wait δ; switch;"

$\Longrightarrow \langle q, 0\rangle \xrightarrow{1.2+a} \langle q', 1.2\rangle$ "wait δ and switch;"

State change in transition system



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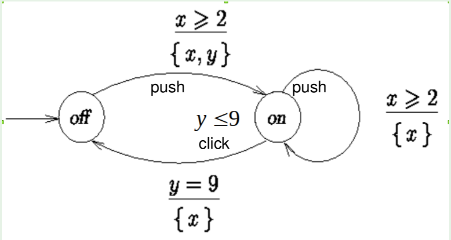

- Switch may be turned on whenever at least 2 time units has elapsed since last "turn off"
- Light automatically switches off after 9 time units.

Example execution

$\langle \mathit{off}, 0, 0 \rangle \xrightarrow{3.5} \langle \mathit{off}, 3.5, 3.5 \rangle \xrightarrow{\mathit{push}} \langle \mathit{on}, 0, 0 \rangle \xrightarrow{3.14} \langle \mathit{on}, 3.14, 3.14 \rangle$
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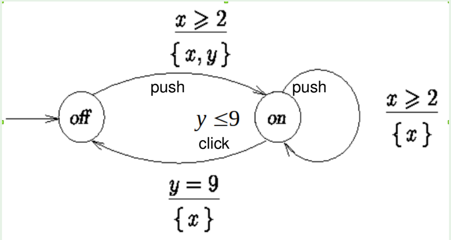

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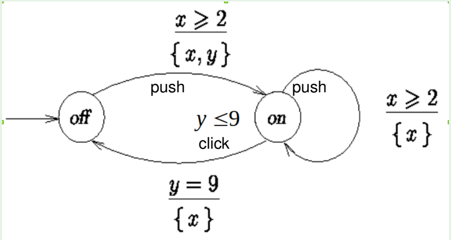

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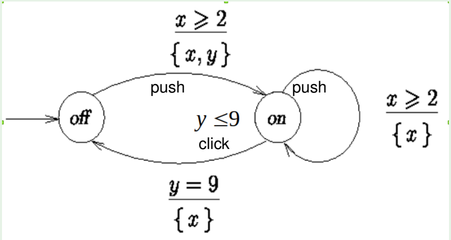

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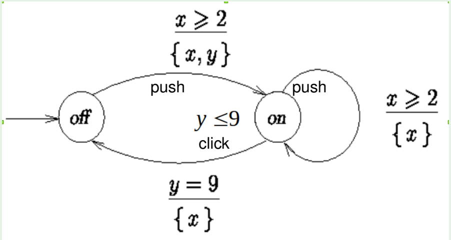

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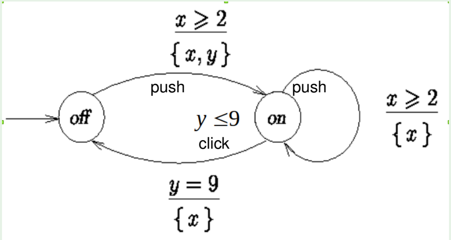

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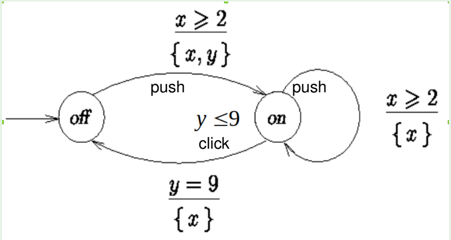

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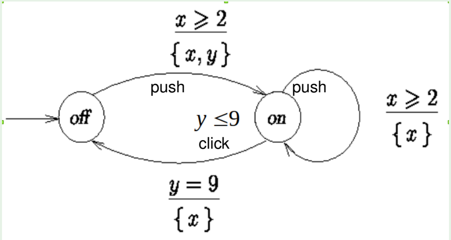

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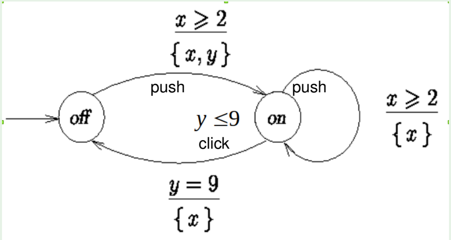

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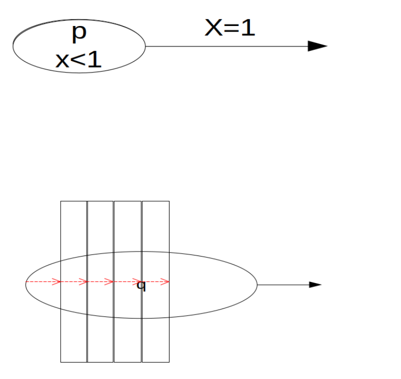
Remark: Non-Zenoness

Beware of Zeno! (paradox)

- When the invariant is violated some edge must be enabled
- Automata should admit the possibility of time to diverge



Combination of Timed Automata

- Complex system = product of interacting systems
- Let $A_1 \stackrel{\text{def}}{=} \langle L_1, L_1^0, \Sigma_1, X_1, \Phi_1(X_1), E_1 \rangle$, $A_2 \stackrel{\text{def}}{=} \langle L_2, L_2^0, \Sigma_2, X_2, \Phi_2(X_2), E_2 \rangle$
- Product: $A_1 || A_2 \stackrel{\text{def}}{=}$ $\langle L_1 \times L_2, L_1^0 \times L_2^0, \Sigma_1 \cup \Sigma_2, X_1 \cup X_2, \Phi_1(X_1) \cup \Phi_2(X_2), E_1 || E_2 \rangle$
- Transition iff:
  - Label a belongs to both alphabets $\Longrightarrow$ synchronized blocking synchronization: a-labeled switches cannot be shot alone
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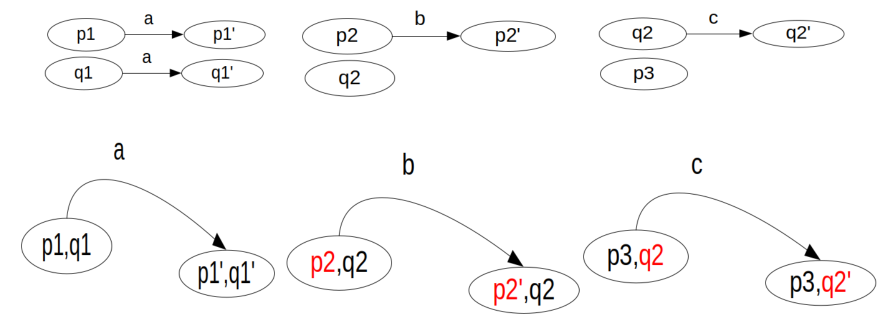
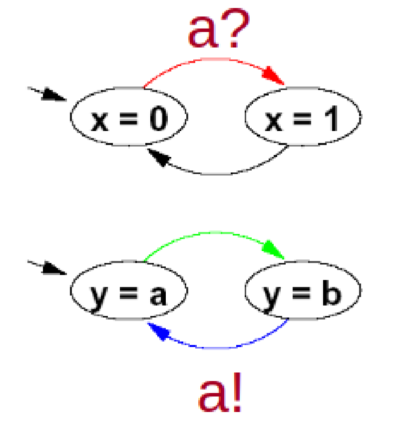
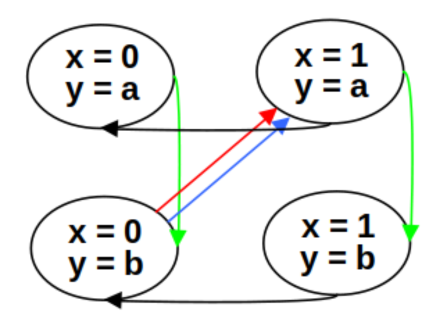
Transition Product

$\Sigma_1 \stackrel{\text{def}}{=} \{a, b\}$
$\Sigma_2 \stackrel{\text{def}}{=} \{a, c\}$

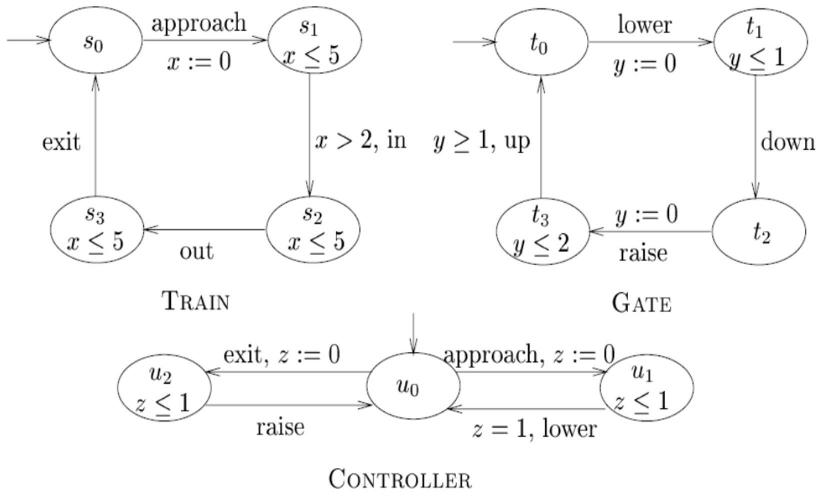


Transition Product: Example



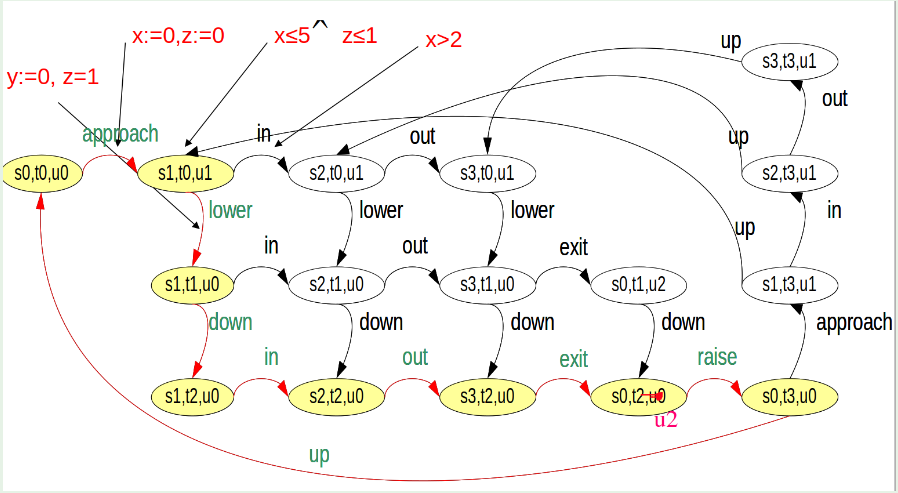


Example: Train-gate controller [Alur CAV'99]



Desired property: $G(s_2 \rightarrow t_2)$

Train-gate controller: Product



Outline

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Reachability Analysis

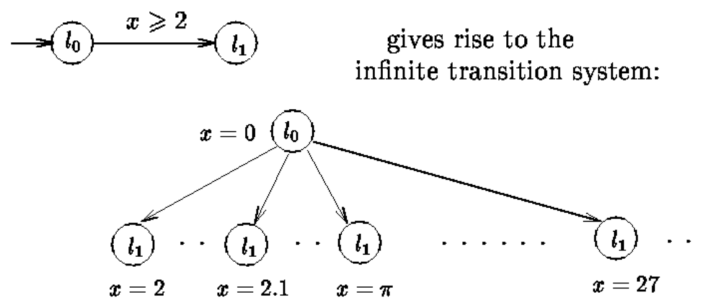
- Verification of safety requirement: reachability problem
- Input: a timed automaton A and a set of target locations $L^F \subseteq L$
- Problem: Determining whether L^F is reachable in a timed automaton A
- A location l of A is reachable if some state q with location component l is a reachable state of the transition system S_A

Timed/hybrid Systems: problem

Problem

The system S_A associated to A has infinitely-many states & symbols.

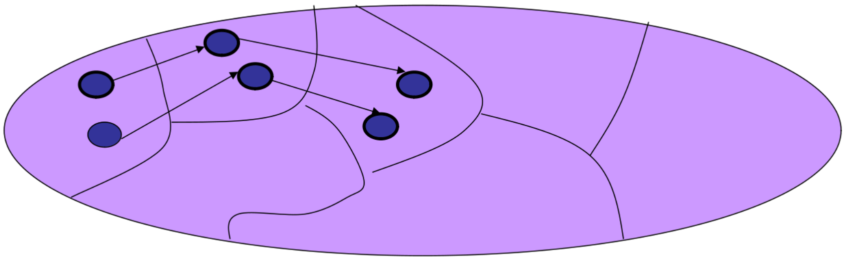
- Is finite state analysis possible?
- Is reachability problem decidable?



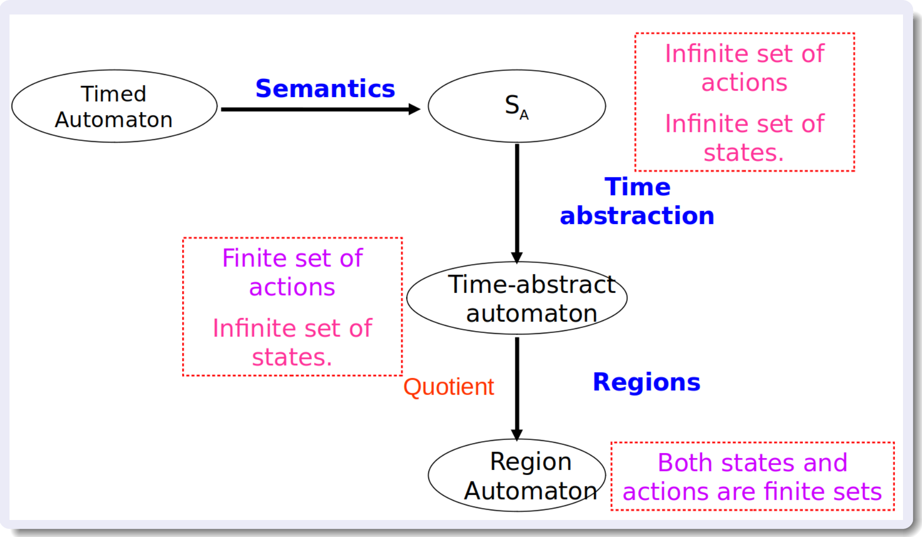
Idea: Finite Partitioning

Goal

Partition the state space into finitely-many equivalence classes, so that equivalent states exhibit (bi)similar behaviors



Reachability analysis



Timed Vs Time-Abstract Relations

Idea

Infinite transition system associated with a timed/hybrid automaton A:

- S_A: Labels on continuous steps are delays in $\mathbb{Q}^+$
- U_A (time-abstract): actual delays are suppressed
  $\Longrightarrow$ all continuous steps have same label
- from "wait δ and switch" to "wait (sometime) and switch"

Time-abstract transition system U_A

U_A (time-abstract): actual delays are suppressed

- Only change due to location switch stated explicitly
- Cut system to finitely many labels
- U_A (instead of S_A) allows for capturing untimed properties (e.g., reachability, safety)

Example

A: ("wait δ; switch;")

$\langle l_0, 0, 0\rangle \xrightarrow{1.2} \langle l_0, 1.2, 1.2\rangle \xrightarrow{a} \langle l_1, 0, 1.2\rangle \xrightarrow{0.7} \langle l_1, 0.7, 1.9\rangle \xrightarrow{b} \langle l_2, 0.7, 0\rangle$

S_A: ("wait δ and switch;")

$\langle l_0, 0, 0\rangle \xrightarrow{1.2+a} \langle l_1, 0, 1.2\rangle \xrightarrow{0.7+b} \langle l_2, 0.7, 0\rangle$

U_A: ("wait (sometime) and switch;")

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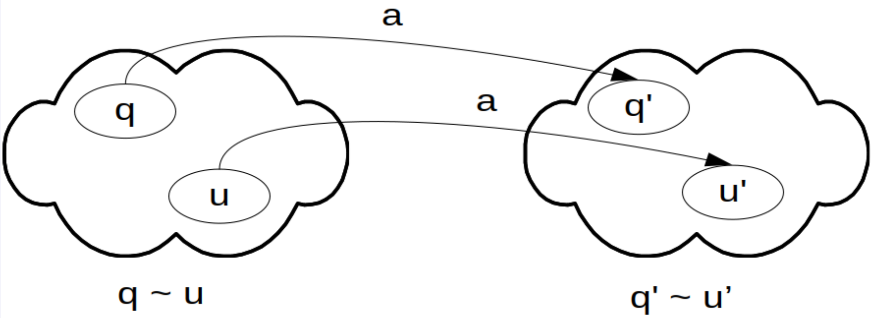
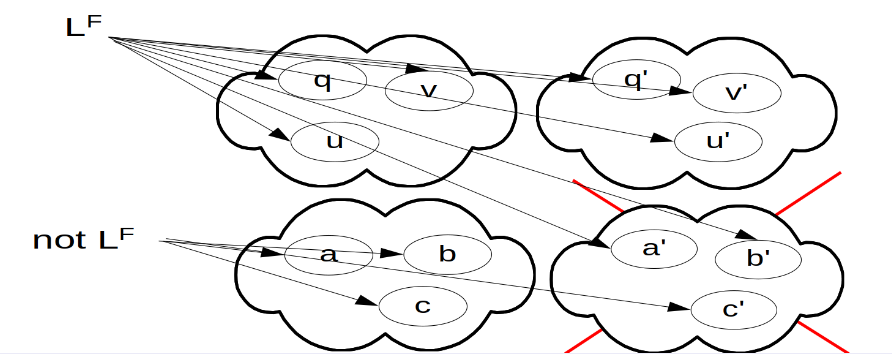
Stable quotients



Idea: Collapse states which are equivalent modulo “wait & switch”

- Cut to finitely many states
- Stable equivalence relation
- Quotient of U_A = transition system $[U_A]$

L^F-sensitive equivalence relation



All equivalent states in a class belong to either L^F or not L^F

- E.g.: states with different labels cannot be equivalent

Stable Quotient: Intuitive example

Task: plan trip from DISI to VR train station

"take the next #5 bus to TN train station and then the 6pm train to VR"

- Constraints:
  - It is 5.18pm
  - Train to VR leaves at TN train station at 6.00pm
  - it takes 3 minutes to walk from DISI to BUS stop
  - Bus #5 passes 5.20pm or at 5.40pm
  - Bus #5 takes 15 minutes to TN train station
  - it takes 2 minutes to walk from BUS stop to TN train station
- Time-Abstract plan (U_A):
  "walk to bus stop; take 5.40 #5 bus to TN train-station stop;
  walk to train station; take the 6pm train to VR"
- Actual (implicit) plan (A):
  "wait δ_1; walk to bus stop; wait δ_2; take 5.40 #5 bus to TN train-station stop;
  wait δ_3 at bus stop; walk to train station; wait δ_4; take the 6pm train to VR"
  where $\delta_1 + \delta_2 = 19min$ and $\delta_3 + \delta_4 = 3min$
- All executions with distinct values of δ_i are bisimilar

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- Time-Abstract plan (U_A):
  "walk to bus stop; take 5.40 #5 bus to TN train-station stop; walk to train station; take the 6pm train to VR"
- Actual (implicit) plan (A):
  "wait δ_1; walk to bus stop; wait δ_2; take 5.40 #5 bus to TN train-station stop; wait δ_3 at bus stop; walk to train station; wait δ_4; take the 6pm train to VR"
  where $\delta_1 + \delta_2 = 19min$ and $\delta_3 + \delta_4 = 3min$
- All executions with distinct values of δ_i are bisimilar

Stable Quotient: Intuitive example

Task: plan trip from DISI to VR train station

"take the next #5 bus to TN train station and then the 6pm train to VR"

- Constraints:
  - It is 5.18pm
  - Train to VR leaves at TN train station at 6.00pm
  - it takes 3 minutes to walk from DISI to BUS stop
  - Bus #5 passes 5.20pm or at 5.40pm
  - Bus #5 takes 15 minutes to TN train station
  - it takes 2 minutes to walk from BUS stop to TN train station
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Outline

Region Equivalence over clock interpretation

Preliminary definitions & terminology

Given a clock x:

- $\lfloor x \rfloor$ is the integral part of x (ex: $\lfloor 3.7 \rfloor = 3$)
- fr(x) is the fractional part of x (ex: $\mathrm{fr}(3.7) = 0.7$)
- C_x is the maximum constant occurring in clock constraints $x \bowtie C_x$

Region Equivalence: $\nu \cong \nu'$

Given a timed automaton A, two clock interpretations ν, ν' are region equivalent ($\nu \cong \nu'$) iff all the following conditions hold:

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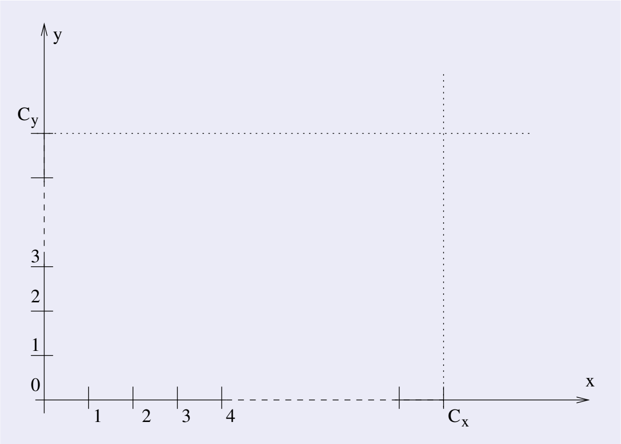
Conditions: C1 + C2 + C3



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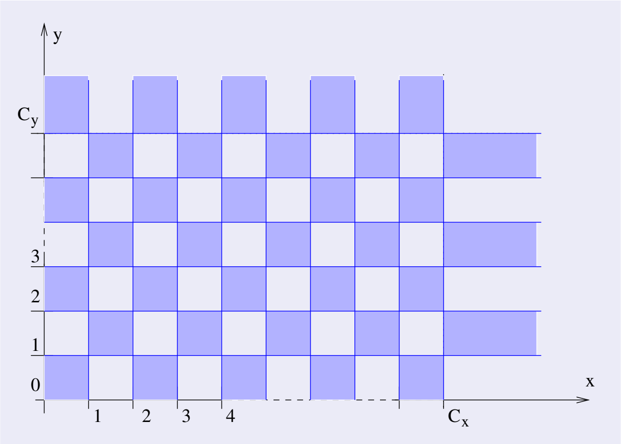

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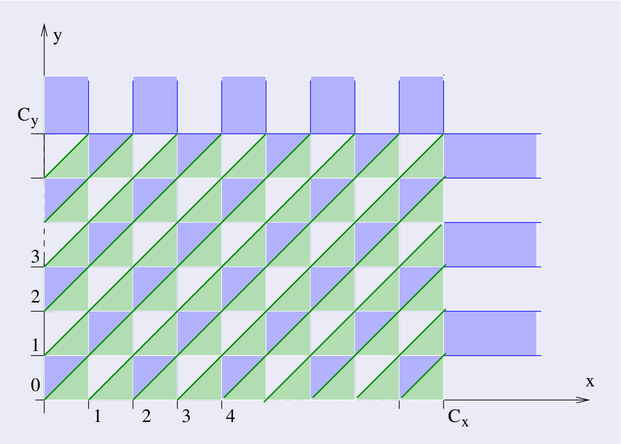

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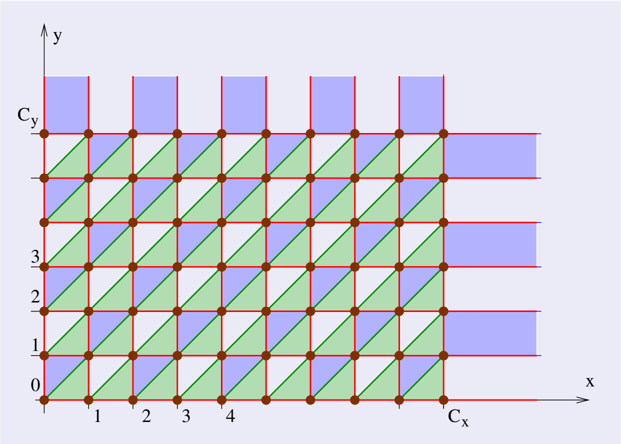

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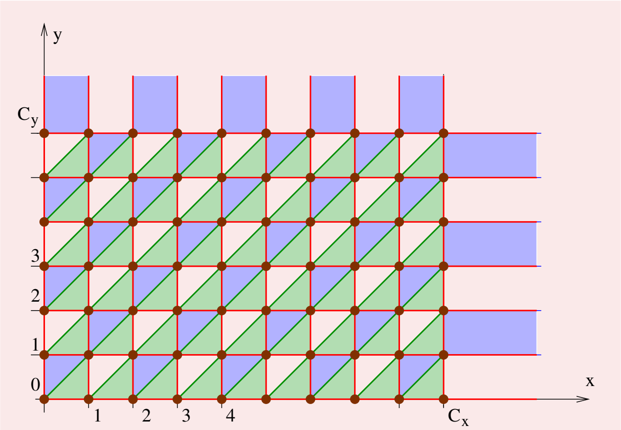
Regions, intuitive idea:

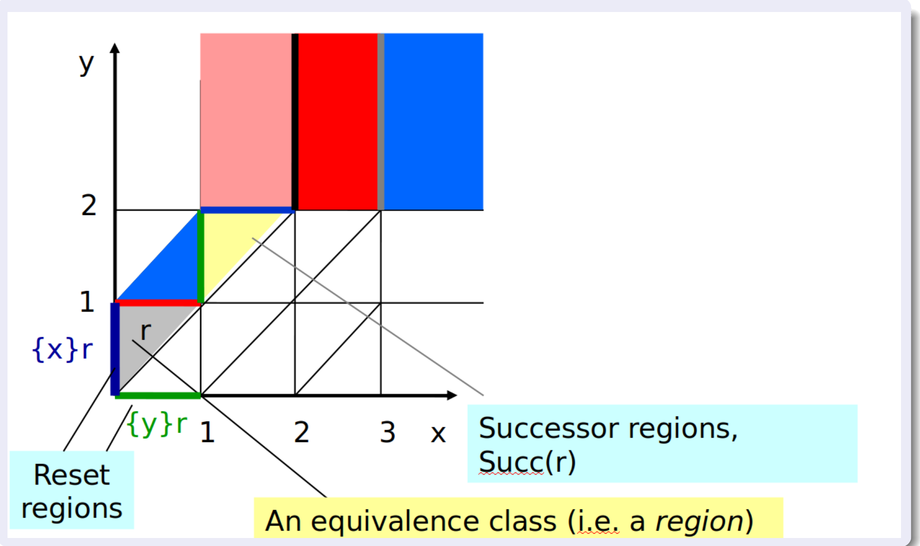


Intuition: $\nu \cong \nu'$ iff they satisfy the same set of constraints in the form

$$x_i < c,\ x_i > c,\ x_i = c,\ x_i - x_j < c,\ x_i - x_j > c,\ x_i - x_j = c$$

s.t. $c \leq C_{x_i}$

Region Operations



Properties of Regions

- The region equivalence relation $\cong$ is a time-abstract bisimulation:
  - Action transitions: if $\nu \cong \mu$ and $\langle l, \nu \rangle \xrightarrow{a} \langle l', \nu' \rangle$ for some l', ν', then there exists μ' s.t. $\nu' \cong \mu'$ and $\langle l, \mu \rangle \xrightarrow{a} \langle l', \mu' \rangle$
  - Wait transitions: if $\nu \cong \mu$, then for every $\delta \in \mathbb{Q}^+$ there exists $\delta' \in \mathbb{Q}^+$ s.t. $\nu + \delta \cong \mu + \delta'$

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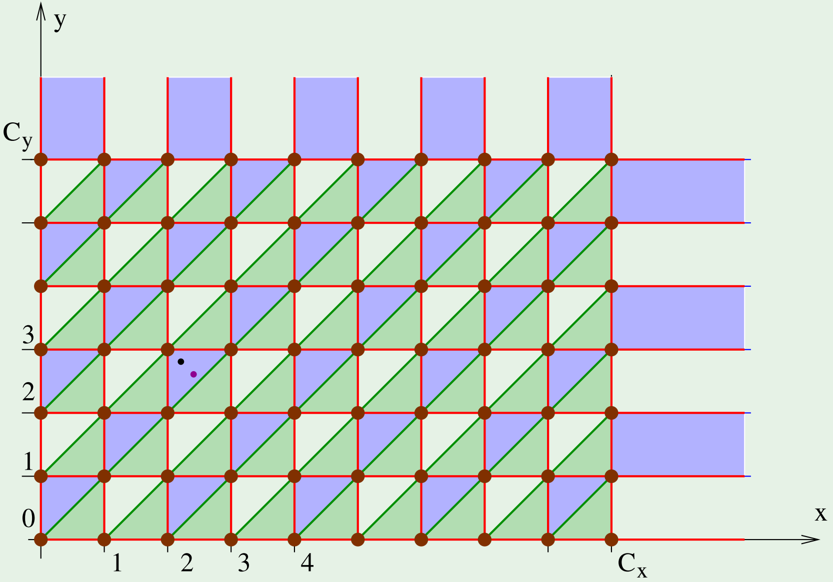

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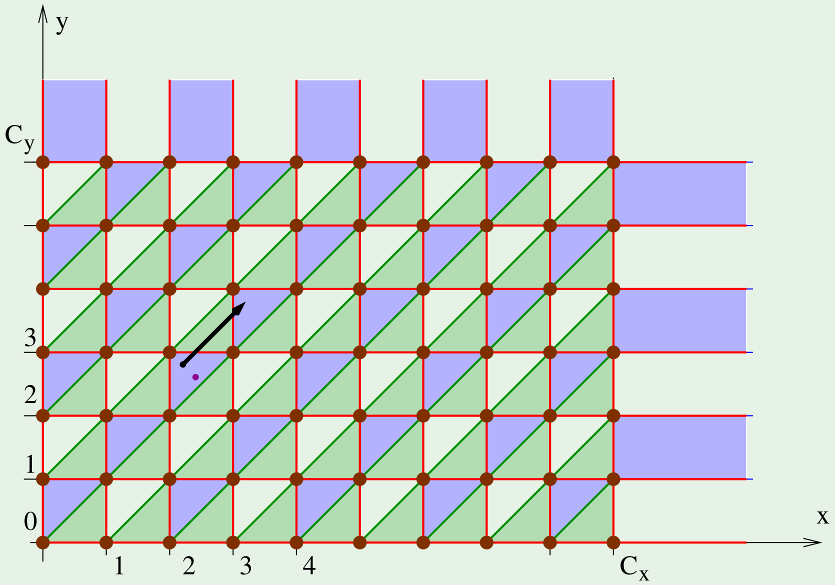

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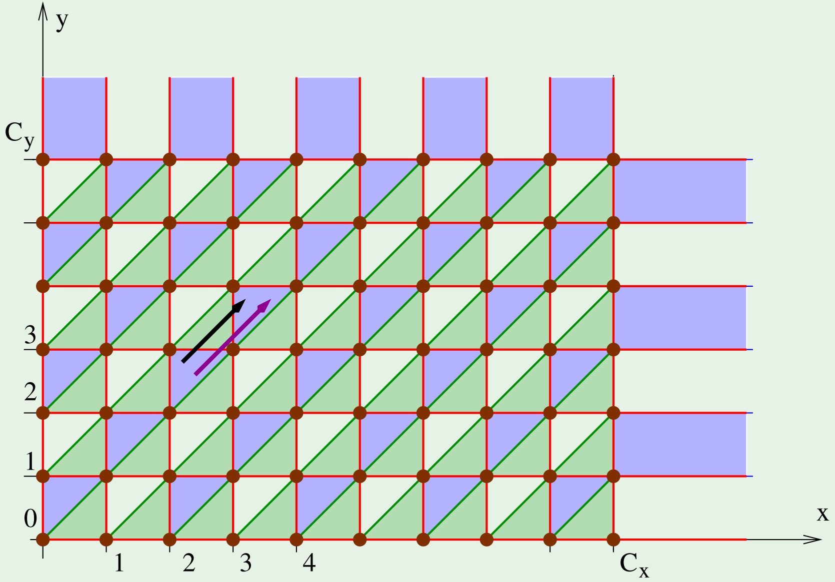

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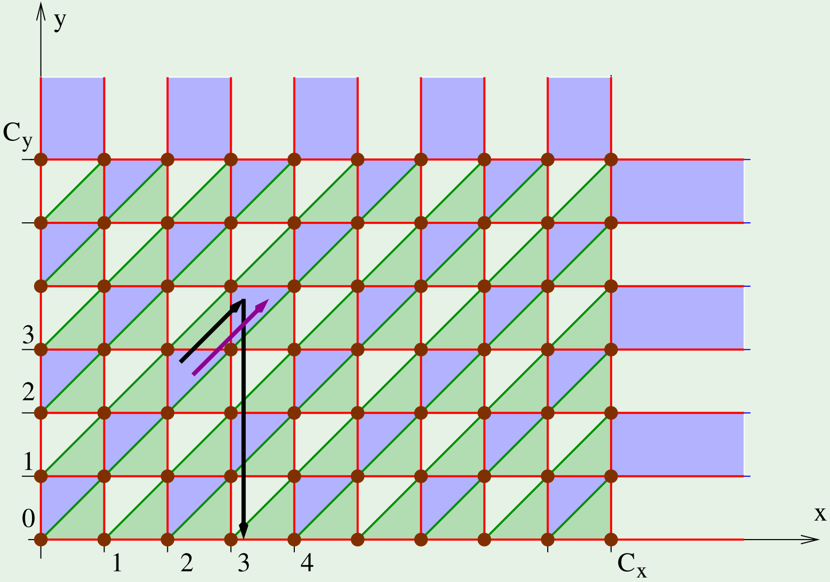

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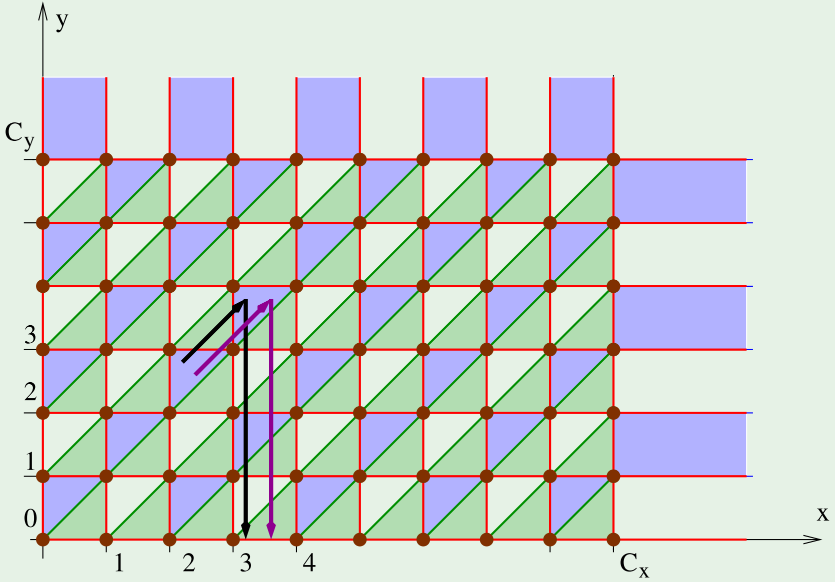

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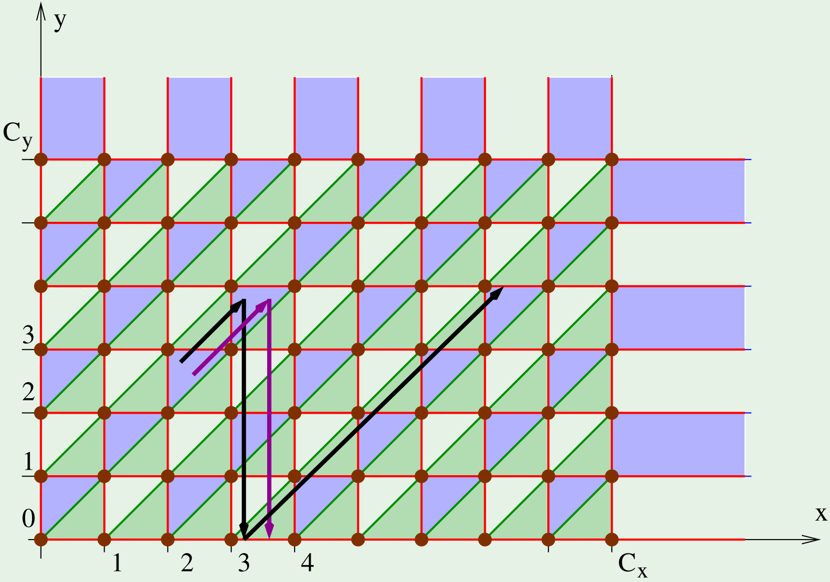

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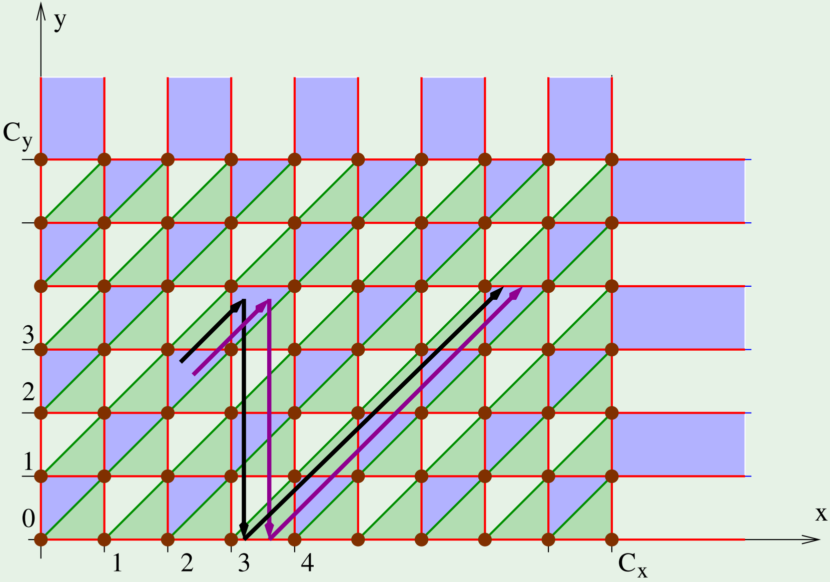

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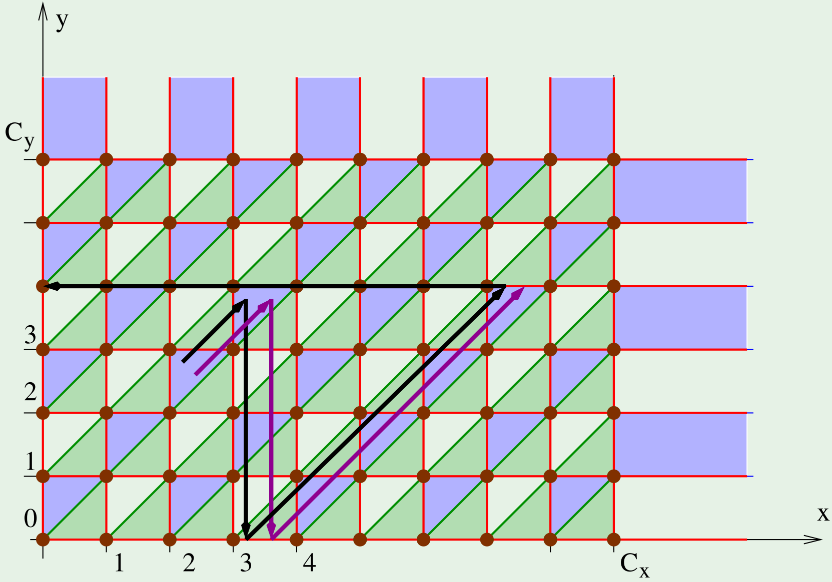

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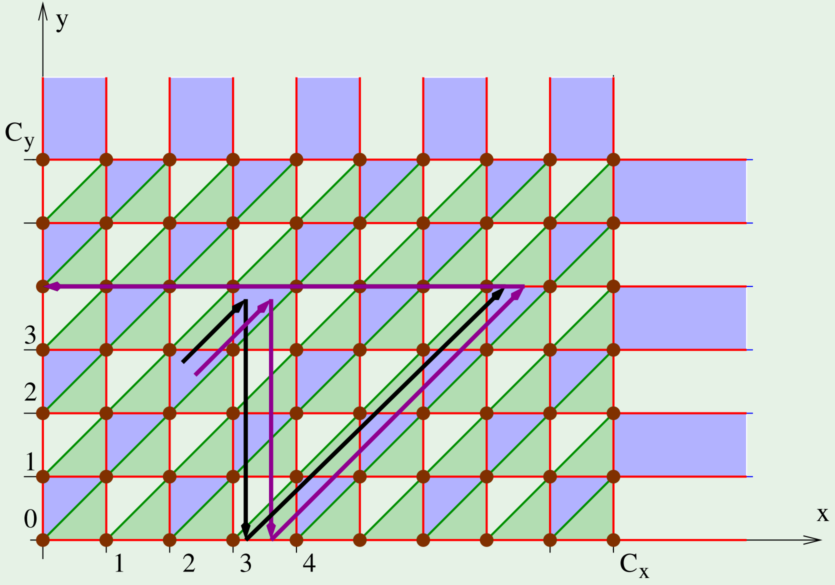

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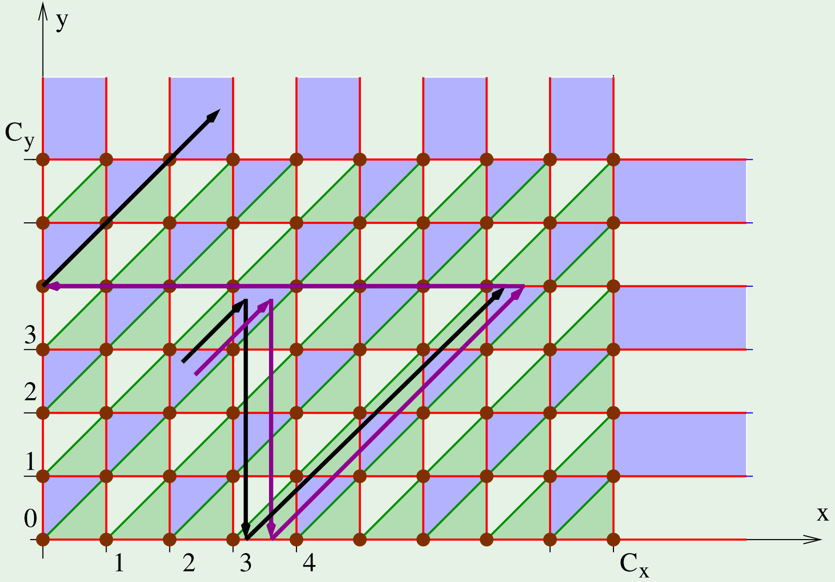

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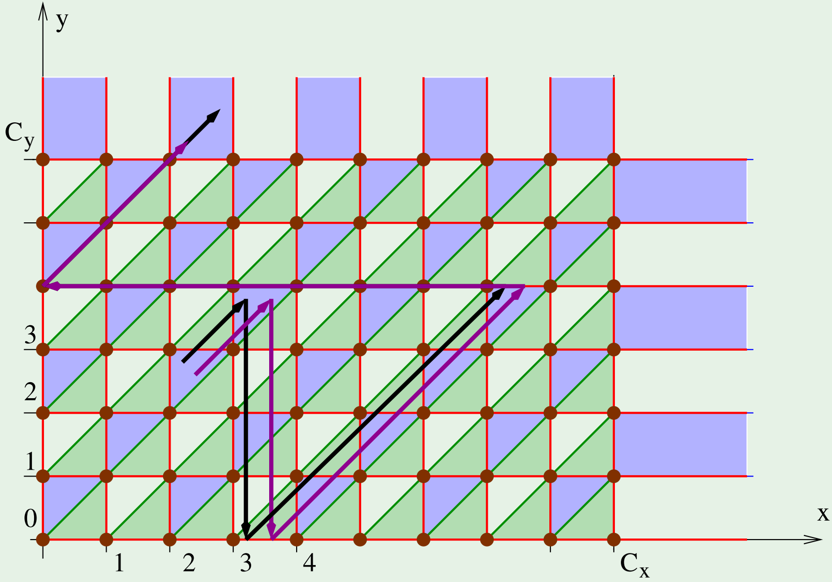

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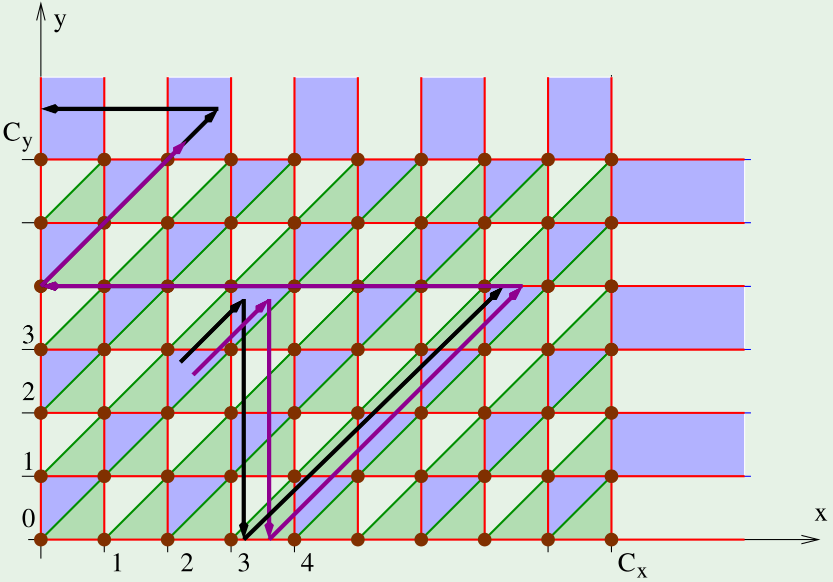

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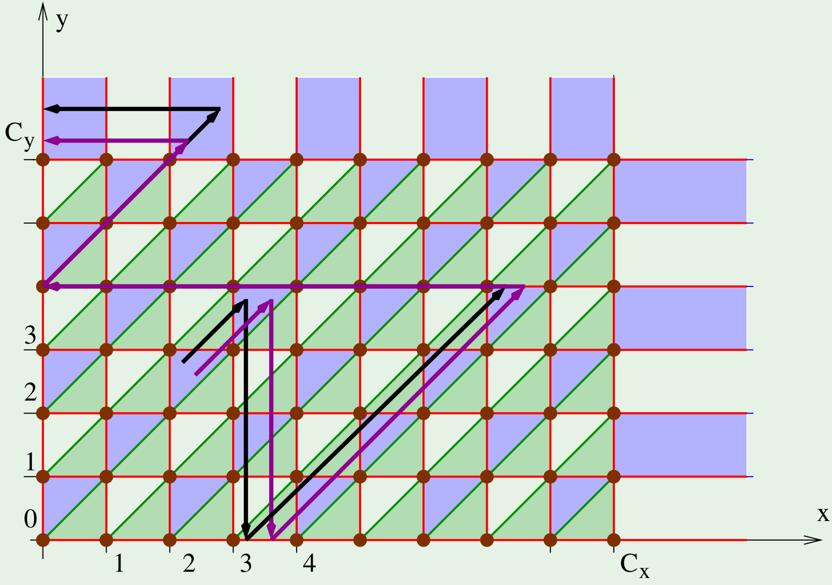

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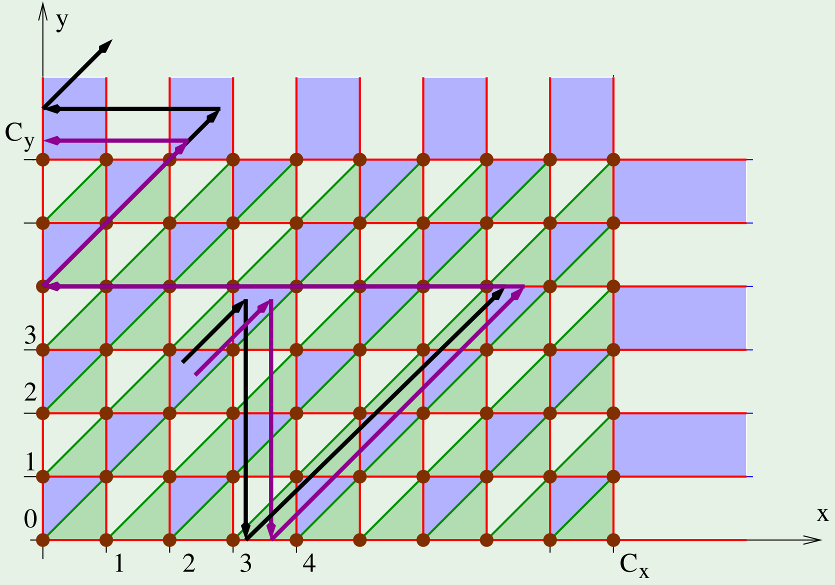

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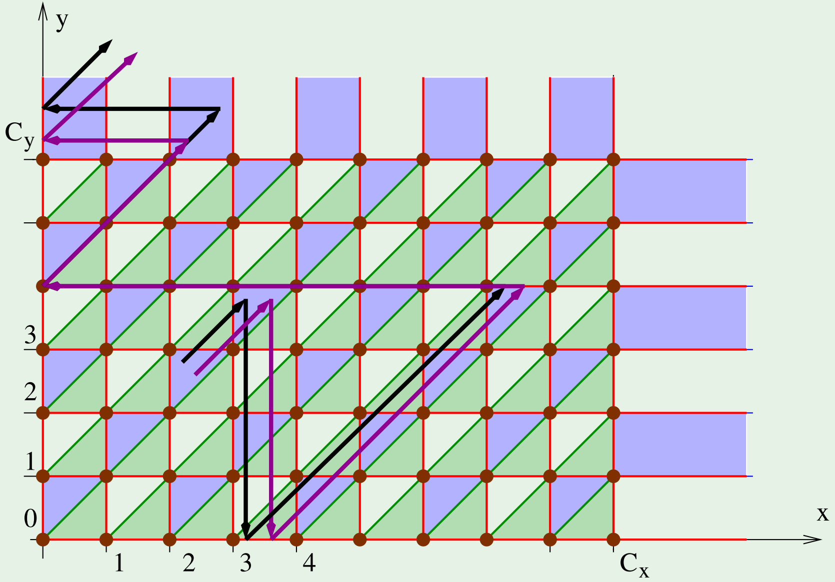

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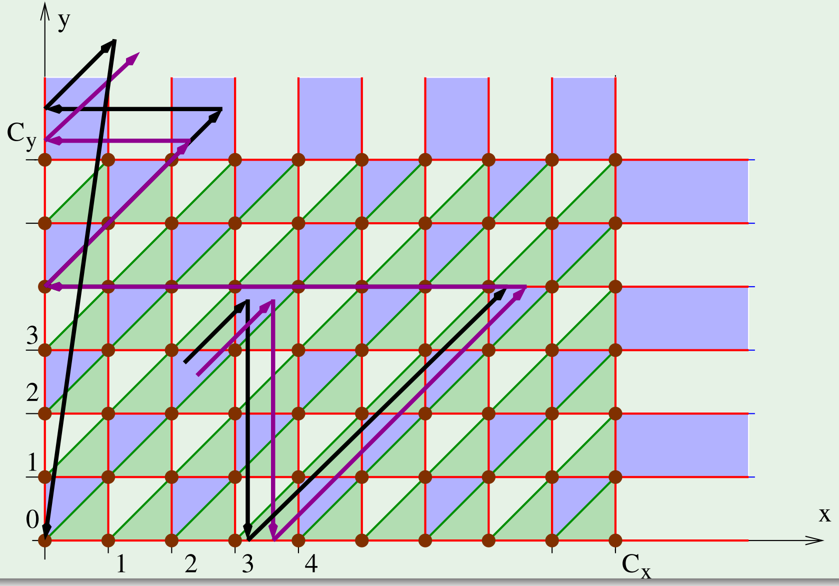

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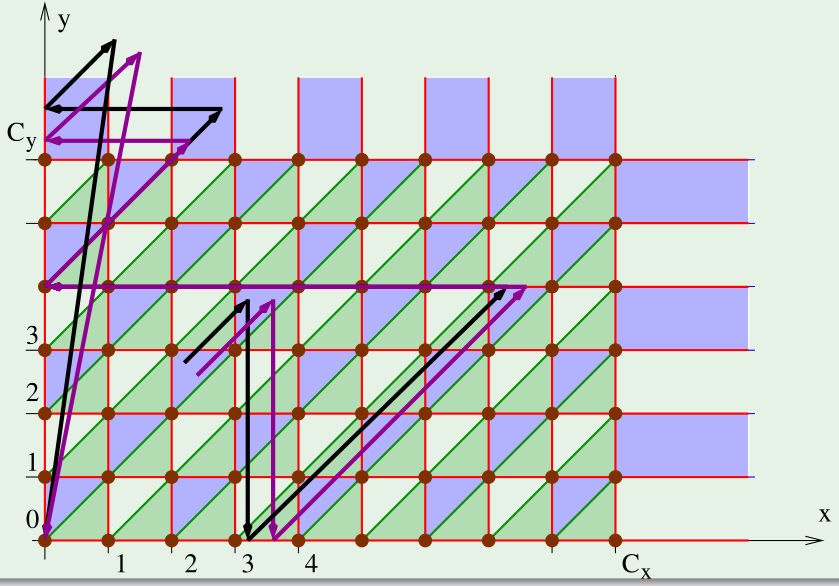


Number of Clock Regions

- Clock region: equivalence class of clock interpretations
- Number of clock regions upper-bounded by

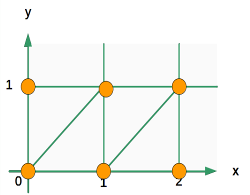
$$k! \cdot 2^k \cdot \Pi_{x \in X}(2 \cdot C_x + 2), \quad s.t.\ k \stackrel{\text{def}}{=} ||X||$$

  - finite!
  - exponential in the number of clocks
  - grows with the values of C_x

Example

- 2 clocks x,y, $C_x = 2$, $C_y = 1$
  - 8 open regions
  - 14 open line segments
  - 6 corner points

  $\Longrightarrow$ 28 regions $< 2 \cdot 2^2 \cdot (2 \cdot 2 + 2) \cdot (2 \cdot 1 + 2) = 192$



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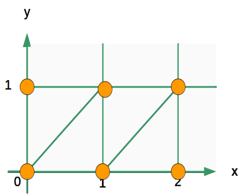

Region automaton

- Equivalent states = identical location + $\cong$-equivalent evaluations
- Equivalent Classes (regions): finite, stable, L^F-sensitive
- $R(A)$: Region automaton of A
  - States: $\langle l, r(A) \rangle$ s.t. $r(A)$ regions of A

  $\Longrightarrow$ Finite state automaton!
- Reachability problem $\langle A, L^F \rangle \Longrightarrow$ Reachability problem $\langle R(A), L^F \rangle$

$\Longrightarrow$ Reachability in timed automata reduced to that in finite automata!

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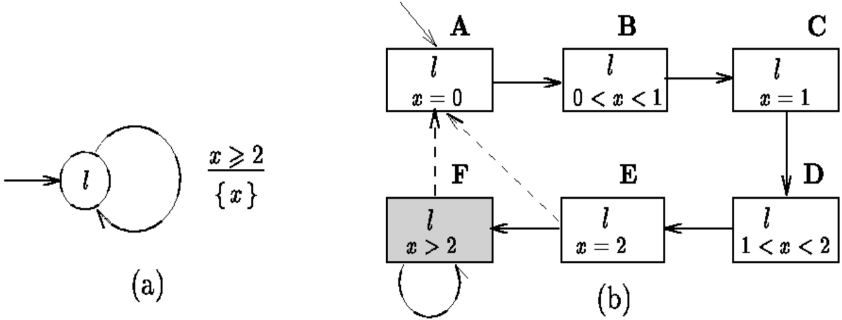
Example: Region graph of a simple timed automata



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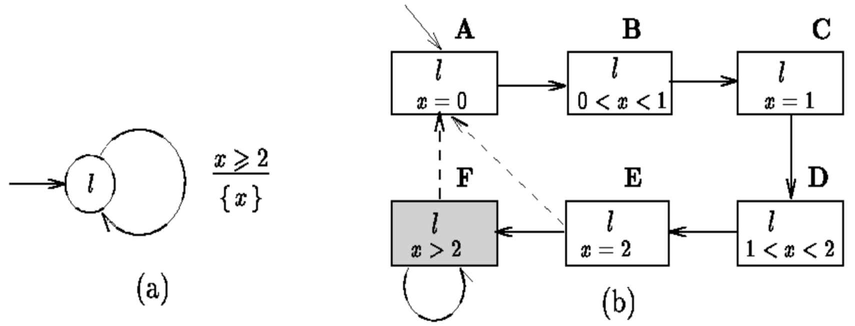

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Complexity of Reasoning with Timed Automata

Reachability in Timed Automata

- Decidable!
- Linear with number of locations
- Exponential in the number of clocks
- Grows with the values of C_x
- Overall, PSPACE-Complete

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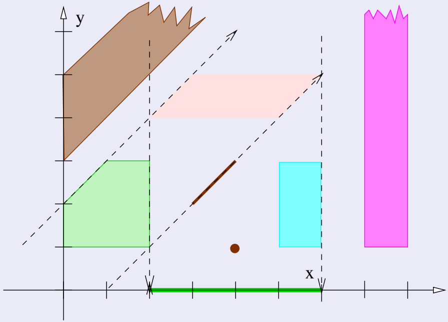
Outline

Zone Automata

- Collapse regions by convex unions of clock regions
- Clock Zone φ: set/conjunction of clock constraints in the form $(x_i \bowtie c)$, $(x_i - x_j \bowtie c)$, $\bowtie \in \{>, <, =, \geq, \leq\}$, $c \in \mathbb{Z}$
- φ is a convex set in the k-dimensional euclidean space
  - possibly unbounded

$\Longrightarrow$ Contains all possible relationship for all clock value in a set

- Symbolic state: $\langle l, \varphi \rangle$
  - l: location
  - φ: clock zone



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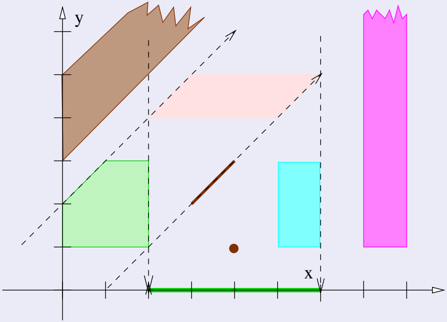

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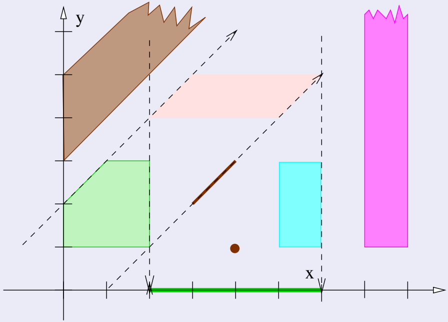

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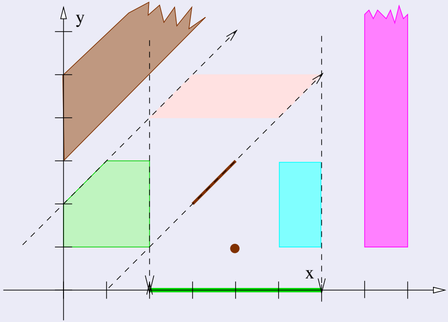

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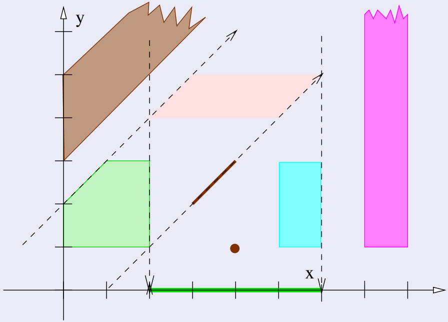

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Definition: Zone Automaton

- Given a Timed Automaton $A \stackrel{\text{def}}{=} \langle L, L^0, \Sigma, X, \Phi(X), E \rangle$, the Zone Automaton Z(A) is a transition system $\langle Q, Q^0, \Sigma, \rightarrow \rangle$ s.t.
  - Q: set of all symbolic states of A (a symbolic state is $\langle l, \varphi \rangle$)
  - $Q^0 \stackrel{\text{def}}{=} \{\langle l, [X := 0] \rangle \mid l \in L^0\}$
  - Σ: set of labels/events in A
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Zone Automata: Symbolic Transitions

Definition: $succ(\varphi, e)$

- Let $e \stackrel{\text{def}}{=} \langle l, a, \psi, \lambda, l' \rangle$, and ϕ, ϕ' the invariants in l, l'
- Then

$$succ(\varphi, e) \stackrel{\text{def}}{=} (((\varphi \wedge \phi)\Uparrow \ \wedge \phi) \wedge \psi)[\lambda := 0]$$

  - $\wedge$: standard conjunction/intersection
  - $\Uparrow$: projection to infinity: $\psi\Uparrow \stackrel{\text{def}}{=} \{\nu + \delta \mid \nu \in \psi, \delta \in [0, +\infty)\}$
  - $[\lambda := 0]$: reset projection: $\psi[\lambda := 0] \stackrel{\text{def}}{=} \{\nu[\lambda := 0] \mid \nu \in \psi\}$
- note: φ is considered "immediately before entering l"

Zone Automata: Symbolic Transitions (cont.)

- Initial zone: values before entering the location
- Intersection with invariant ϕ: values allowed to enter the location
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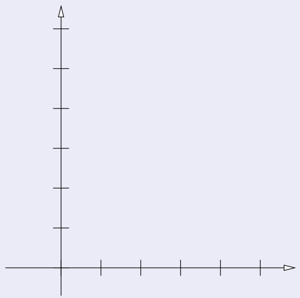

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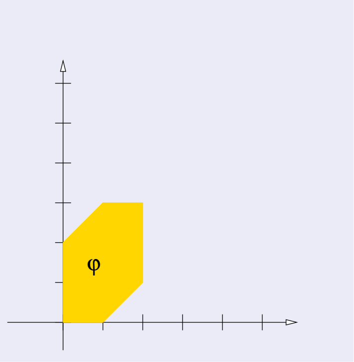

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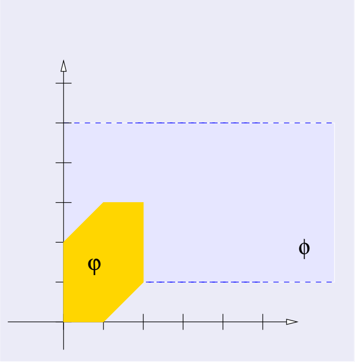

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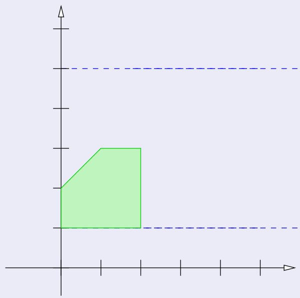

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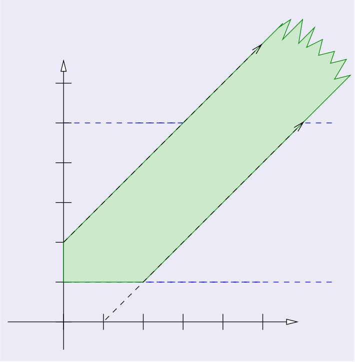

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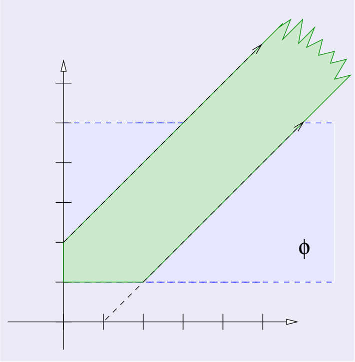

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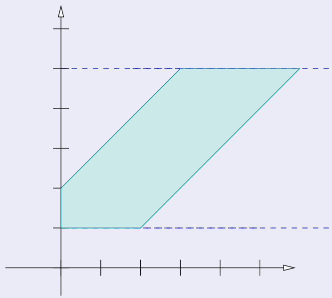

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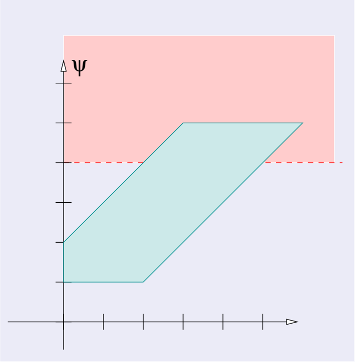

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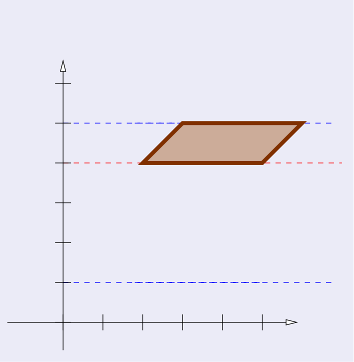

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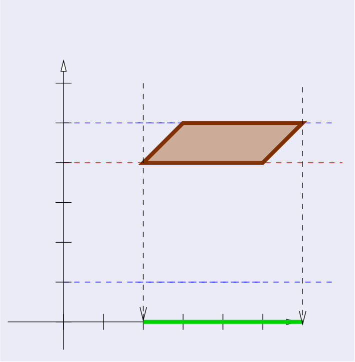

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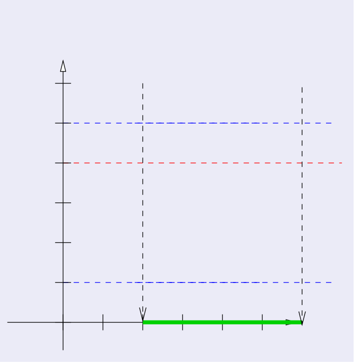

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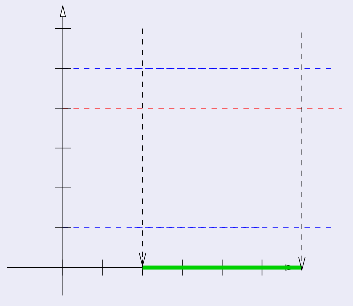

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Example: Zone Automata, Symbolic Transitions

- Initial zone: $(x \geq 0) \wedge (x \leq 2) \wedge$ $(y \geq 0) \wedge (y \leq 3) \wedge (y - x \geq -1) \wedge (y - x \leq 2)$
- Intersection with invariant ϕ : $(y \geq 1) \wedge (y \leq 5)$
  $\Longrightarrow (x \geq 0) \wedge (x \leq 2) \wedge (y \geq 1) \wedge$ $(y \leq 3) \wedge (y - x \leq 2)$
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- Intersection with guard ψ : $(y \geq 4)$
  $\Longrightarrow (y \geq 4) \wedge (y \leq 5) \wedge$ $(y - x \geq -1) \wedge (y - x \leq 2)$
- Reset projection $\lambda \stackrel{\text{def}}{=} \{y := 0\}$
  $\Longrightarrow (x \geq 2) \wedge (x \leq 6) \wedge (y \geq 0) \wedge (y \leq 0)$

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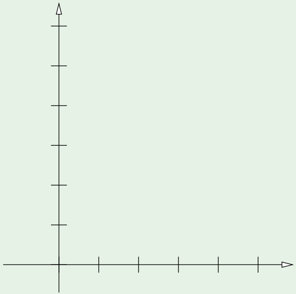

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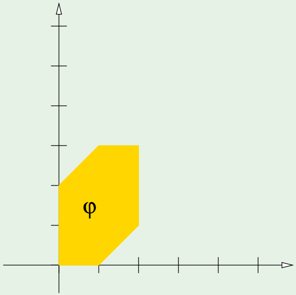

Example: Zone Automata, Symbolic Transitions

- Initial zone: $(x \geq 0) \wedge (x \leq 2) \wedge$
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  $\Longrightarrow \; (x \geq 2) \wedge (x \leq 6) \wedge (y \geq 0) \wedge (y \leq 0)$

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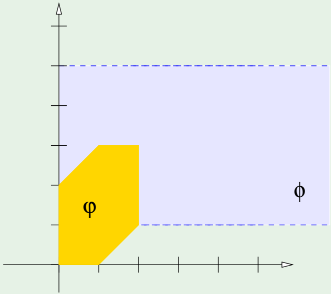

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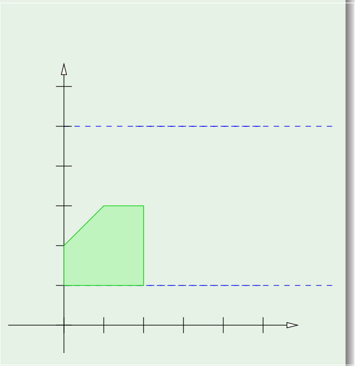

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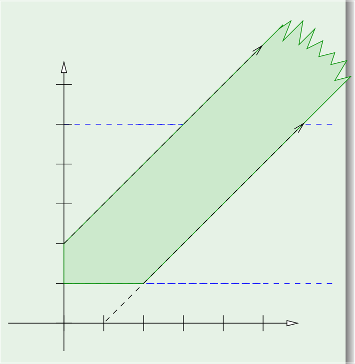

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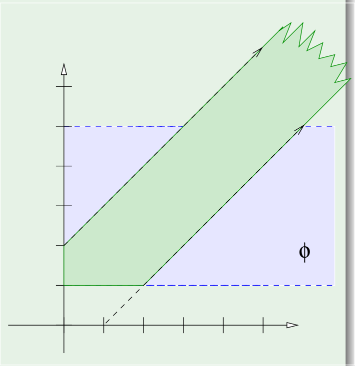

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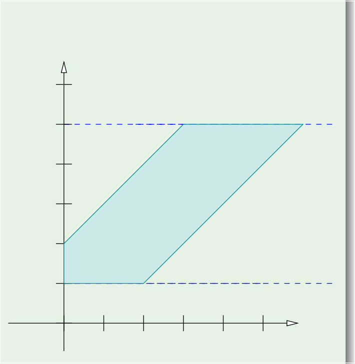

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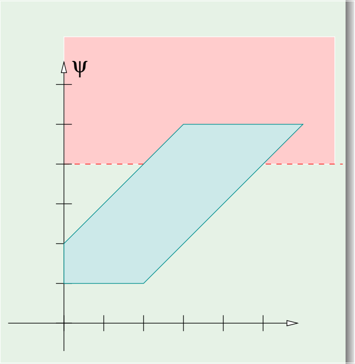

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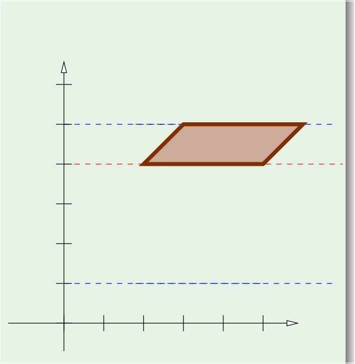

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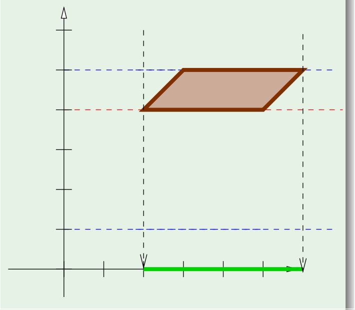

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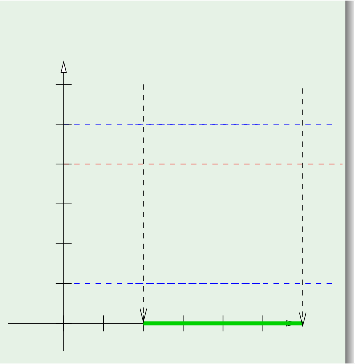

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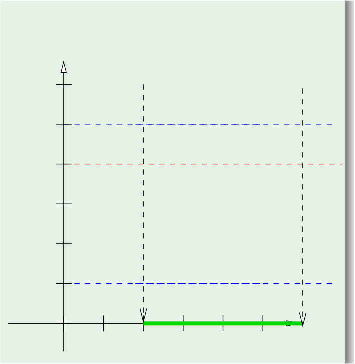

$\Longrightarrow$ Final!

Remark on $succ(\varphi, e)$

- In the above definition of $succ(\varphi, e)$, φ is considered "immediately before entering l":

$$succ(\varphi, e) \stackrel{\text{def}}{=} (((\varphi \wedge \phi)\Uparrow \ \wedge \phi) \wedge \psi)[\lambda := 0]$$

- Alternative definition of $succ(\varphi, e)$, φ is considered "immediately after entering l":

$$succ(\varphi, e) \stackrel{\text{def}}{=} (((\varphi\Uparrow \ \wedge \phi) \wedge \psi)[\lambda := 0] \wedge \phi')$$

  - no initial intersection with the invariant ϕ of source location l (here φ is assumed to be already the result of such intersection)
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Symbolic Reachability Analysis

function Reachable (A, L^F) $\quad$ // $A \stackrel{\text{def}}{=} \langle L, L^0, \Sigma, X, \Phi(X), E \rangle$
$\quad$ $\mathit{Reachable} = \emptyset$
$\quad$ $\mathit{Frontier} = \{\langle l_i, \{X = 0\}\rangle \mid l_i \in L^0\}$
$\quad$ **while** $(\mathit{Frontier} \neq \emptyset)$ **do**
$\quad\quad$ *extract* $\langle l, \varphi \rangle$ *from* $\mathit{Frontier}$
$\quad\quad$ **if** $(l \in L^F$ *and* $\varphi \neq \bot)$ **then**
$\quad\quad\quad$ **return** True
$\quad\quad$ **end if**
$\quad\quad$ **if** $(\nexists\, \langle l, \varphi' \rangle \in \mathit{Reachable}\ s.t.\ \varphi \subseteq \varphi')$ **then**
$\quad\quad\quad$ *add* $\langle l, \varphi \rangle$ *to* $\mathit{Reachable}$
$\quad\quad\quad$ **for** $e \in \mathit{outcoming}(l)$ **do**
$\quad\quad\quad\quad$ *add* $\mathit{succ}(\varphi, e)$ *to* $\mathit{Frontier}$
$\quad\quad\quad$ **end for**
$\quad\quad$ **end if**
$\quad$ **end while**
$\quad$ **return** False

Canonical Data-structures for Zones: DBMs

Difference-bound Matrices (DBMs)

- Matrix representation of constraints
  - bounds on a single clock
  - differences between 2 clocks
- Reduced form computed by all-pairs shortest path algorithm (e.g. Floyd-Warshall)
- Reduced DBM is canonical:
  equivalent sets of constraints produce the same reduced DBM
- Operations s.a reset, time-successor, inclusion, intersection are efficient

$\Longrightarrow$ Popular choice in timed-automata-based tools

Difference-bound matrices, DBMs

- DBM: matrix $(k+1) \times (k+1)$, k being the number of clocks
  - added an implicit fake variable $x_0 \stackrel{\text{def}}{=} 0$ s.t. $x_i \bowtie c \implies x_i - x_0 \bowtie c$
  - each element is a pair (value,$\{0,1\}$), s.t "$\{0,1\}$" means "$\{<, \leq\}$"

Example:

$$(0 \leq x_1) \quad \wedge(0 < x_2) \quad \wedge(x_1 < 2) \quad \wedge(x_2 < 1) \quad \wedge(x_1 - x_2 \geq 0)$$
$$(x_0 - x_1 \leq 0) \quad \wedge(x_0 - x_2 < 0) \quad \wedge(x_1 - x_0 < 2) \quad \wedge(x_2 - x_0 < 1) \quad \wedge(x_2 - x_1 \leq 0)$$

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Example:

$(0 \leq x_1)$ $\wedge(0 < x_2)$ $\wedge(x_1 < 2)$ $\wedge(x_2 < 1)$ $\wedge(x_1 - x_2 \geq 0)$

$(x_0 - x_1 \leq 0)$ $\wedge(x_0 - x_2 < 0)$ $\wedge(x_1 - x_0 < 2)$ $\wedge(x_2 - x_0 < 1)$ $\wedge(x_2 - x_1 \leq 0)$

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Example:

$$
\begin{array}{lllll}
(0 \leq x_1) & \wedge(0 < x_2) & \wedge(x_1 < 2) & \wedge(x_2 < 1) & \wedge(x_1 - x_2 \geq 0) \\
(x_0 - x_1 \leq 0) & \wedge(x_0 - x_2 < 0) & \wedge(x_1 - x_0 < 2) & \wedge(x_2 - x_0 < 1) & \wedge(x_2 - x_1 \leq 0)
\end{array}
$$

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Matrix D	0	1	2
0	∞	(0,1)	(0,0)
1	(2,0)	∞	∞
2	(1,0)	(0,1)	∞

D_{0i} = lower bound

D_{i0} = upper bound

D_{ij} = upper bound of x_i and x_j difference

- i,j: $(c,1)$ → Xi-Xj $\leq c$
- i,j: $(c,0)$ → Xi-Xj $< c$
- i,j: ∞ → absence of bound

Difference-bound matrices, DBMs (cont.)

- Use all-pairs shortest paths, check DBM
  - idea: given $x_i - x_j \bowtie c$, $x_i - x_k \bowtie c_1$ and $x_k - x_j \bowtie c_2$ s.t. $\bowtie \in \{\leq, <\}$,
    then c is updated with $c_1 + c_2$ if $c_1 + c_2 < c$
  - Satisfiable (no negative loops) $\Longrightarrow$ a non-empty clock zone
  - Canonical: matrices with tightest possible constraints
- Canonical DBMs represent clock zones:
  equivalent sets of constraints $\Longleftrightarrow$ same reduced DBM

	Matrix D			Matrix D'		
	0	1	2	0	1	2
0	∞	(0,1)	(0,0)	(0, 1)	(0,1)	(0,0)
1	(2,0)	∞	∞	(2,0)	(0,1)	(2,0)
2	(1,0)	(0,1)	∞	(1,0)	(0,1)	(0,1)

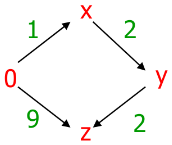
Canonical Data-structures for Zones: DBMs

When are two sets of constraints equivalent?

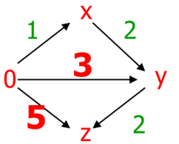
D1

x<=1
y-x<=2
z-y<=2
z<=9

Graph



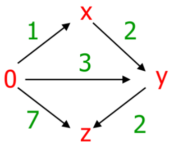
Shortest Path Closure



D2

x<=1
y-x<=2
y<=3
z-y<=2
z<=7

Graph



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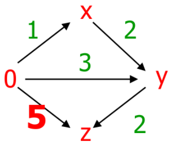

Complexity Issues

- In theory:
  - Zone automaton might be exponentially bigger than the region automaton
- In practice:
  - Fewer reachable vertices $\Longrightarrow$ performances much improved

Timed Automata: summary

- Only continuous variables are timers
- Invariants and Guards: $x \bowtie const$, $\bowtie \in \{<, >, \leq, \geq\}$
- Actions: x:=0
- Reachability is decidable
- Clustering of regions into zones desirable in practice
- Tools: Uppaal, Kronos, RED ...
- Symbolic representation: matrices

Decidable Problems with Timed Automata

- Model checking branching-time properties of timed automata
- Reachability in rectangular automata
- Timed bisimilarity: are two given timed automata bisimilar?
- Optimization: Compute shortest paths (e.g. minimum time reachability) in timed automata with costs on locations and edges
- Controller synthesis: Computing winning strategies in timed automata with controllable and uncontrollable transitions

Outline

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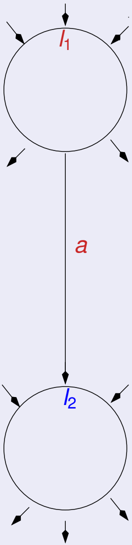
Hybrid Automata

Hybrid Automata

- Locations, Switches, Labels (like in standard aut.)
- Continuous variables: $X \stackrel{\text{def}}{=} \{x_1, x_2, ..., x_k\} \in \mathbb{R}$
  - value evolves with time
  - e.g., distance, speed, pressure, temperature, ...
- Guards: $g(X) \geq 0$
  - sets of inequalities (equalities) on functions on X
  - constrain the execution of the switch
- Jump Transformations $J(X, X')$
  - discrete transformation on the values of X
- Invariants: $X \in Inv_l(X)$
  - set of invariant constraints on X
  - ensure progress
- Continuous Flow: $\frac{dX}{dt} \in flow_l(X)$
  - set of degree-1 differential (in)equalities
  - describe continuous dynamics
- Initial: $X \in Init_l(X)$
  - initial conditions ($Init_l(X) = \perp$ iff $l \notin L^0$)



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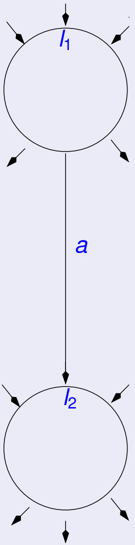

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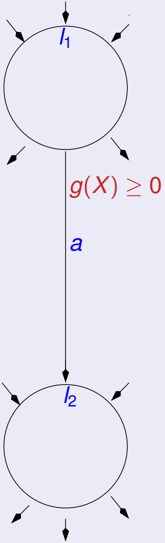

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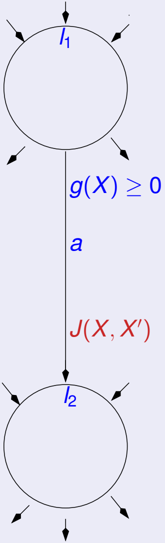

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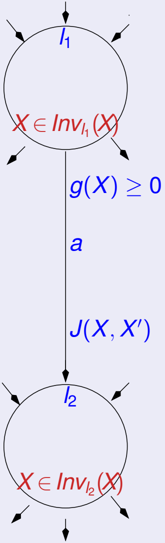

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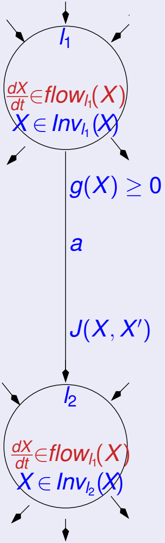

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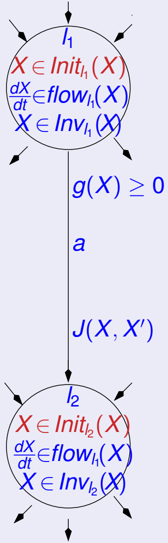

Hybrid Automata $A = \langle L, L^0, X, \Sigma, \Phi(X), E \rangle$

- L: Set of locations,
- $L^0 \in L$: Set of initial locations (s.t. $Init_l(X) = \perp$ iff $l \notin L_0$)
- X: Set of k continuous variables
- $\Phi(X)$: Set of Constraints on X
- Σ: Set of synchronization labels (alphabet)
- E: Set of edges
- State space: $L \times \mathbb{R}^k$,
  - state: $\langle l, \psi \rangle$ s.t. $l \in L$ and $\psi \in \mathbb{R}^k$
  - region ψ: subset of $\mathbb{R}^k$
- For each location l:
  - Initial states: region $Init_l(X)$
  - Invariant: region $Inv_l(X)$
  - Continuous dynamics: $\frac{dX}{dt} \in flow_l(X)$
- For each edge e from location l to location l'
  - Guard: region $g(X) \geq 0$
  - Update relation "Jump" $J(X, X')$ over $\mathbb{R}^k \times \mathbb{R}^k$
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Remark: Degree of $flow_l(X)$

- Continuous dynamics described w.l.o.g. with sets of degree-1 differential (in)equalities $flow_l(X)$
- Sets/conjunctions of higher-degree differential (in)equalities can be reduced to degree 1 by renaming
- Ex:

$$\left(a_1 \frac{d^2 s}{dt^2} + a_2 \frac{ds}{dt} + a_3 s + a_4 \bowtie 0\right)$$
$$\Downarrow$$
$$\left(v = \frac{ds}{dt}\right) \wedge \left(a_1 \frac{dv}{dt} + a_2 v + a_3 s + a_4 \bowtie 0\right)$$

(Finite) Executions of Hybrid Automata

- State: pair $\langle l, X \rangle$ such that $X \in Inv_l(X)$
- Initialization: $\langle l, X \rangle$ such that $X \in Init_l(X)$
- Two types of state updates (transitions)
  - Discrete switches: $\langle l, X \rangle \xrightarrow{a} \langle l', X' \rangle$
    if there there is an a-labeled edge e from l to l' s.t.
    - X, X' satisfy $Inv_l(X)$ and $Inv_{l'}(X)$ respectively
    - X satisfies the guard of e (i.e., $g(X) \geq 0$) and
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    $f(t) \stackrel{\text{def}}{=} \langle f_0(t), ..., f_k(t) \rangle \ : \ [0, \delta] \longmapsto \mathbb{R}^k$ is a continuous function s.t.
    - $f(0) = X$
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    - for every $t \in [0, \delta]$, $f(t) \in Inv_l(X)$
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(Finite) Executions of Hybrid Automata

- State: pair $\langle l, X \rangle$ such that $X \in Inv_l(X)$
- Initialization: $\langle l, X \rangle$ such that $X \in Init_l(X)$
- Two types of state updates (transitions)
  - Discrete switches: $\langle l, X \rangle \xrightarrow{a} \langle l', X' \rangle$
    if there there is an a-labeled edge e from l to l' s.t.
    - X, X' satisfy $Inv_l(X)$ and $Inv_{l'}(X)$ respectively
    - X satisfies the guard of e (i.e. $g(X) \geq 0$) and
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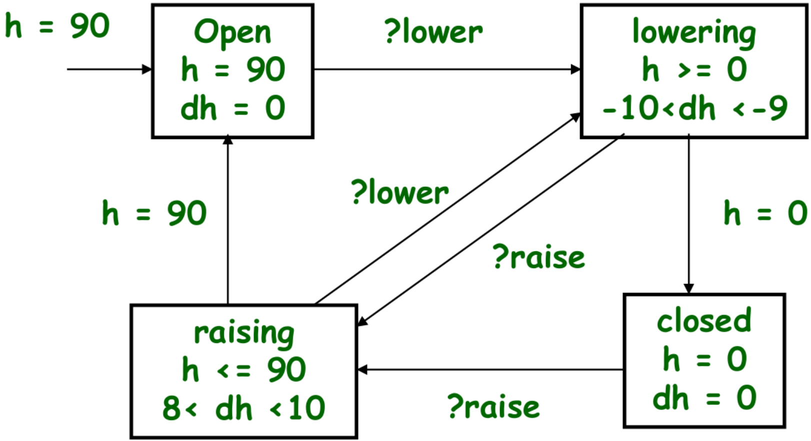
Example: Gate for a railroad controller



Notation: “*dh*” shortcut for “$\frac{dh}{dt}$”

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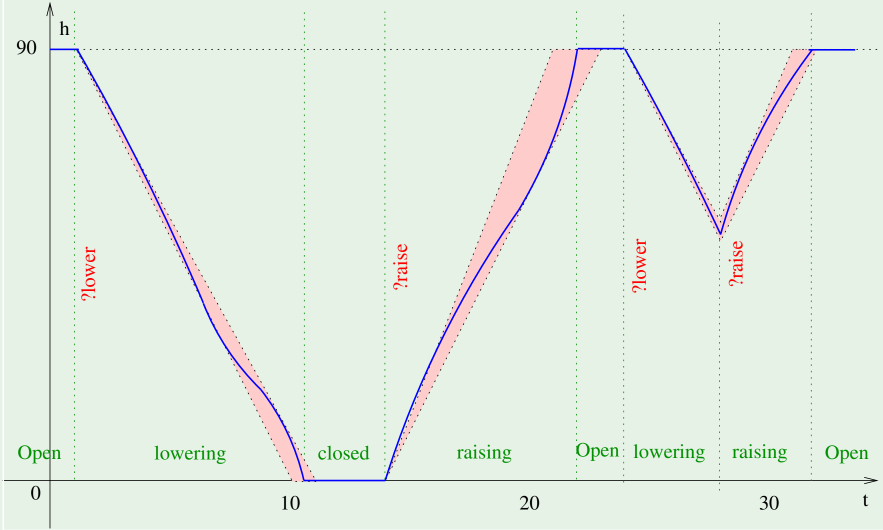

Outline

General Symbolic-Reachability Schema

```
R = I(X)
while (True) do
    if (R intersects F) then
        return True
    else
        if (Image(R) ⊆ R) then
            return False
        else
            R = R ∪ Image(R)
        end if
    end if
end while
```

- I: initial; F: Final; R: Reachable; Image(R): successors of R
- need a data type to representt state sets (regions)
- Termination may or may not be guaranteed

Symbolic Representations

- Necessary operations on Regions
  - Union
  - Intersection
  - Negation
  - Projection
  - Renaming
  - Equality/containment test
  - Emptiness test
- Different choices for different classes of problems
  - BDDs for Boolean variables in hardware verification
  - DBMs in Timed automata
  - Polyhedra in Linear Hybrid Automata
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Reachability for Hybrid Systems

- Same algorithm works in principle
- Problem: What is a suitable representation of regions?
  - Region: subset of $\mathbb{R}^k$
  - Main problem: handling continuous dynamics
- Precise solutions available for restricted continuous dynamics
  - Timed automata
  - Multi-rate & Rectangular Hybrid Automata (reduced to Timed aut.)
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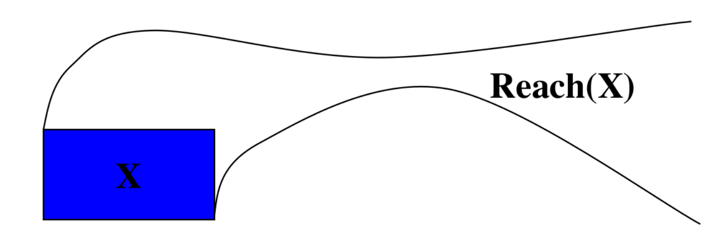
Reachability Analysis for Dynamical Systems

- Goal: Given an initial region, compute whether a bad state can be reached
- Key step: compute Reach(X) for a given set X under $\frac{dX}{dt} = f(X)$



Notation: (hereafter we often use "dX" or "$\dot{X}$" as a shortcut of "$\frac{dX}{dt}$"

Outline

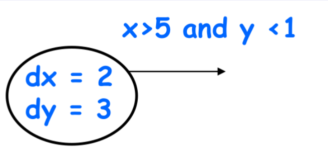
Simple Hybrid Automata: Multi-Rate and Rectangular

Two simple forms of Hybrid Automata

- Multi-Rate Automata
- Rectangular Automata
- Idea: can be reduced to Timed Automata
- typically used as over-approximations of complex hybrid automata

Multi-rate Automata

- Modest extension of timed automata
  - Dynamics of the form $\frac{dX}{dt} = const$
    s.t. the rate of of each variable is the same in all locations
  - Guards and invariants: $x < const$, $x > const$
  - Resets: $x := const$
- Simple translation to timed automata by shifting and scaling:
  - if $x_i := d_i$ then rename it with a fresh var v_i s.t. $v_i + d_i = x_i$
  - if $\frac{dx_i}{dt} = c_i$, then rename it with a fresh var u_i s.t. $c_i \cdot u_i = x_i$
  - shift & rescale constants in constraints accordingly



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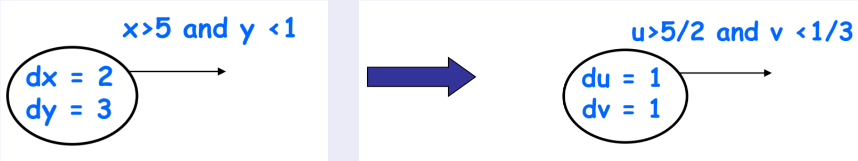

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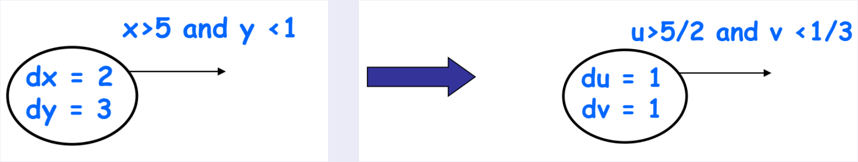

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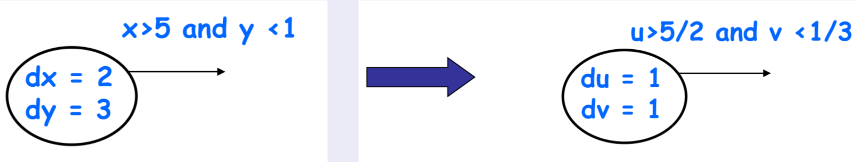

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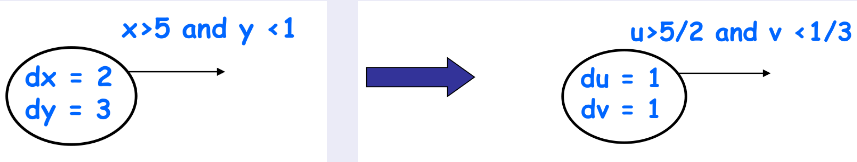

Rectangular Automata (simplified)

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  - invariants: substitute $Inv_l(x)$ with $Inv_l(x_M), Inv_l(x_m)$
  - guards: substitute $x > c$ with $x_M > c$, add jump $x_m := c$ (if none)
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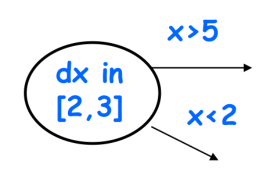

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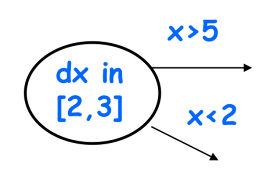

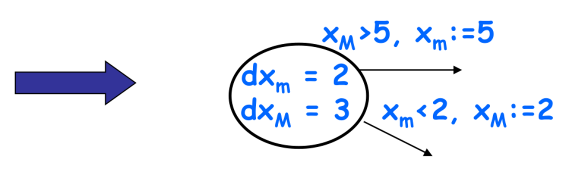

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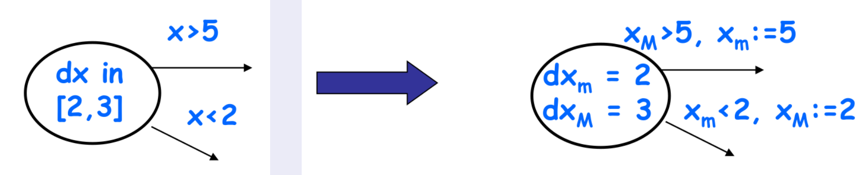

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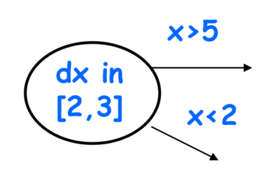

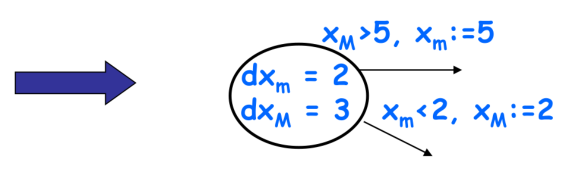

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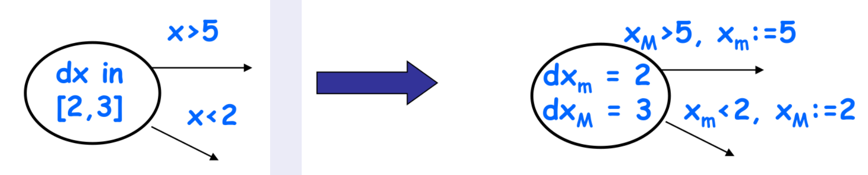

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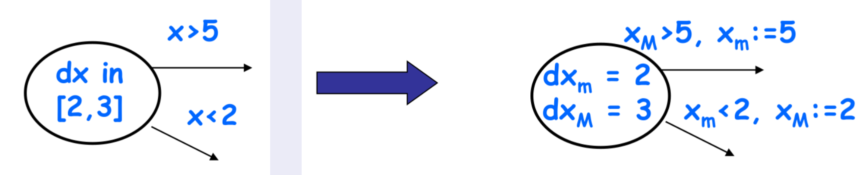

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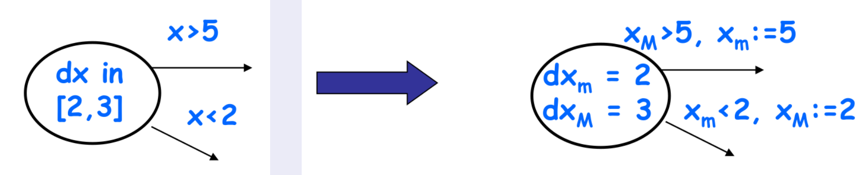

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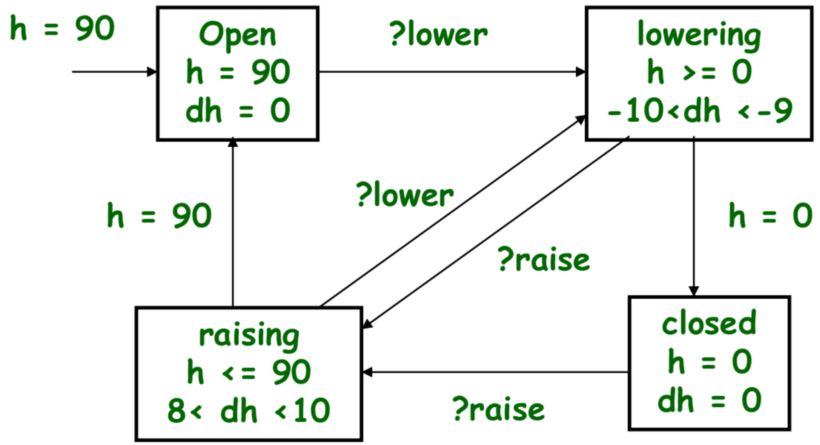


Outline

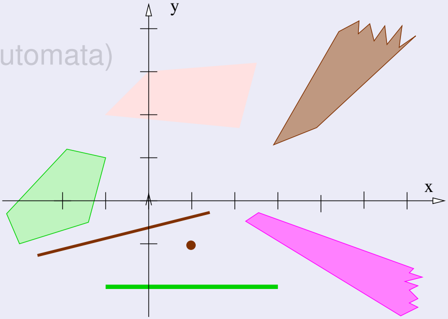
Linear Hybrid Automata

- Polyhedron φ: set/conjunction of linear inequalities on X in the form $(A \cdot X \geq B)$, s.t. $A \in \mathbb{R}^m \times \mathbb{R}^k$ and $B \in \mathbb{R}^m$ for some m.
- φ is a convex set in the k-dimensional euclidean space
  - possibly unbounded

$\Longrightarrow$ Contains all possible values for all variables in a set

- Symbolic state: $\langle l, \varphi \rangle$
  - l: location
  - φ: polyhedron

(generalization of zone automata)



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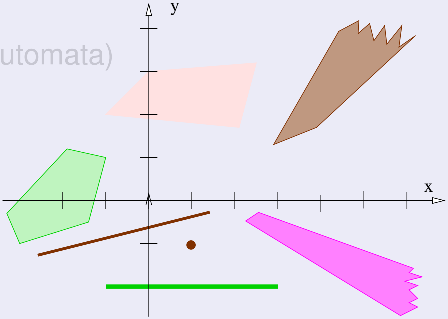

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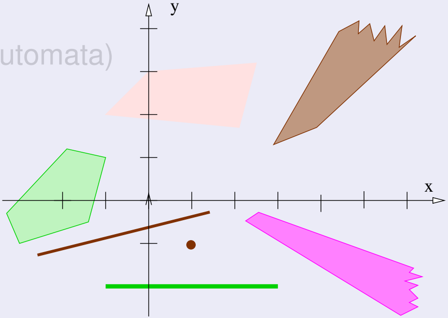

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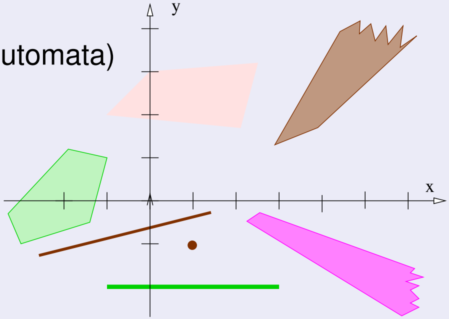
(generalization of zone automata)



Linear Hybrid Automata $A = \langle L, L^0, X, \Sigma, \Phi(X), E \rangle$

- State space: $L \times \mathbb{R}^k$,
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Continuous Dynamics

Time-invariant, state-independent dynamics specified by a convex polyhedron constraining first derivatives
Es: $\frac{dx}{dt} \geq 3$, $\frac{dx}{dt} = \frac{dy}{dt}$, $2.1\frac{dx}{dt} - 3.5\frac{dy}{dt} + 1.7\frac{dz}{dt} \geq 3.1$, ...

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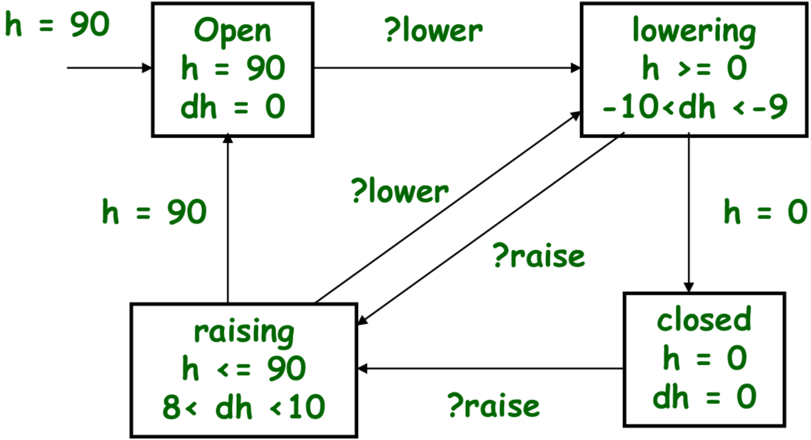
Example: Gate for a railroad controller



Reachability Computation: Key Steps

- Compute "discrete" successors of $\langle l, \psi \rangle$
- Compute "continuous" successor of $\langle l, \psi \rangle$
- Check if ψ intersects with "bad" region
- Check if newly-found ψ is covered by already-visited polyhedra $\psi_1, ..., \psi_n$ (expensive!)

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Computing Discrete Successors of $\langle l, \psi \rangle$

- Intersect ψ with the guard ϕ
  $\Longrightarrow$ result is a polyhedron
- Apply linear transformation of J to the result
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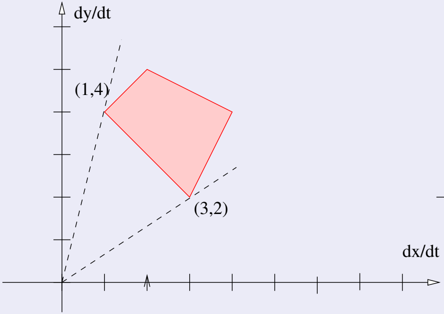
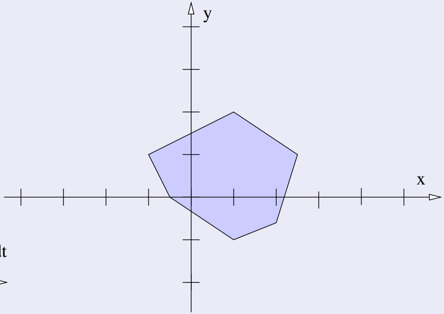
- Consider maximum and minimum rates between derivatives (external vertices in the flow polyhedron)
- Apply these extremal rates for computing the projection to infinity (to be intersected with invariant)
  - Hint: $\frac{dy}{dx} = \frac{\frac{dy}{dt}}{\frac{dx}{dt}}$, s.t. $max_{x,y}\frac{dy}{dx} = max_{x,y}\frac{\frac{dy}{dt}}{\frac{dx}{dt}}$ and $min_{x,y}\frac{dy}{dx} = min_{x,y}\frac{\frac{dy}{dt}}{\frac{dx}{dt}}$





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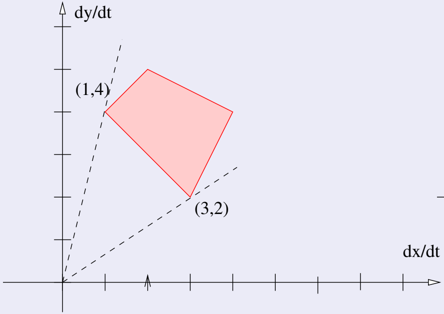

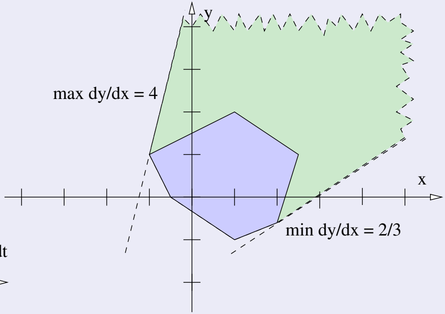

Linear Hybrid Automata: Symbolic Transitions

Definition: $succ(\varphi, e)$

- Let $e \stackrel{\text{def}}{=} \langle l, a, \psi, J, l' \rangle$, and ϕ, ϕ' the invariants in l, l'
- Then

$$succ(\varphi, e) \stackrel{\text{def}}{=} J(((\varphi \wedge \phi)\Uparrow \wedge \phi) \wedge \psi)$$

(φ immediately before entering the location)

$$succ(\varphi, e) \stackrel{\text{def}}{=} J((\varphi\Uparrow \wedge \phi) \wedge \psi) \wedge \phi'$$

(φ immediately after entering the location):

  - $\wedge$: standard conjunction/intersection
  - $\Uparrow$: continuous successor $\psi\Uparrow$
  - J: Jump transformation $J(X) \stackrel{\text{def}}{=} T \cdot X$
- note: φ is considered “immediately after entering l”

Linear Hybrid Automata: Symbolic Transitions (cont.)

- Initial zone: values allowed to enter location *l*
- Projection to infinity: ... after waiting unbounded time
- Intersection with invariant ϕ: ... waiting a legal amount of time
- Intersection with guard ψ: ... from which the switch can be shot
- Jump *J*: ..., after jump
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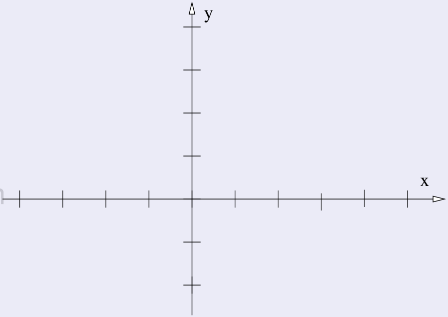
$\Longrightarrow$ Final!



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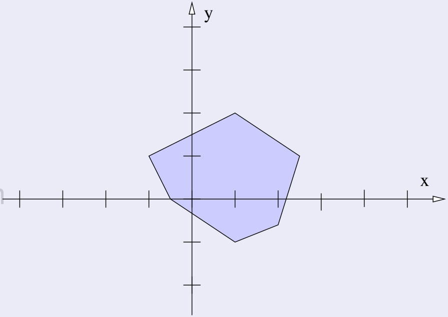

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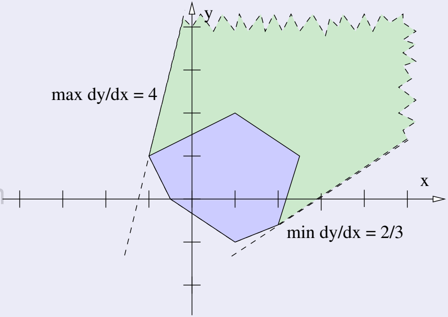

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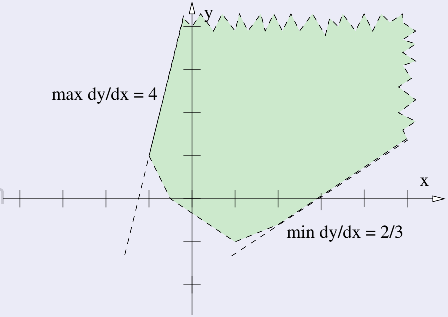

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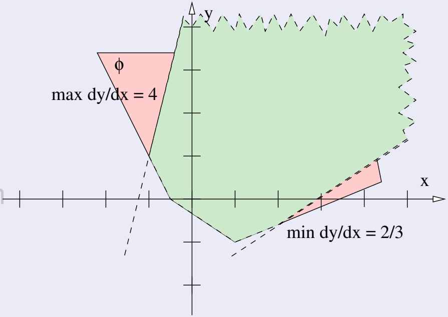

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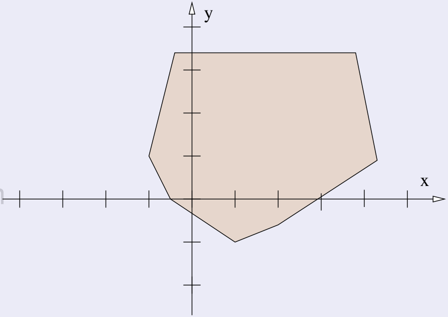

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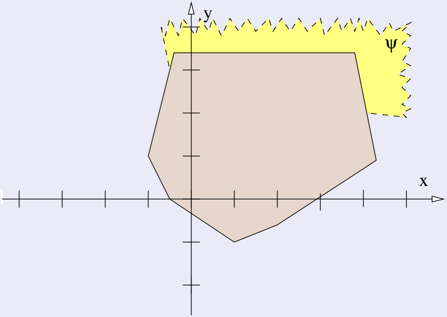

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Linear Hybrid Automata: Symbolic Transitions (cont.)

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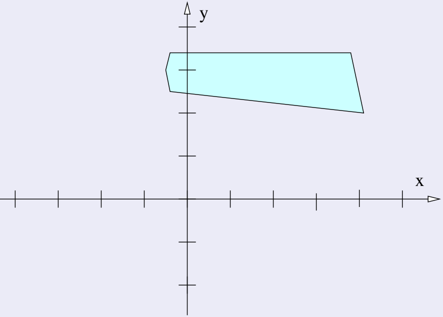

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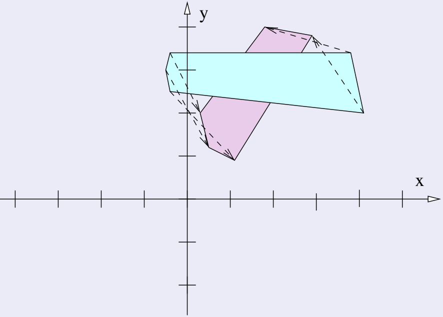

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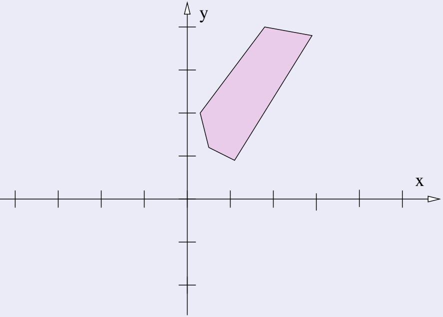

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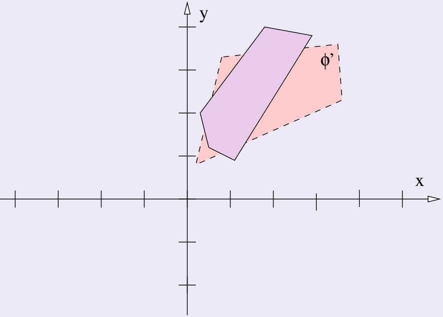

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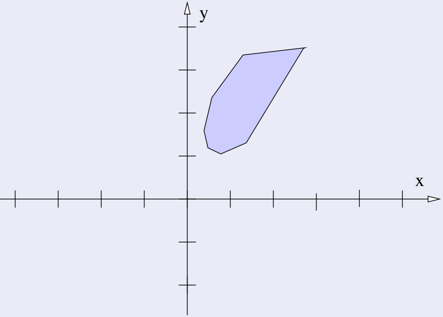

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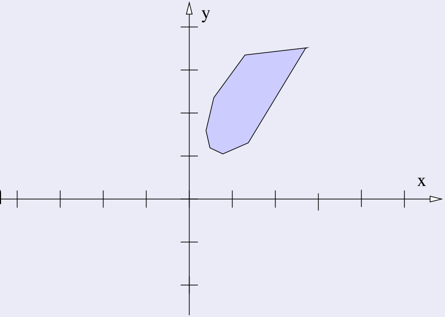

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Symbolic Reachability Analysis

function Reachable (A, F)
  // $A \stackrel{\text{def}}{=} \langle L, L^0, \Sigma, X, \Phi(X), E \rangle$, $F \stackrel{\text{def}}{=} \{\langle l_i, \phi_i \rangle\}_i$
  $\mathit{Reachable} = \emptyset$
  $\mathit{Frontier} = \{\langle l, \mathit{Init}_l(X) \rangle \mid l \in L^0\}$
  while ($\mathit{Frontier} \neq \emptyset$) **do**
    extract $\langle l, \varphi \rangle$ *from* *Frontier*
    if ($(\varphi \wedge \phi) \neq \perp$ for some $\langle l, \phi \rangle \in F$) **then**
      return True
    end if
    if ($\nexists\, \langle l, \varphi' \rangle \in \mathit{Reachable}$ $s.t.$ $\varphi \subseteq \varphi'$) **then**
      add $\langle l, \varphi \rangle$ *to* *Reachable*
      for $e \in \mathit{outcoming}(l)$ **do**
        add $\mathit{succ}(\varphi, e)$ *to* *Frontier*
      end for
    end if
  end while
  return False

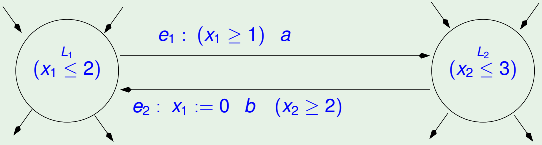
Summary: Linear Hybrid Automata

- Strategy implemented in HyTech
- Core computation: manipulation of polyhedra
- Bottlenecks
  - proliferation of polyhedra (unions)
  - computing with high-dimension polyhedra
- Many case studies

Outline

Ex: Execution of a Timed System

Consider only the following piece of a timed automaton A, x_1 and x_2 being clocks.



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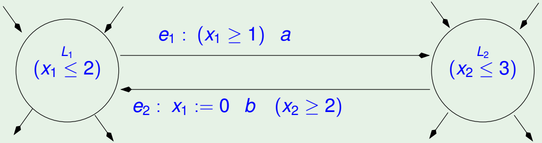

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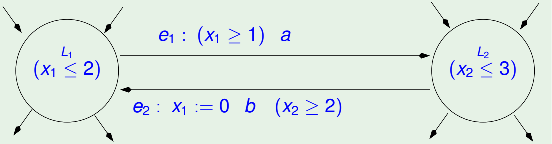

(a) In general, what is the minimum amount of time from an occurrence of event b and the subsequent occurrence of the event a? [Solution: 1 time unit.]

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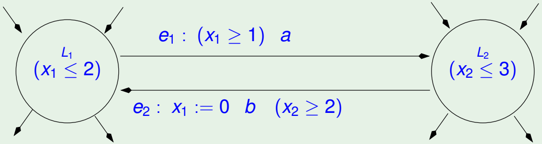

(a) In general, what is the minimum amount of time from an occurrence of event b and the subsequent occurrence of the event a? [Solution: 1 time unit.]

(b) Write a legal execution from state $\langle L_1, 0.0, 2.0\rangle$ to state $\langle L_1, 0.0, 3.0\rangle$.

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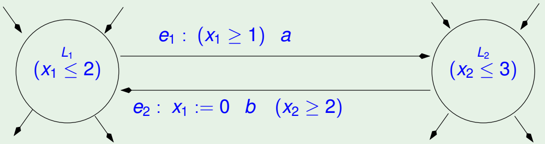

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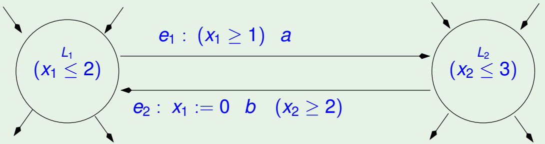

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(c) Is it possible to have a legal execution in which switches e_2, e_1, e_2 are shot consecutively (possibly interleaved by time elapses), without being interleaved by other switches? If yes, write one such execution. If not, explain why.

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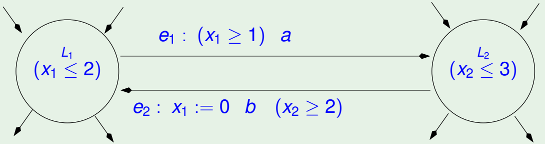

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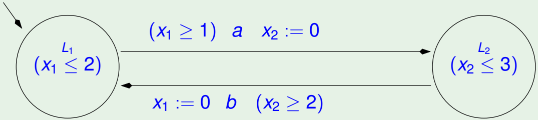
Note: if the guard of e_2 were strictly greater than 2, this would not be possible.]

Ex: Timed Automata: Regions

Consider the following timed automaton A.



Considere the correponding Region automaton R(A). For each of the following pairs of states of A, say if the two states belong to the same region.

(a) $s_0 = (L_1, 2.5, 3.2)$, $s_1 = (L_1, 2.5, 3.7)$

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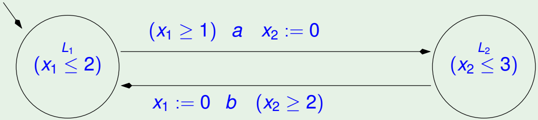

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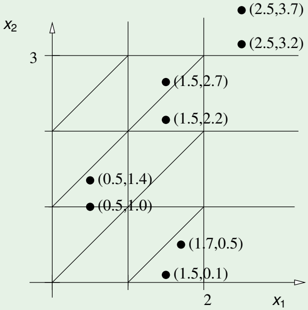

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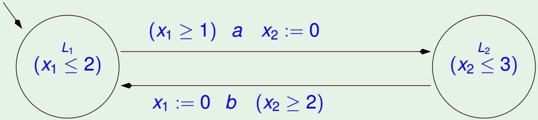

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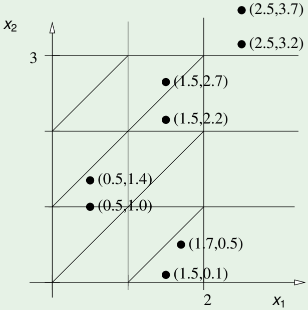

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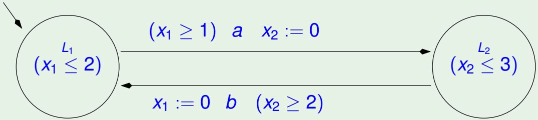

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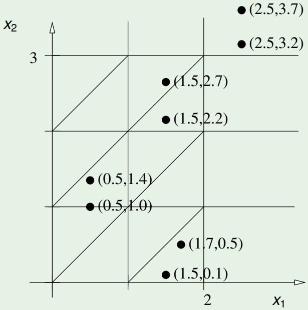

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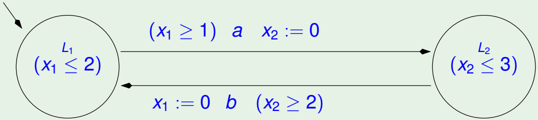

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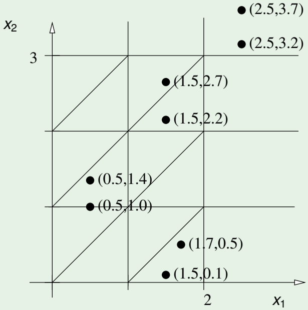
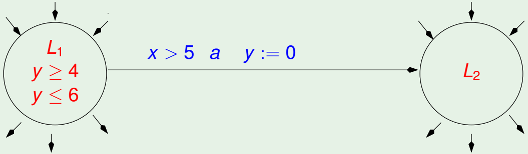


Ex: Timed Automata: Zones

Consider the following switch e in a timed automaton, x and y being clocks:



and let $Z_1 \stackrel{\text{def}}{=} \langle L_1, \varphi \rangle$ s.t $\varphi \stackrel{\text{def}}{=} (x \geq 2) \wedge (x \leq 3) \wedge (y \geq 2) \wedge (y \leq 5) \wedge (y - x \leq 2)$.
Compute $succ(Z_1, e)$, drawing the process on the cartesian space $\langle x, y \rangle$.

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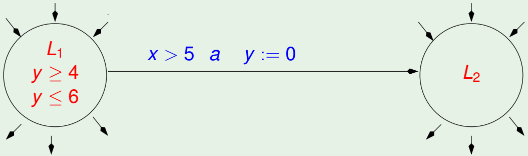

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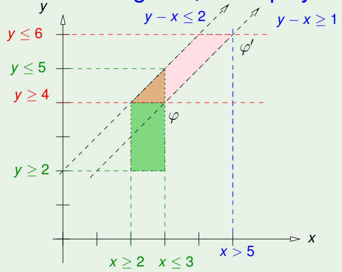
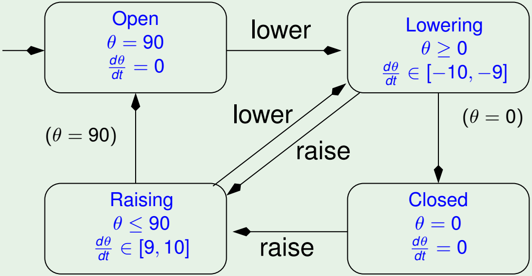
Compute $succ(Z_1, e)$, drawing the process on the cartesian space $\langle x, y \rangle$.
[Solution: The solution is $succ(Z_1, e) = \langle Z_2, \perp \rangle$. In fact, the zone reached by waiting in L_1 has empty intersection with the guard, as displayed in figure:



]

Hybrid Automata

A railway-crossing gate, whose dynamics is represented by the hybrid automaton in the figure, receives from a controller two possible input signals {lower,raise}. (θ, in degrees, represents the angle between the bar and the ground.)
When the gate is open the controller receives a signal "incoming" when a train is incoming, it waits a fixed amount of time Δt, then it sends the gate the lower order.
It is known that an incoming train takes an amount of time within the interval [70,100] time units to get from the remote sensor to the gate.
Compute the *maximum* amount of time Δt which guarantees that the train does not reach the gate before the bar is completely lowered, and briefly explain why.



[Solution: Δt is 60 time units. In fact, the maximum value of Δt the controller can afford waiting is given by the minimum time the train may take to reach the gate (70), minus the maximum time taken by the bar to lower, that is, the time taken to lower the angle from 90 to 0 at the lowest absolute speed (90/|-9|). Overall, we have thus $\Delta t = 70 - 90/(|-9|) = 60$.]

Difference Bound Matrices

Consider the zone:

$\varphi \stackrel{\text{def}}{=} (x_1 \leq 3) \wedge (x_2 \leq 2) \wedge (x_3 \leq 5) \wedge$
$(x_1 - x_3 \leq 2) \wedge (x_2 - x_1 \leq -2) \wedge (x_3 - x_1 \leq 3) \wedge (x_3 - x_2 \leq 1)$

(*a*) Compute the corresponding DBM

(*b*) Compute the reduced DBM

Difference Bound Matrices

[Solution: $\varphi \stackrel{\text{def}}{=} (x_1 \leq 3) \land (x_2 \leq 2) \land (x_3 \leq 5) \land$
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Difference Bound Matrices

[Solution: $\varphi \stackrel{\text{def}}{=} (x_1 \leq 3) \wedge (x_2 \leq 2) \wedge (x_3 \leq 5) \wedge$
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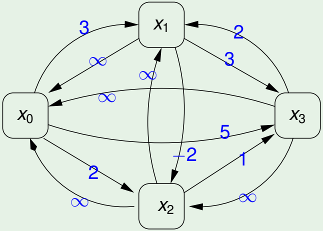
Initial DBM:

	x_0	x_1	x_2	x_3
x_0	$\langle\infty, \leq\rangle$	$\langle\infty, \leq\rangle$	$\langle\infty, \leq\rangle$	$\langle\infty, \leq\rangle$
x_1	$\langle 3, \leq\rangle$	$\langle\infty, \leq\rangle$	$\langle\infty, \leq\rangle$	$\langle 2, \leq\rangle$
x_2	$\langle 2, \leq\rangle$	$\langle -2, \leq\rangle$	$\langle\infty, \leq\rangle$	$\langle\infty, \leq\rangle$
x_3	$\langle 5, \leq\rangle$	$\langle 3, \leq\rangle$	$\langle 1, \leq\rangle$	$\langle\infty, \leq\rangle$



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Difference Bound Matrices

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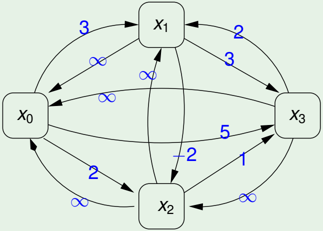
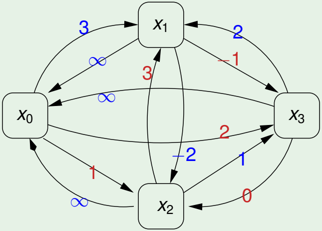
Initial DBM:

	x_0	x_1	x_2	x_3
x_0	$\langle\infty, \leq\rangle$	$\langle\infty, \leq\rangle$	$\langle\infty, \leq\rangle$	$\langle\infty, \leq\rangle$
x_1	$\langle 3, \leq\rangle$	$\langle\infty, \leq\rangle$	$\langle\infty, \leq\rangle$	$\langle 2, \leq\rangle$
x_2	$\langle 2, \leq\rangle$	$\langle -2, \leq\rangle$	$\langle\infty, \leq\rangle$	$\langle\infty, \leq\rangle$
x_3	$\langle 5, \leq\rangle$	$\langle 3, \leq\rangle$	$\langle 1, \leq\rangle$	$\langle\infty, \leq\rangle$

Reduced DBM:

	x_0	x_1	x_2	x_3
x_0	$\langle 0, \leq\rangle$	$\langle\infty, \leq\rangle$	$\langle\infty, \leq\rangle$	$\langle\infty, \leq\rangle$
x_1	$\langle 3, \leq\rangle$	$\langle 0, \leq\rangle$	$\langle 3, \leq\rangle$	$\langle 2, \leq\rangle$
x_2	$\langle 1, \leq\rangle$	$\langle -2, \leq\rangle$	$\langle 0, \leq\rangle$	$\langle 0, \leq\rangle$
x_3	$\langle 2, \leq\rangle$	$\langle -1, \leq\rangle$	$\langle 1, \leq\rangle$	$\langle 0, \leq\rangle$





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