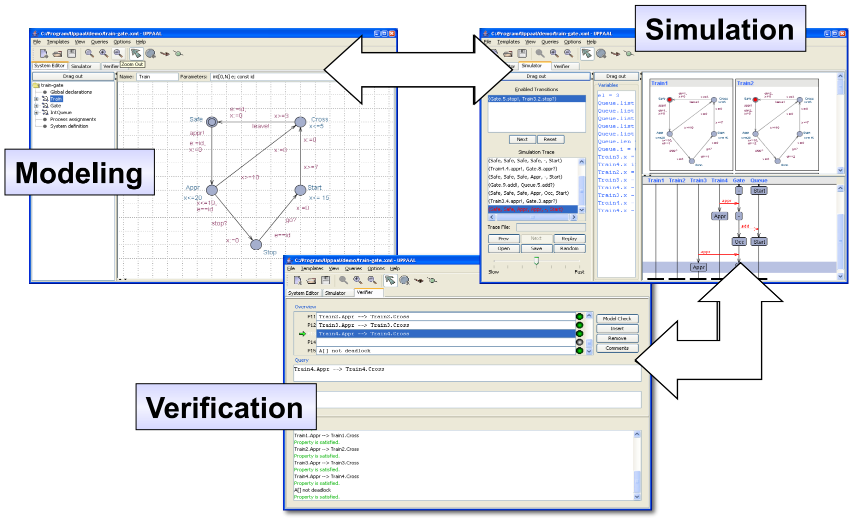
UPPAAL tutorial

- What's inside UPPAAL
- The UPPAAL input languages

UPPAAL tool

- Developed jointly by Uppsala & Aalborg University
- >>28,000 downloads since 1999

UPPAAL Tool



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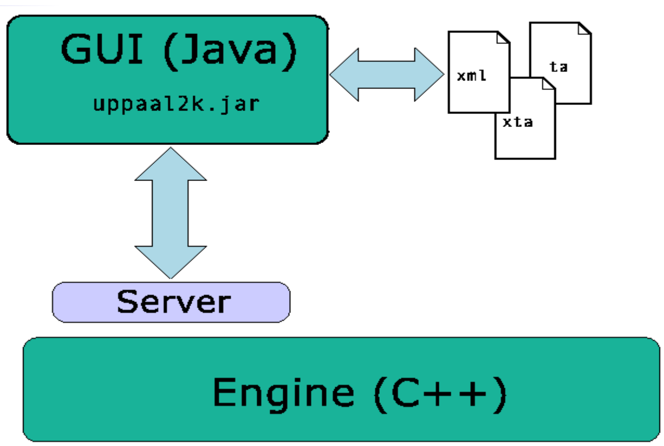
Architecture of UPPAAL



Linux, Windows, Solaris, MacOS

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What’s inside UPPAAL

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OUTLINE

- Data Structures
  - DBM’s (Difference Bounds Matrices)
  - Canonical and Minimal Constraints
- Algorithms
  - Reachability analysis
  - Liveness checking
- Verification Options

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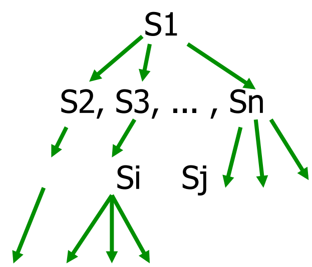
All Operations on Zones

(needed for verification)

- Transformation
  - Conjunction
  - Post condition (delay)
  - Reset
- Consistency Checking
  - Inclusion
  - Emptiness



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Zones = Conjuctive constraints

- A zone Z is a conjunctive formula:
  g_1 & g_2 & ... & g_n
  where g_i may be $x_i \sim b_i$ or $x_i - x_j \sim b_{ij}$
- Use a zero-clock x_0 (constant 0), we have
  $\{x_i - x_j \sim b_{ij} \mid \sim \text{ is } < \text{ or } \leq, i,j \leq n\}$
- This can be represented as a MATRIX, DBM
  (Difference Bound Matrices)

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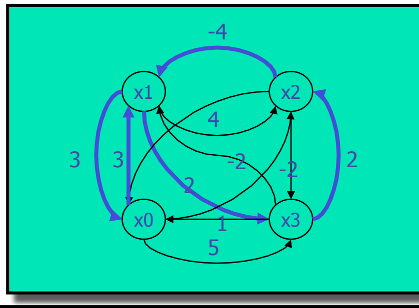
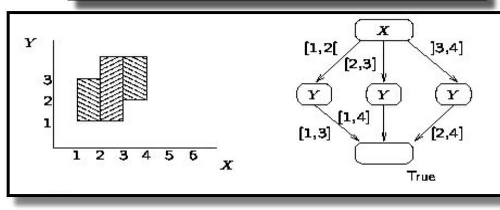
Datastructures for Zones in UPPAAL

- Difference Bounded Matrices
  [Bellman58, Dill89]
- Minimal Constraint Form
  [RTSS97]
- Clock Difference Diagrams
  [CAV99]





Canonical Datastructures for Zones

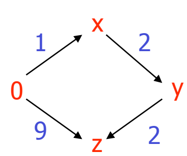
Difference Bounded Matrices Bellman 1958, Dill 1989

Inclusion

Z1

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

Graph

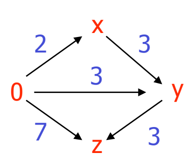


? ⊆ ?

Z2

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

Graph



Canonical Dastructures for Zones

Difference Bounded Matrices

Bellman 1958, Dill 1989

Inclusion

Z1

x<=1
y-x<=2
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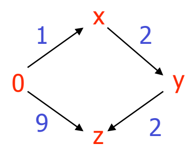
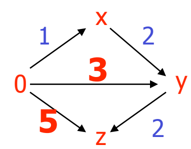
Graph



Shortest Path Closure



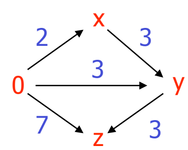
? ⊆ ?

Z1 ⊆ Z2 !

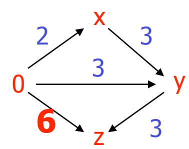
Z2

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

Graph



Shortest Path Closure



Canonical Datastructures for Zones

Difference Bounded Matrices

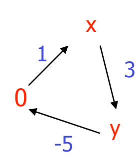
Bellman 1958, Dill 1989

Emptiness

Z

x<=1
y>=5
y-x<=3

Graph

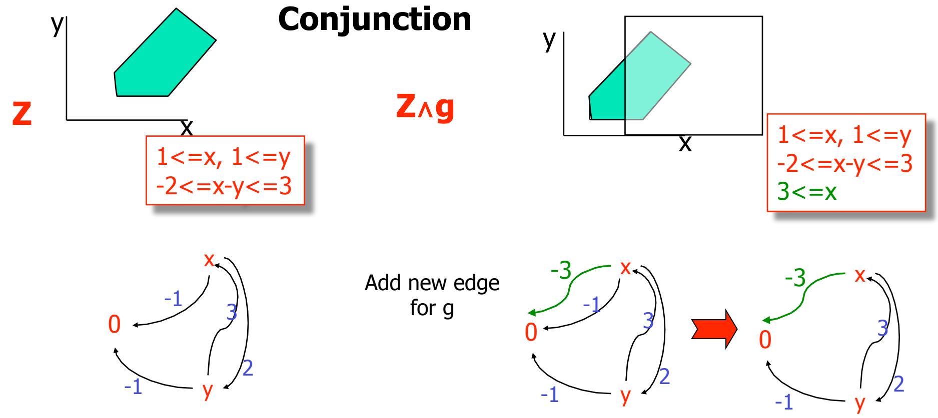


Negative Cycle
iff
empty solution set

Canonical Datastructures for Zones

Difference Bounded Matrices

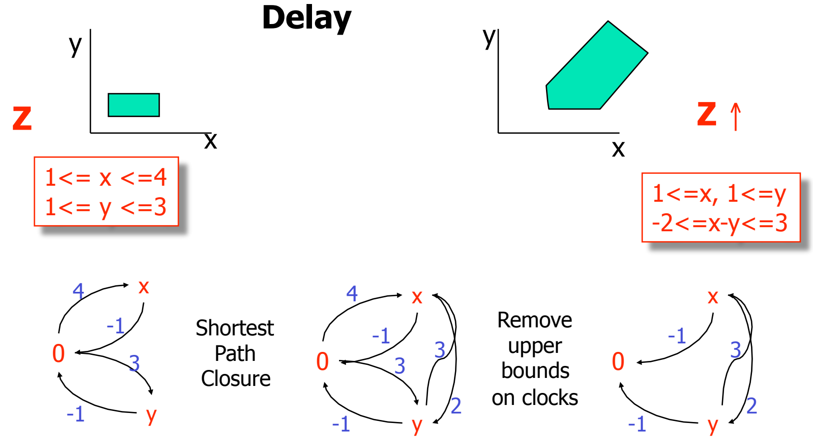
Conjunction



Canonical Dastructures for Zones

Difference Bounded Matrices

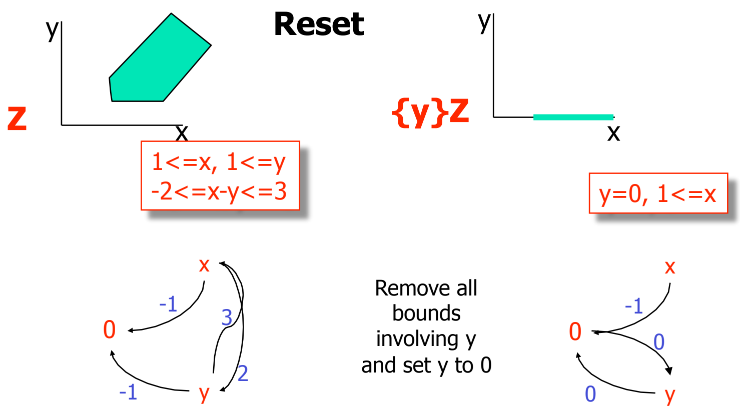
Delay



Canonical Datastructures for Zones

Difference Bounded Matrices

Reset



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COMPLEXITY

- Computing the shortest path closure, the cannonical form of a zone: $O(n^3)$ [Dijkstra's alg.]
- Run-time complexity, mostly in O(n)

  (when we keep all zones in cannonical form)

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Datastructures for Zones in UPPAAL

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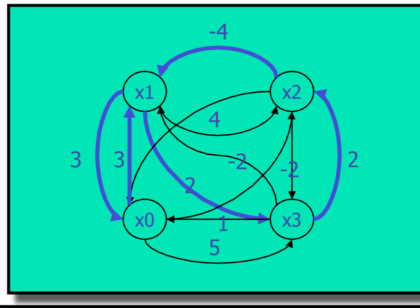
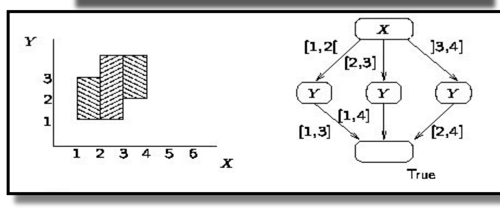
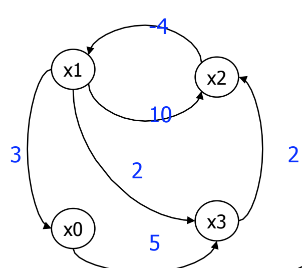
  [Bellman58, Dill89]
- Minimal Constraint Form
  [RTSS97]
- Clock Difference Diagrams
  [CAV99]



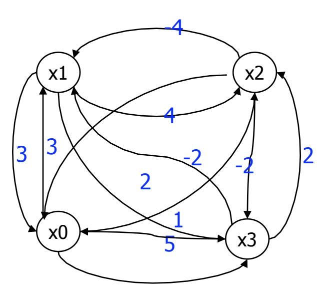


Minimal Graph

x1-x2<=-4
x2-x1<=10
x3-x1<=2
x2-x3<=2
x0-x1<=3
x3-x0<=5

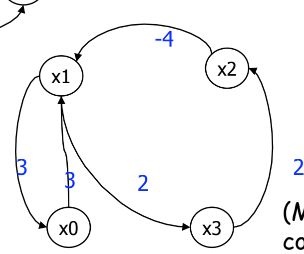


Shortest Path Closure $O(n^3)$



(DBM)

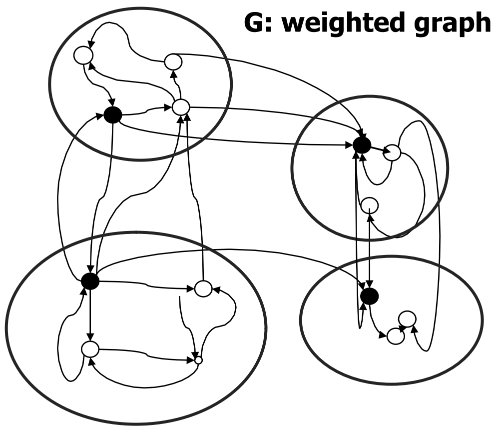
Shortest Path Reduction $O(n^3)$



Space worst $O(n^2)$
practice $O(n)$

(Minimal graph, a.ka. compact data structure)

Graph Reduction Algorithm



G: weighted graph

1. Equivalence classes based on 0-cycles.

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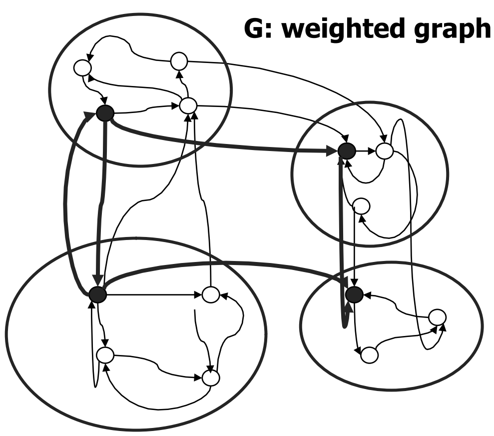
Graph Reduction Algorithm



G: weighted graph

1. Equivalence classes based on 0-cycles.

2. Graph based on representatives.
   Safe to remove redundant edges

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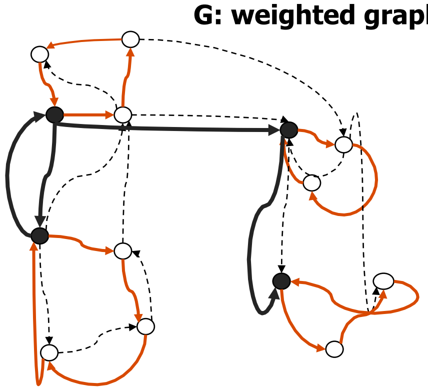
Graph Reduction Algorithm

G: weighted graph



1. Equivalence classes based on 0-cycles.
2. Graph based on representatives. Safe to remove redundant edges
3. **Shortest Path Reduction**
   =
   One cycle pr. class
   +
   Removal of redundant edges between classes

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Datastructures for Zones in UPPAAL

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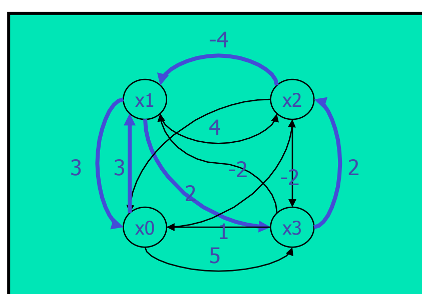

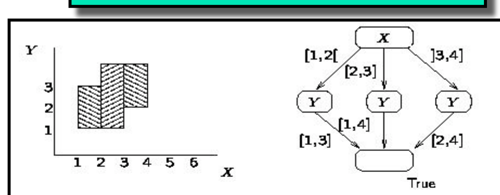

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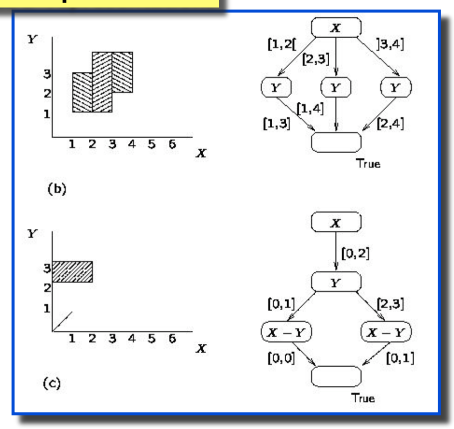
Other Symbolic Datastructures

- NDD's Maler et. al.
- CDD's UPPAAL/CAV99
- DDD's Møller, Lichtenberg
- Polyhedra HyTech
- ……

CDD-representations



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Inside the UPPAAL tool

- Data Structures
  - DBM's (Difference Bounds Matrices)
  - Canonical and Minimal Constraints
- Algorithms
  - Reachability analysis
  - Liveness checking
- Verification Options

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Timed CTL in UPPAAL

EF p | AG p | EG p | AF p | p - -> q

P ::= A.l | g_c | g_d | not p| p or p | p and p | p imply p

Process Location (a location in automaton A)

Clock constraint

predicate over data variables

p leads to q *denotes* **AG (p imply AF q)**

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Timed CTL in UPPAAL

EF p | AG p | EG p | AF p | p - -> q

P ::= A.l | g_c | g_d | not p| p or p | p and p | p imply p

Process Location (a location in automaton A)

Clock constraint

predicate over data variables

p leads to q *denotes* **AG (p imply AF q)**

SAFETY PROPERTIES

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in UPPAAL

SAFETY Properties

F ::= EF P | AG P

Reachability

Invariant = ¬ EF ¬ P
Thus, **AG P** is also checked by reachability analysis!

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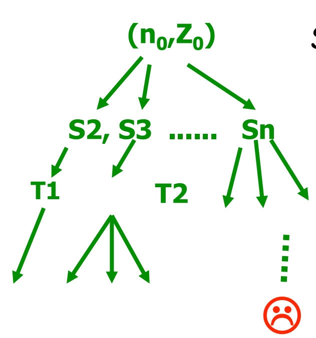
We have a search problem



Symbolic state

Symbolic transitions

Reachable?

EF ☹

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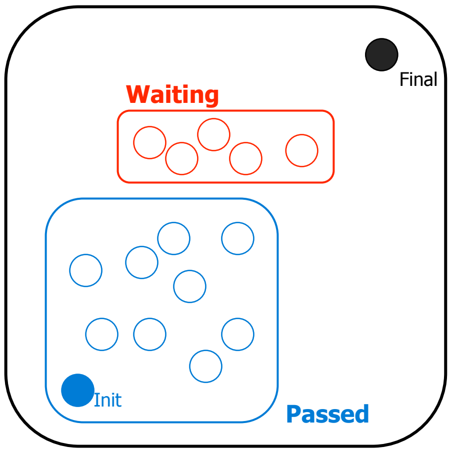
Forward Reachability

Init -> Final ?



INITIAL **Passed** := Ø;
Waiting := {(n0,Z0)}

REPEAT
- pick (n,Z) in **Waiting**
- **if** for some $Z' \sqsupseteq Z$
  (n,Z') in **Passed** **then STOP**
- **else** /explore/ add
  { (m,U) : (n,Z) => (m,U) }
  to **Waiting**;
  Add (n,Z) to **Passed**

UNTIL **Waiting** = Ø
or
Final is in **Waiting**

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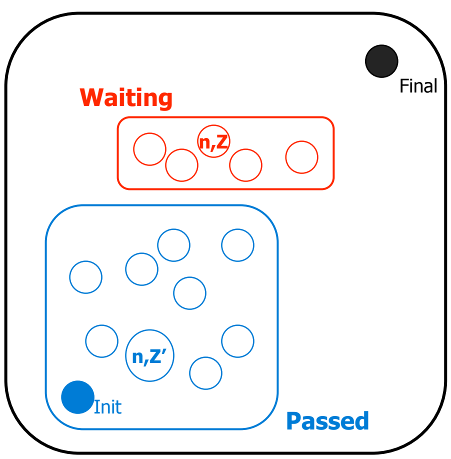
Forward Reachability

Init -> Final ?



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REPEAT
- pick (n,Z) in **Waiting**
- **if** for some $Z' \sqsupseteq Z$
  (n,Z') in **Passed** **then STOP**
- **else** (explore) add
  { (m,U) : (n,Z) => (m,U) }
  to **Waiting**;
  Add (n,Z) to **Passed**

UNTIL **Waiting** = Ø
or
Final is in **Waiting**

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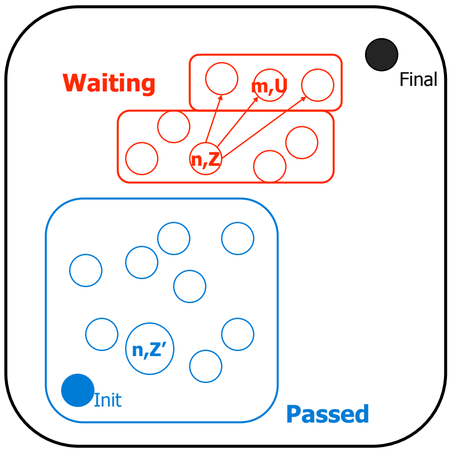
Forward Reachability

Init -> Final ?



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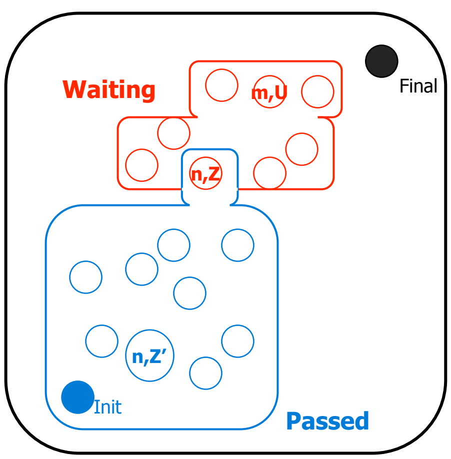
Forward Reachability

Init -> Final ?



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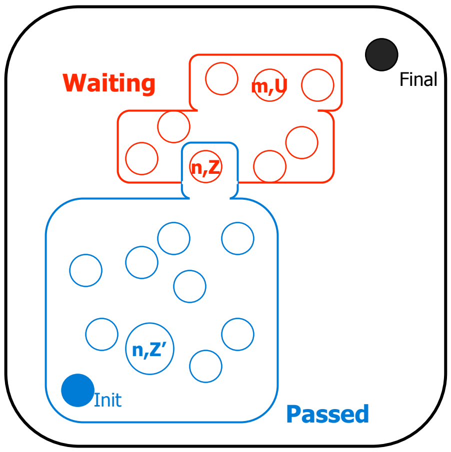
Forward Reachability

Init -> Final ?



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Waiting := {(n0,Z0)}

REPEAT
- pick (n,Z) in **Waiting**
- **if** for some Z' ⊒ Z
  (n,Z') in **Passed** **then** **STOP**
- **else** /explore/ add
  { (m,U) : (n,Z) => (m,U) }
  to **Waiting**;
  Add (n,Z) to **Passed**

UNTIL **Waiting** = Ø
or
Final is in **Waiting**

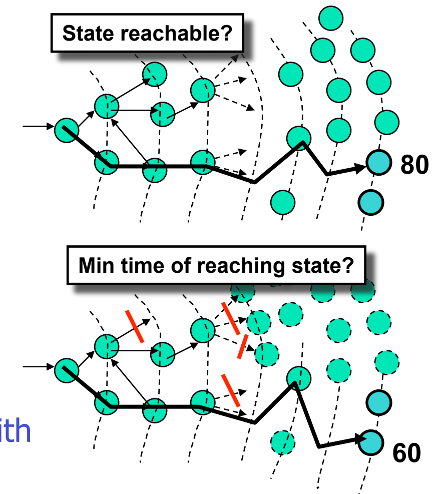
Further question

Can we find the path with shortest delay, leading to P ?
(i.e. a state satisfying P)

OBSERVATION:
Many scheduling problems can be phrased naturally as reachability problems for timed automata.

Verification vs. Optimization

- Verification Algorithms:
  - Checks a logical property of the entire state-space of a model.
  - Efficient Blind search.
- Optimization Algorithms:
  - Finds (near) optimal solutions.
  - Uses techniques to avoid non-optimal parts of the state-space (e.g. Branch and Bound).
- Goal: solve opt. problems with verification.



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OPTIMAL REACHABILITY

The maximal and minimal delay problem

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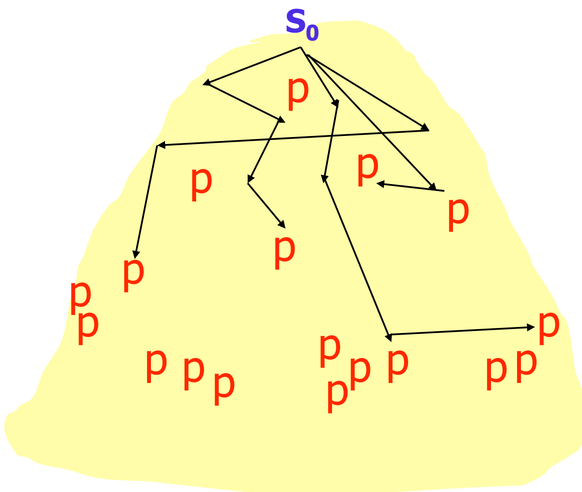
Find the trace leading to P with min delay



There may be a lot of pathes leading to P

Which one with the shortest delay?

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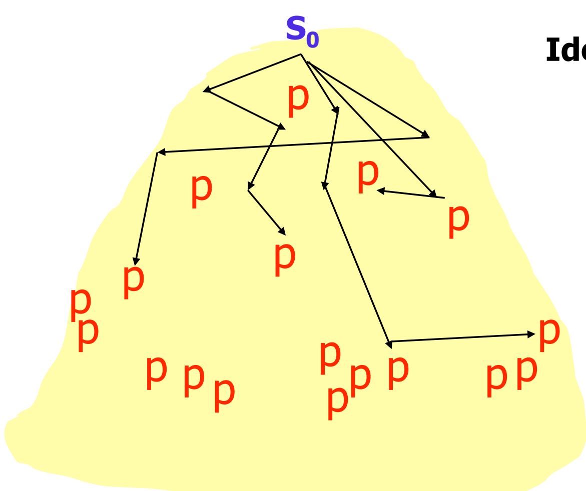
Find the trace leading to P with min delay



Idea: delay as "**Cost**" to reach a state, thus **cost** increases with time at rate 1

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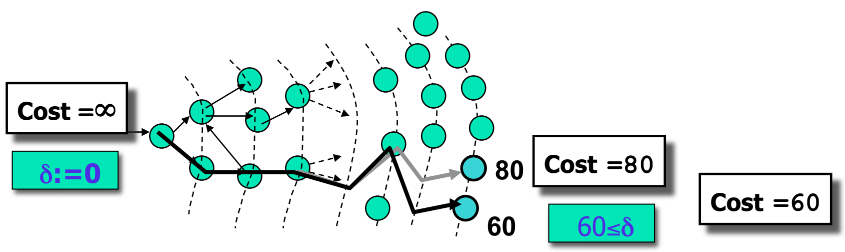
An Simple Algorithm for minimal-cost reachability

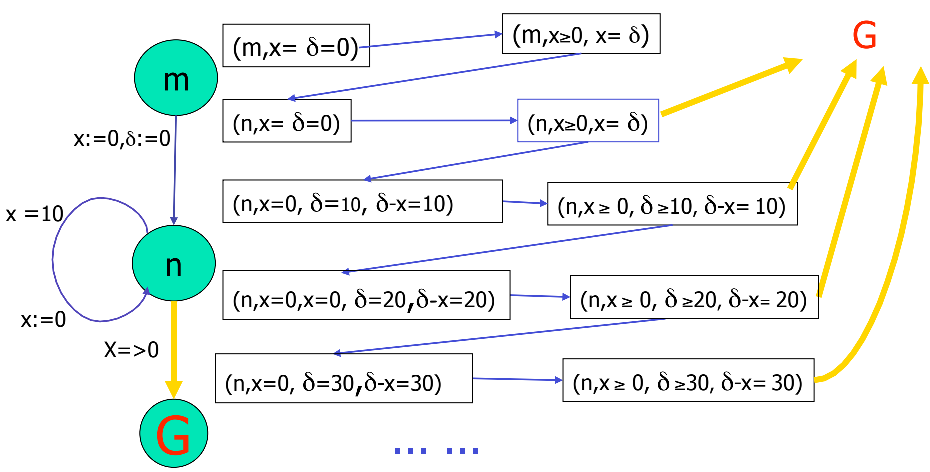
- State-Space Exploration + Use of global variable **Cost** and global clock δ
- Update **Cost** whenever goal state with **min(C) < Cost** is found:



- Terminates when entire state-space is explored.

Problem: The search may never terminate!

Example (min delay to reach G)



The minimal **delay** = 0 but the search may never terminate!

Problem: How to **symbolically** represent the zone **C.**

Priced-Zone

- Cost = minimal total time
- **C** can be represented as the zone Z^δ, where:
  - Z^δ original (ordinary) DBM plus…
  - δ clock keeping track of the cost/time.
- Delay, Reset, Conjunction etc. on Z are the standard DBM-operations
- Delay-Cost is incremented by Delay-operation on Z^δ.

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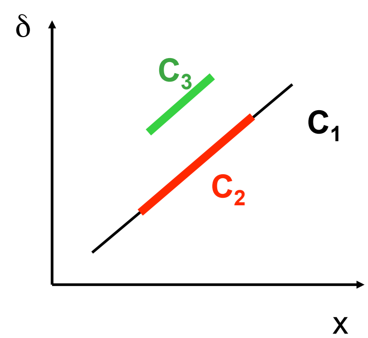
Priced-Zone

- Cost = min total time
- **C** can be represented as the zone Z^δ, where:
  - Z^δ is the original zone Z extended with the global clock δ keeping track of the cost/time.
  - Delay, Reset, Conjunction etc. on C are the standard DBM-operations
- But inclusion-checking will be different



Then: $C_3 \sqsubseteq C_2 \sqsubseteq C_1$

But: $C_3 \not\subseteq C_2 \subseteq C_1$

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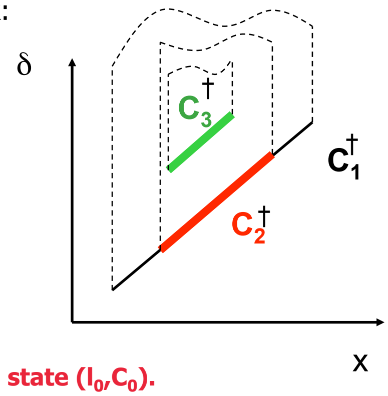
Solution: $()^{\dagger}$-widening operation

- **$()^{\dagger}$** removes upper bound on the δ–clock:

  $C_3 \sqsubseteq C_2 \sqsubseteq C_1$

  $C_3^{\dagger} \subseteq C_2^{\dagger} \subseteq C_1^{\dagger}$



- In the Algorithm:
  - $Delay(C^{\dagger}) = (Delay(C^{\dagger}))^{\dagger}$
  - $Reset(x,C^{\dagger}) = (Reset(x,C^{\dagger}))^{\dagger}$
  - $C_1^{\dagger} \wedge g = (C_1^{\dagger} \wedge g)^{\dagger}$
  - **It is suffices to apply $()^{\dagger}$ to the initial state (l_0,C_0).**

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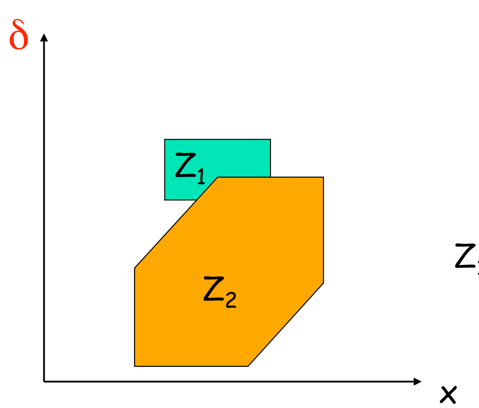
Example (widening for Min)



$Z_1 \not\subseteq Z_2$

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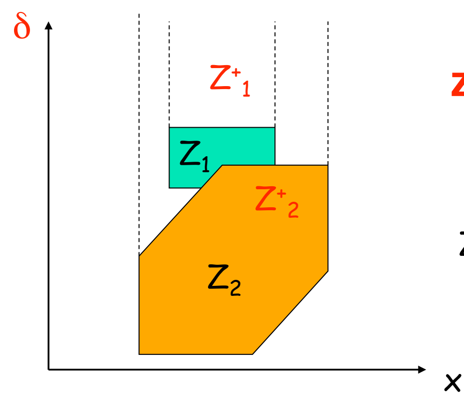
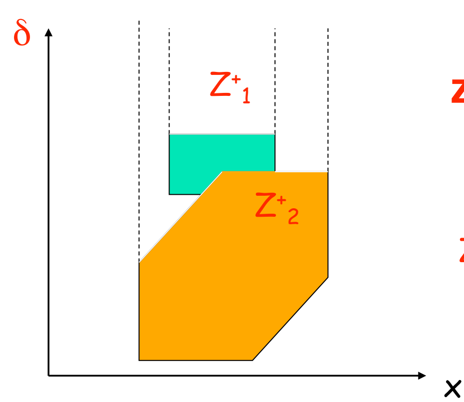
Example (widening for Min)



Z^+= Widen(Z)

$Z_1 \not\subseteq Z_2$

Example (widening for Min)



Z^+= Widen(Z)

$Z^+_1 \subseteq Z^+_2$!

$Z_1 \sqsubseteq Z_2$

An Algorithm (Min)

```
Cost:=∞, Pass := {}, Wait := {(l0,C0)}
while Wait ≠ {} do
   select (l,C) from Wait
   if (l,C) ⊨ P and Min(C)<Cost then Cost:= Min(C)
   if (l,C) ⊑ (l,C’) for some (l,C’) in Pass then skip
       otherwise add (l,C) to Pass
       and forall (m,C’) such that (l,C)⇝(m,C’):
         add (m,C’) to Wait
Return Cost
```

One-step reachability relation

Output: `Cost` = the min cost of a found trace satisfying `P`.

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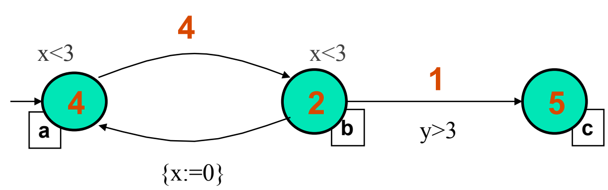
Further reading: Priced Timed Automata [Larsen et al]



- Timed Automata + Costs on transitions and locations.
- Uniformly Priced = Same cost in all locations (edges may have different costs).

- Cost of performing transition: Transition cost.
- Cost of performing delay **d**: (**d** x location cost).

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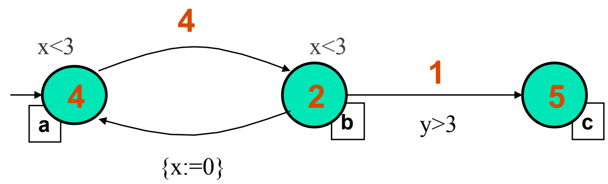
Priced Timed Automata



Trace:

(**a**,x=y=0) $\xrightarrow[4]{}$ (**b**,x=y=0) $\xrightarrow[2.5 \times 2]{\varepsilon(2.5)}$ (**b**,x=y=2.5) $\xrightarrow[0]{}$ (**a**,x=0,y=2.5)

Cost of Execution Trace:

Sum of costs: **4 + 5 + 0 = 9**

Problem: Finding the minimum cost of reaching c !

Inside the UPPAAL tool

- Data Structures
  - DBM's (Difference Bounds Matrices)
  - Canonical and Minimal Constraints
- Algorithms
  - Reachability analysis
  - Liveness checking
- Verification Options

Timed CTL in UPPAAL

EF p | AG p | EG p | AF p | p - -> q

P ::= A.l | g_c | g_d | not p | p or p | p and p | p imply p

Process Location (a location in automaton A)

Clock constraint

predicate over data variables

LIVENESS PROPERTIES

SAFETY PROPERTIES

p leads to q *denotes* **AG (p imply AF q)**

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LIVENESS Properties

in UPPAAL

F ::= EG p | AF p | p - -> q

Possibly always P
is equivalent to (: AF : P)

Eventually P
is equivalent to (: EG : P)

P **leads to** Q
is equivalent to
AG (P imply AF Q)

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Algorithm for checking AF P

Eventually P

Bouajjani, Tripakis, Yovine'97
On-the-fly symbolic model checking of TCTL

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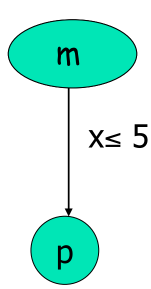
Question

AF P

"P will be true for sure in future"



?? Does this automaton satisfy AF P

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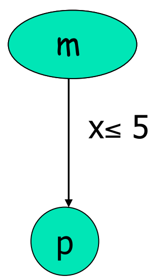
Note that

AF P

"P will be true for sure in future"



NO !!!! there is a path:

(m, x=0) →(m,x=1)→(m,2) … (m,x=k) …

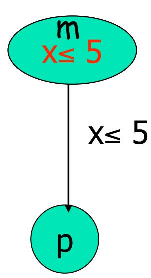
Idling forever in location m

55

Note that

AF P

"P will be true for sure in future"



This automaton satisfies AF P

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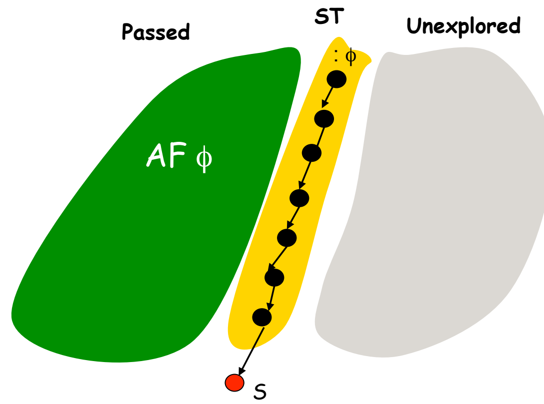
Liveness Algorithm

Bouajjani, Tripakis, Yovine, 97

```
proc Eventually(S₀, φ) ≡
  ST := ∅
  Passed := ∅
  Search(delay(S₀, ¬φ))
  exit(true)
end
proc Search(S) ≡
  if loop(S, ST) then exit(false) fi
  S := S ∧ ¬φ
  push(ST, S)
  if unbounded(S) ∨ deadlocked(S) then
                          exit(false) fi
  if ∀S' ∈ Passed : S ⊄ S'
    then foreach S' : S ⇒ᵃ S' do
           Search(delay(S', ¬φ))
         od
  fi
  Passed := Passed ∪ {pop(ST)}
end
```



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Liveness Algorithm

```
proc Eventually(S₀, φ) ≡
  ST := ∅
  Passed := ∅
  Search(delay(S₀, ¬φ))
  exit(true)
end
proc Search(S) ≡
  if loop(S, ST) then exit(false) fi
  S := S ∧ ¬φ
  push(ST, S)
  if unbounded(S) ∨ deadlocked(S) then
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    then foreach S' : S ⇒ᵃ S' do
           Search(delay(S', ¬φ))
         od
  fi
  Passed := Passed ∪ {pop(ST)}
end
```

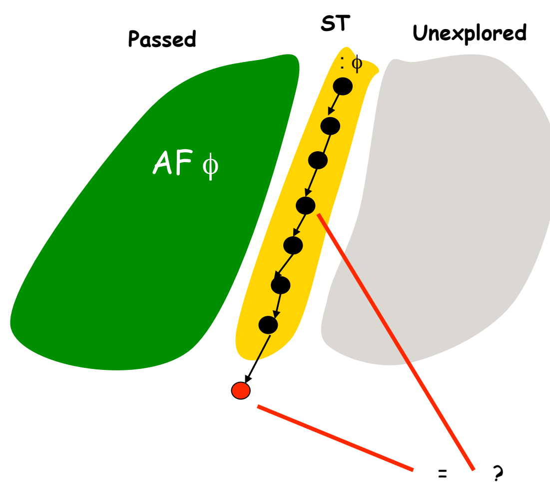

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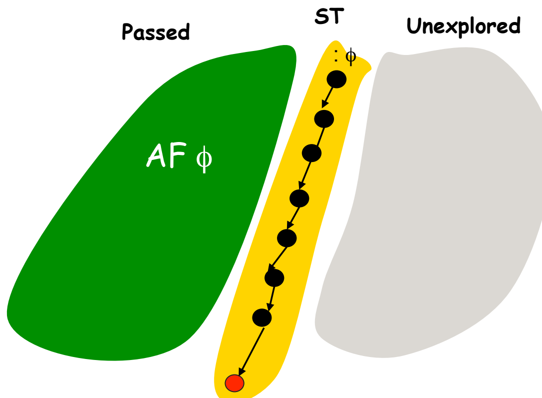
Liveness Algorithm

proc *Eventually*$(S_0, \varphi) \equiv$
  $ST := \emptyset$
  $Passed := \emptyset$
  $Search(delay(S_0, \neg\varphi))$
  exit(*true*)
end
proc *Search*$(S) \equiv$
  if $loop(S, ST)$ **then** **exit**(*false*) **fi**
  $S := S \wedge \neg\varphi$
  $push(ST, S)$
  if $unbounded(S) \vee deadlocked(S)$ **then**
    exit(*false*) **fi**
  if $\forall S' \in Passed : S \not\subseteq S'$
    then **foreach** $S' : S \overset{a}{\Rightarrow} S'$ **do**
      $Search(delay(S', \neg\varphi))$
    od
  fi
  $Passed := Passed \cup \{pop(ST)\}$
end



59

Liveness Algorithm

proc *Eventually*$(S_0, \varphi) \equiv$
  $ST := \emptyset$
  $Passed := \emptyset$
  $Search(delay(S_0, \neg\varphi))$
  exit(*true*)
end
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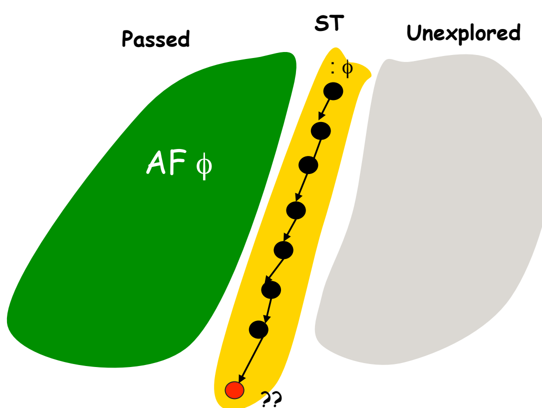
  if $loop(S, ST)$ **then** **exit**(*false*) **fi**
  $S := S \wedge \neg\varphi$
  $push(ST, S)$
  if $unbounded(S) \vee deadlocked(S)$ **then**
    exit(*false*) **fi**
  if $\forall S' \in Passed : S \not\subseteq S'$
    then **foreach** $S' : S \overset{a}{\Rightarrow} S'$ **do**
      $Search(delay(S', \neg\varphi))$
    od
  fi
  $Passed := Passed \cup \{pop(ST)\}$
end



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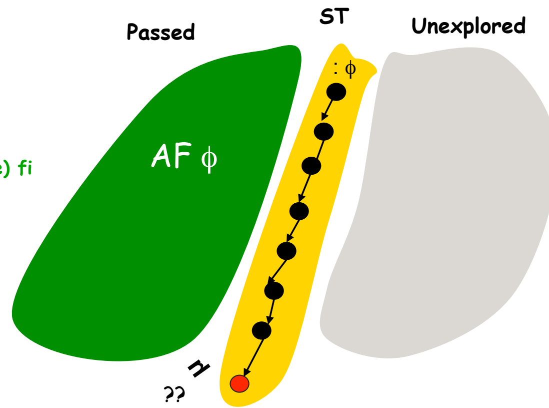
Liveness Algorithm

$\underline{\mathbf{proc}}$ $Eventually(S_0, \varphi)$ $\equiv$
  $ST := \emptyset$
  $Passed := \emptyset$
  $Search(delay(S_0, \neg\varphi))$
  $\underline{\mathbf{exit}}(true)$
$\underline{\mathbf{end}}$
$\underline{\mathbf{proc}}$ $Search(S)$ $\equiv$ if empty(S) then exit(true) fi
  $\underline{\mathbf{if}}$ $loop(S, ST)$ $\underline{\mathbf{then}}$ $\underline{\mathbf{exit}}(false)$ $\underline{\mathbf{fi}}$
  $S := S \wedge \neg\varphi$
  $push(ST, S)$
  $\underline{\mathbf{if}}$ $unbounded(S) \vee deadlocked(S)$ $\underline{\mathbf{then}}$ $\underline{\mathbf{exit}}(false)$ $\underline{\mathbf{fi}}$
  $\underline{\mathbf{if}}$ $\forall S' \in Passed : S \not\subseteq S'$
    $\underline{\mathbf{then}}$ $\underline{\mathbf{foreach}}$ $S' : S \overset{a}{\Rightarrow} S'$ $\underline{\mathbf{do}}$
      $Search(delay(S', \neg\varphi))$
    $\underline{\mathbf{od}}$
  $\underline{\mathbf{fi}}$
  $Passed := Passed \cup \{pop(ST)\}$
$\underline{\mathbf{end}}$



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Liveness Algorithm

$\underline{\mathbf{proc}}$ $Eventually(S_0, \varphi)$ $\equiv$
  $ST := \emptyset$
  $Passed := \emptyset$
  $Search(delay(S_0, \neg\varphi))$
  $\underline{\mathbf{exit}}(true)$
$\underline{\mathbf{end}}$
$\underline{\mathbf{proc}}$ $Search(S)$ $\equiv$
  $\underline{\mathbf{if}}$ $loop(S, ST)$ $\underline{\mathbf{then}}$ $\underline{\mathbf{exit}}(false)$ $\underline{\mathbf{fi}}$
  $S := S \wedge \neg\varphi$
  $push(ST, S)$
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      $Search(delay(S', \neg\varphi))$
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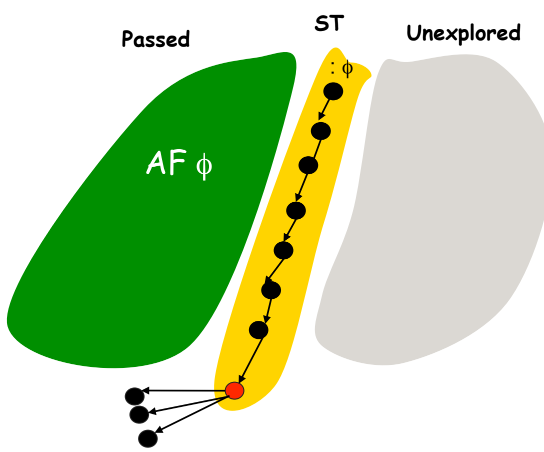
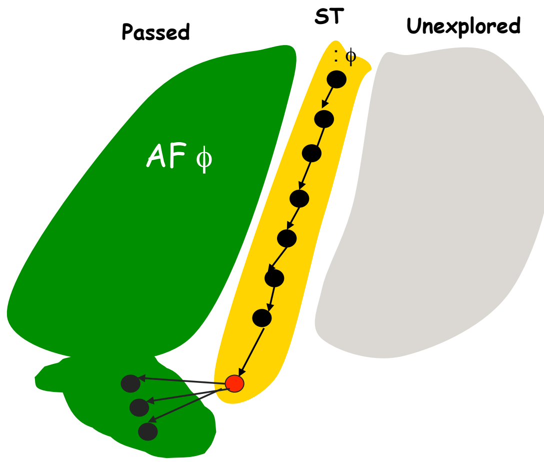
  $\underline{\mathbf{fi}}$
  $Passed := Passed \cup \{pop(ST)\}$
$\underline{\mathbf{end}}$



62

Liveness Algorithm

```
proc Eventually(S₀, φ) ≡
  ST := ∅
  Passed := ∅
  Search(delay(S₀, ¬φ))
  exit(true)
end
proc Search(S) ≡
  if loop(S, ST) then exit(false) fi
  S := S ∧ ¬φ
  push(ST, S)
  if unbounded(S) ∨ deadlocked(S) then
                          exit(false) fi
  if ∀S' ∈ Passed : S ⊈ S'
    then foreach S' : S ⇒ᵃ S' do
           Search(delay(S', ¬φ))
         od
  fi
  Passed := Passed ∪ {pop(ST)}
end
```



63

Liveness Algorithm

```
proc Eventually(S₀, φ) ≡
  ST := ∅
  Passed := ∅
  Search(delay(S₀, ¬φ))
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proc Search(S) ≡
  if loop(S, ST) then exit(false) fi
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    then foreach S' : S ⇒ᵃ S' do
           Search(delay(S', ¬φ))
         od
  fi
  Passed := Passed ∪ {pop(ST)}
end
```

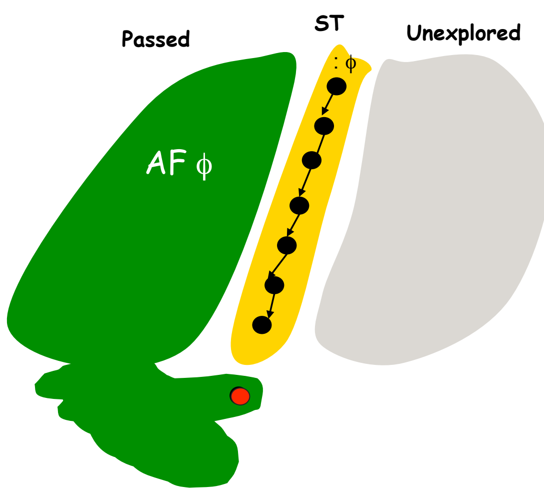

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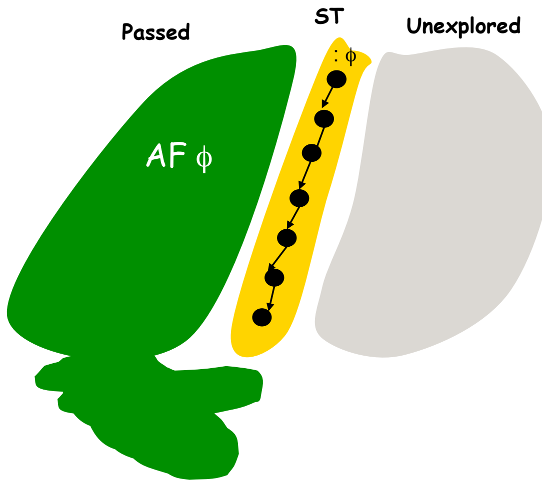
Liveness Algorithm

```
proc Eventually(S0, φ) ≡
  ST := ∅
  Passed := ∅
  Search(delay(S0, ¬φ))
  exit(true)
end
proc Search(S) ≡
  if loop(S, ST) then exit(false) fi
  S := S ∧ ¬φ
  push(ST, S)
  if unbounded(S) ∨ deadlocked(S) then
                          exit(false) fi
  if ∀S' ∈ Passed : S ⊈ S'
    then foreach S' : S ⇒a S' do
             Search(delay(S', ¬φ))
           od
  fi
● Passed := Passed ∪ {pop(ST)}
end
```



65

Liveness Algorithm

```
proc Eventually(S0, φ) ≡
  ST := ∅
  Passed := ∅
  Search(delay(S0, ¬φ))
  exit(true)
end
proc Search(S) ≡
  if loop(S, ST) then exit(false) fi
  S := S ∧ ¬φ
  push(ST, S)
  if unbounded(S) ∨ deadlocked(S) then
                          exit(false) fi
  if ∀S' ∈ Passed : S ⊈ S'
    then foreach S' : S ⇒a S' do
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           od
  fi
● Passed := Passed ∪ {pop(ST)}
end
```

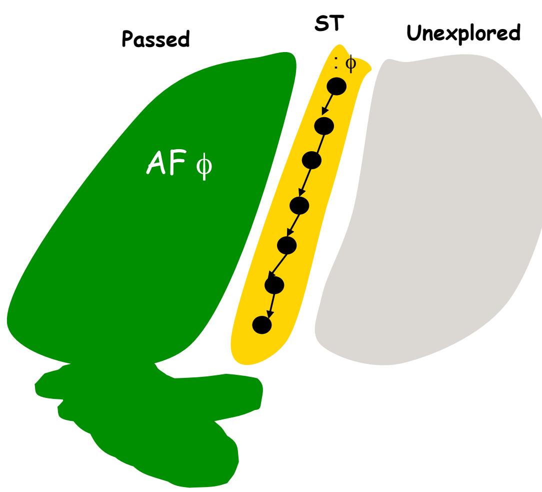

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Question: Time bound synthesis

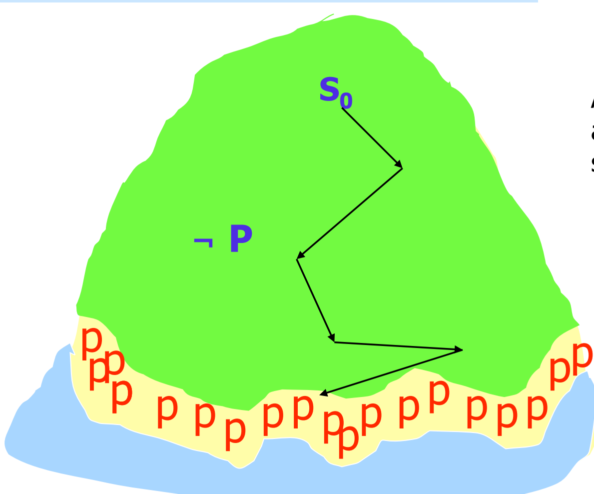
AF P "P will be true eventually"
But no time bound is given.

Assume AF P is satisfied by an automaton A.
Can we calculate the Max time bound?

OBS: we know how to calculate the Min !

Assume AF P is satisfied

Find the trace leading to P with the max delay



Almost the same algorithm as for synthesizing Min

We need to explore the Green part

An Algorithm (Max)

```
Cost:=0, Pass := {}, Wait := {(l0,C0)}
while Wait ≠ {} do
   select (l,C) from Wait
   if (l,C) ⊨ P and Max(C)>Cost then Cost:= Max(C)
   else if forall (l,C') in Pass: C ⋢ C' then
      add (l,C) to Pass
      forall (m,C') such that (l,C) ⇝ (m,C'):
         add (m,C') to Wait
Return Cost
```

One-step reachability relation

Output: **Cost** = the min cost of a found trace satisfying **P**.

BUT: $\sqsubseteq$ is defined on zones where the lower bound of "cost" is removed

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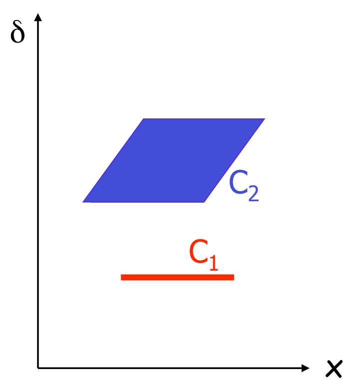
Zone-Widening operation for Max



$C_1 \not\sqsubseteq C_2$

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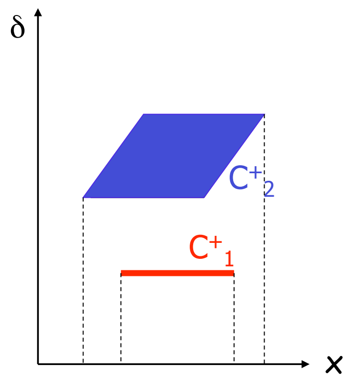
Zone-Widening operation for Max



$C_1 \not\subseteq C_2$

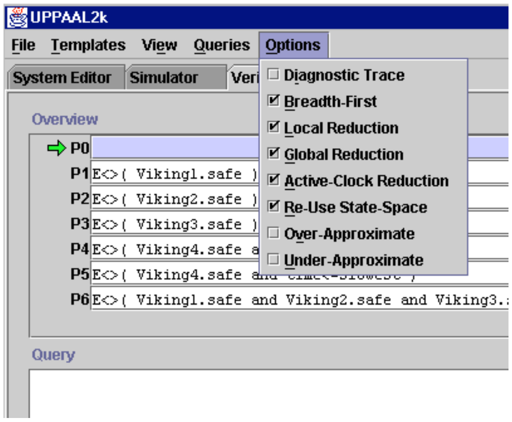
$C^+_1 \subseteq C^+_2$

$C_1 \sqsubseteq C_2$!

Inside the UPPAAL tool

- Data Structures
  - DBM's (Difference Bounds Matrices)
  - Canonical and Minimal Constraints
- Algorithms
  - Reachability analysis
  - Liveness checking
  - Termination
- Verification Options

Verification Options



- Diagnostic Trace

- Breadth-First
- Depth-First

- Local Reduction
- Active-Clock Reduction
- Global Reduction

- Re-Use State-Space

- Over-Approximation
- Under-Approximation

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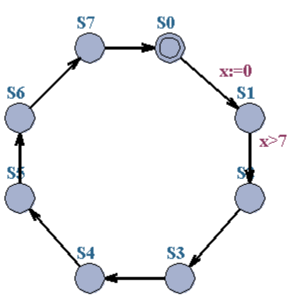
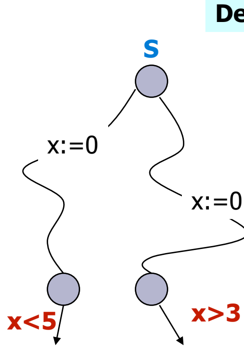
Inactive (passive) Clock Reduction



x is only ***active*** in location **S1**

Definition

x is ***inactive*** at **S** if on all path from **S**, x is always reset before being tested.



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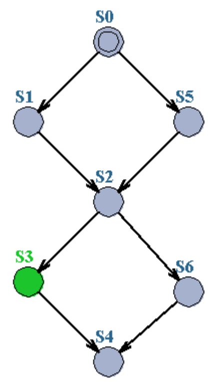
Global Reduction
(When to store symbolic state)



However,
Passed list useful for efficiency

No Cycles: **Passed** list not needed for *termination*

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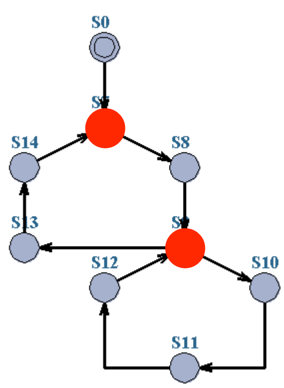
Global Reduction [RTSS97]
(When to store symbolic state)



Cycles:
Only symbolic states involving loop-entry points need to be saved on **Passed** list

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[RTSS97,CAV03]

To Store Or Not To Store?

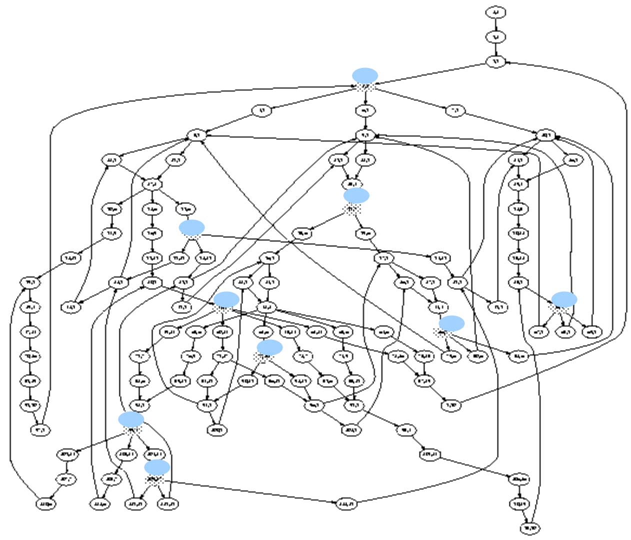
117 $states_{total}$

↓

81 $states_{entrypoint}$

↓

9 states

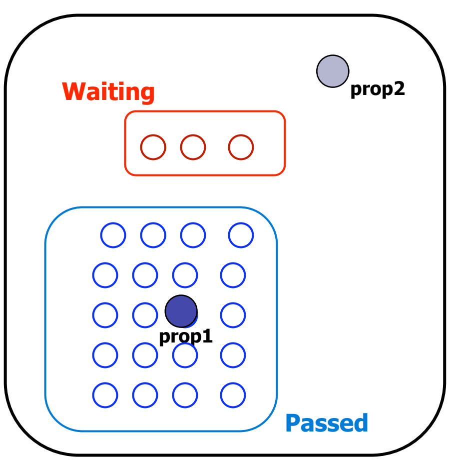


Time OH less than 10%

(need to re-explore some states)

'7

Reuse of State Space




```
A[]  prop1

A[]  prop2
A[]  prop3
A[]  prop4
A[]  prop5
 .
 .
 .
A[]  propn
```

Search in existing **Passed** list before continuing search

Which order to search?

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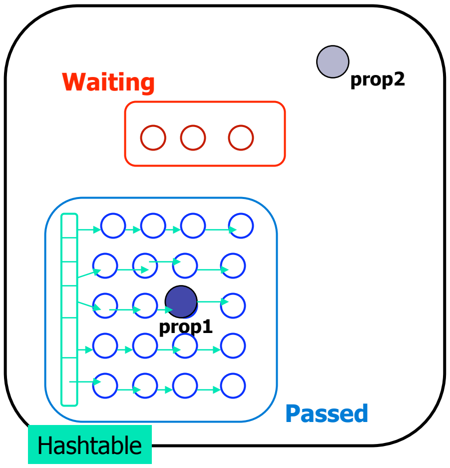
Reuse of State Space




```
A[]  prop1

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A[]  prop5
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A[]  propn
```

Search in existing **Passed** list before continuing search

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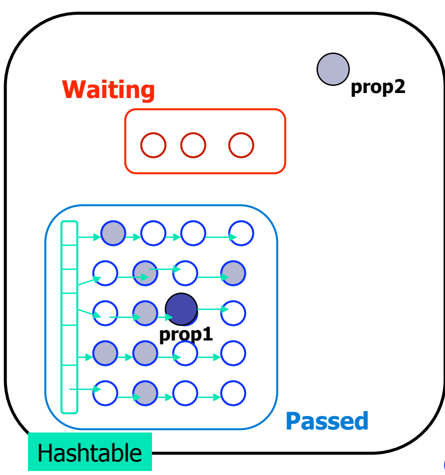
Reuse of State Space



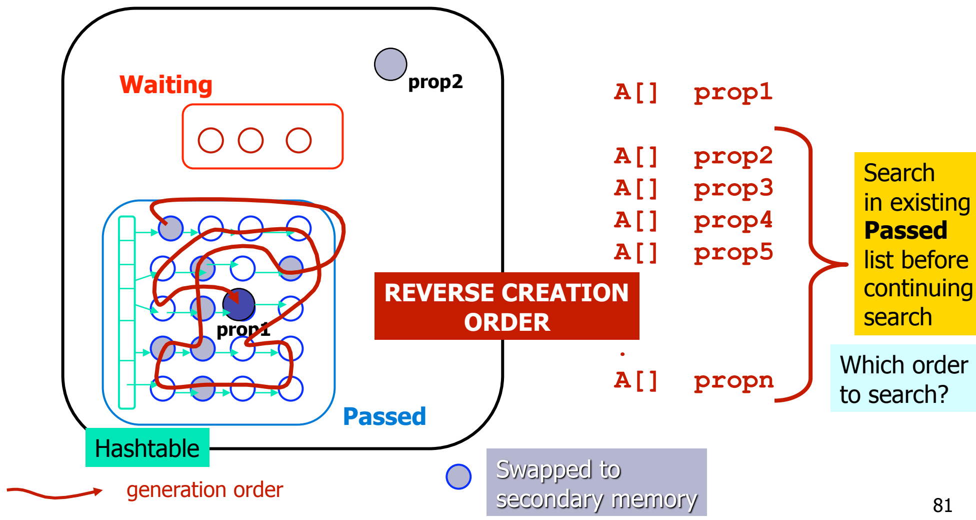

```
A[]  prop1

A[]  prop2
A[]  prop3
A[]  prop4
A[]  prop5
 .
 .
 .
A[]  propn
```

Search in existing **Passed** list before continuing search

Which order to search?

Swapped to secondary memory

Reuse of State Space



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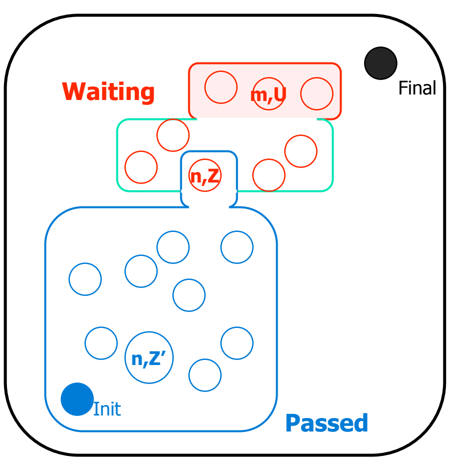
Under-approximation

Bitstate Hashing (Holzman,SPIN)



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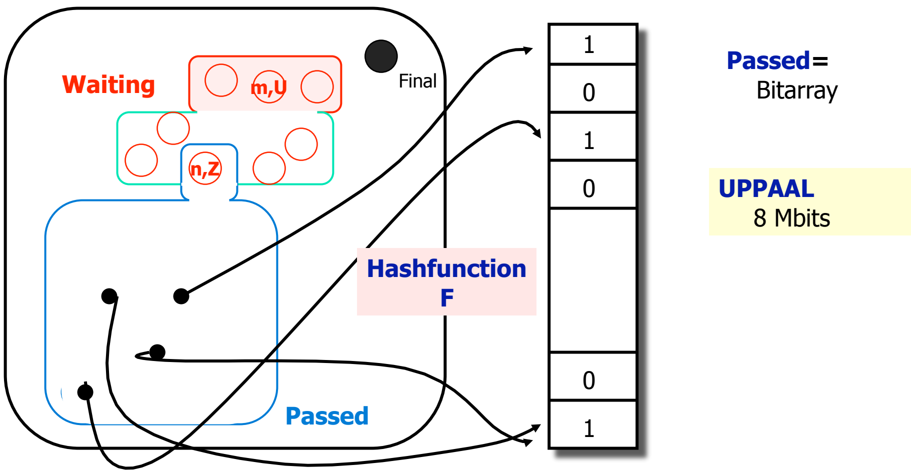
Under-approximation

Bitstate Hashing



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Bit-state Hashing

INITIAL **Passed** := Ø;
Waiting := {(n0,Z0)}

REPEAT
- pick (n,Z) in **Waiting**
- **if** for some Z' ⊒ Z
(n,Z') in **Passed** **then** **STOP**
- **else** /explore/ add
{ (m,U) : (n,Z) => (m,U) }
to **Waiting**;
Add (n,Z) to **Passed**

UNTIL **Waiting** = Ø
or
Final is in **Waiting**

Passed(F(n,Z)**)** = **1**

Passed(F(n,Z)**)** := **1**

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Under Approximation
(good for finding Bugs quickly, debugging)

- Possitive answer is safe (you can trust)
  - You can trust your tool if it tells:
    a state is reachable (it means Reachable!)
- Negative answer is Inconclusive
  - You should not trust your tool if it tells:
    a state is non-reachable
  - Some of the branch may be terminated by conflict (the same hashing value of two states)

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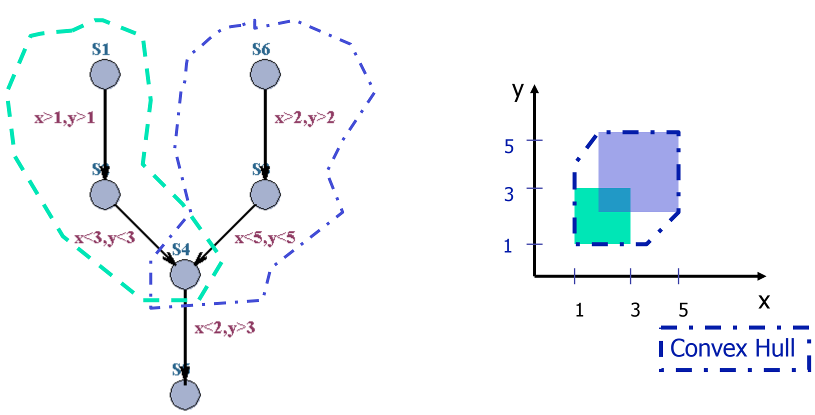
Over-approximation

Convex Hull



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Over-Approximation
(good for safety property-checking)

- Possitive answer is Inconclusive
  - a state is reachable means Nothing
    (you should not trust your tool when it says so)
  - Some of the transitions may be enabled by Enlarged zones
- Negative answer is safe
  - a state is not reachable means Non-reachable
    (you can trust your tool when it says so)

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