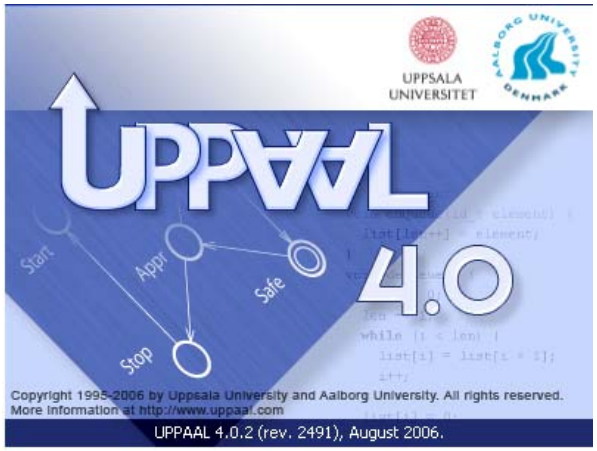


UPPAAL

Verification Engine, Options & Patterns

Alexandre David

1.2.05

Outline

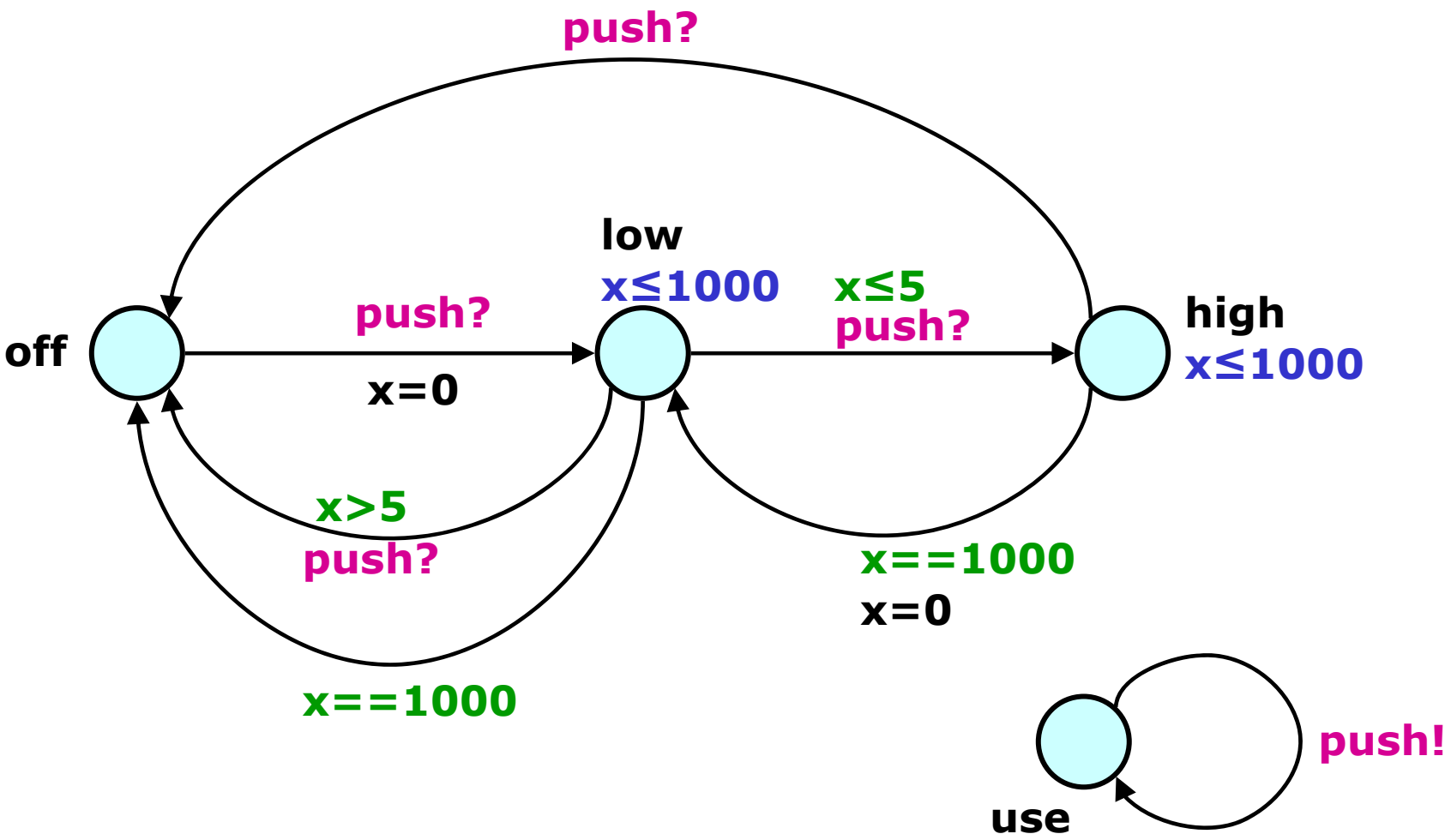
- UPPAAL
  - Modelling Language
  - Specification Language
- UPPAAL Verification Engine
  - Symbolic exploration algorithm
  - Zones & DBMs
- Verification Options
- Modelling Patterns

Intuition only

Goal: Be able to use the tool & understand what you are doing, not what the tool is doing.

Modelling Language

TA in a Nutshell

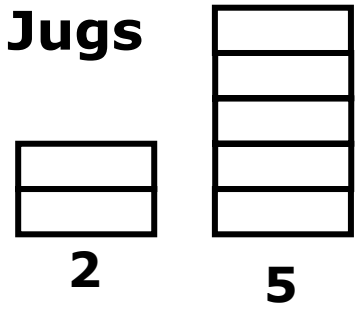


Modeling Language

- Network of TA = instances of templates
  - argument *const type expression*
  - argument *type& name*
- Types
  - built-in types: *int*, *int[min,max]*, *bool*, arrays
  - *typedef struct { … } name*
  - *typedef built-in-type name*

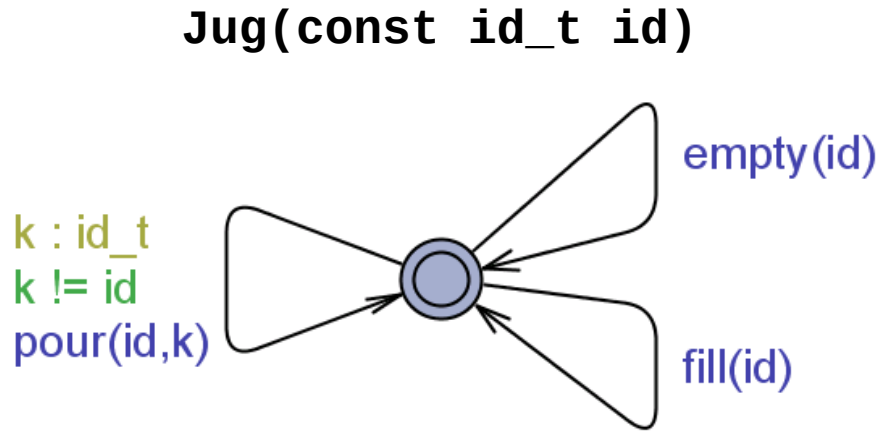
  +*scalar sets*
- Functions
  - C-style syntax, no pointer but references OK.
- Select
  - *name : type*

Un-timed Example: Jugs



Actions:
- **fill**
- **empty**
- **pour**

Goal: obtain 1 unit.



- Scalable, compact, & readable model.
  - const int N = 2; typedef int[0,N-1] id_t;
  - Jugs have their own id.
  - Actions = functions.
  - Pour: from id to another k *different from id*.

Jugs cont.

- Jug levels & capacities:
  int level[N];
  const int capa[N] = {2,5};

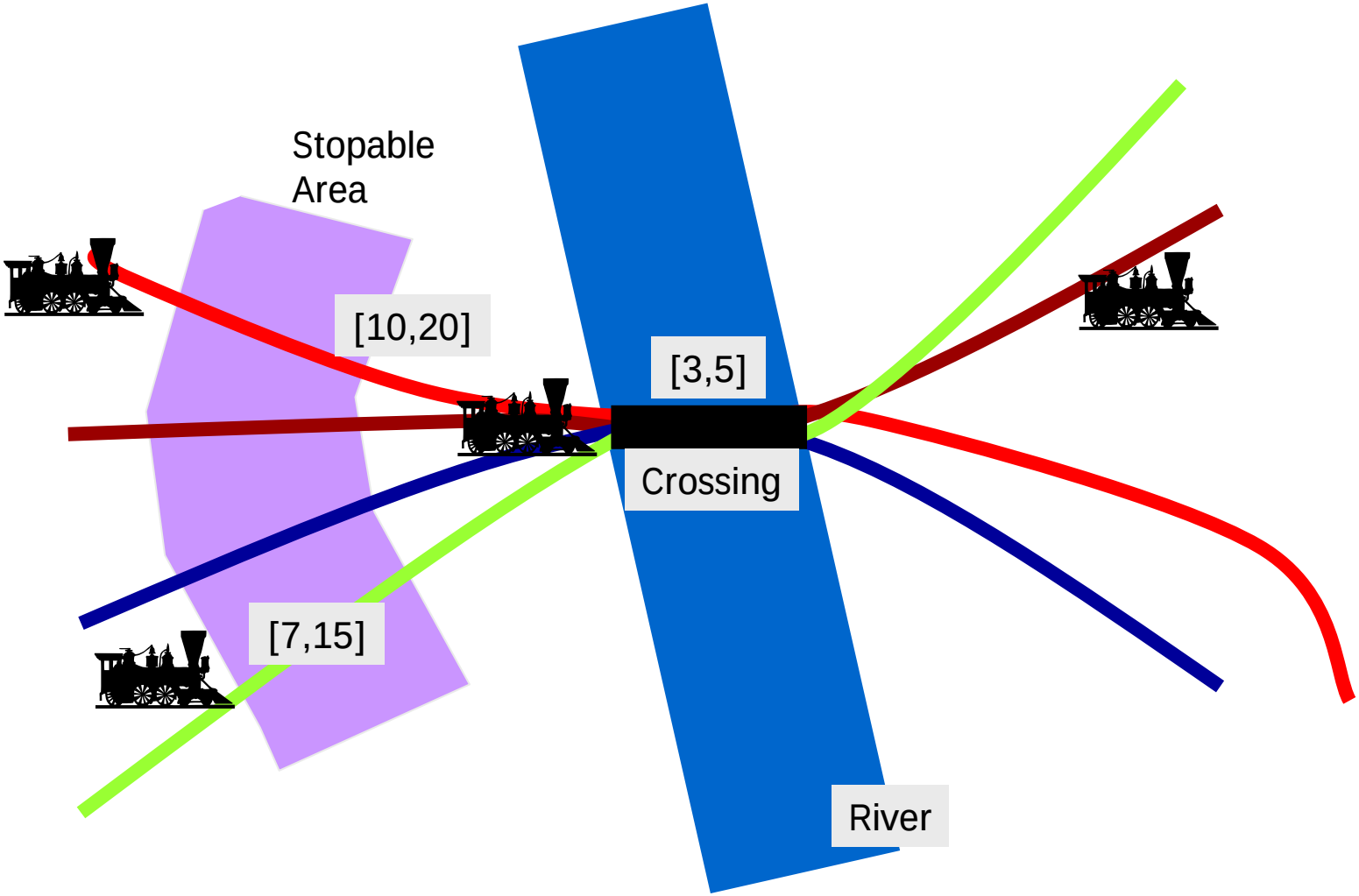
- void empty(id_t i) { level[i]=0; }

- void fill(id_t i) { level[i] = capa[i]; }

- void pour(id_t i, id_t j)
  {
  int max = capa[j] - level[j];
  int poured = level[i] <? max;
  level[i] -= poured;
  level[j] += poured;
  }

- Auto-instantiation: system Jug;

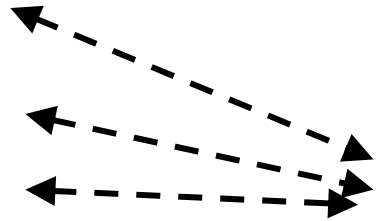
Train-Gate Crossing (Exercise)



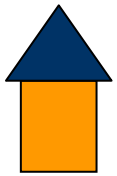
Train-Gate Modeling

Train(const id_t id)

N trains...



Gate



controller

Communication via channels.

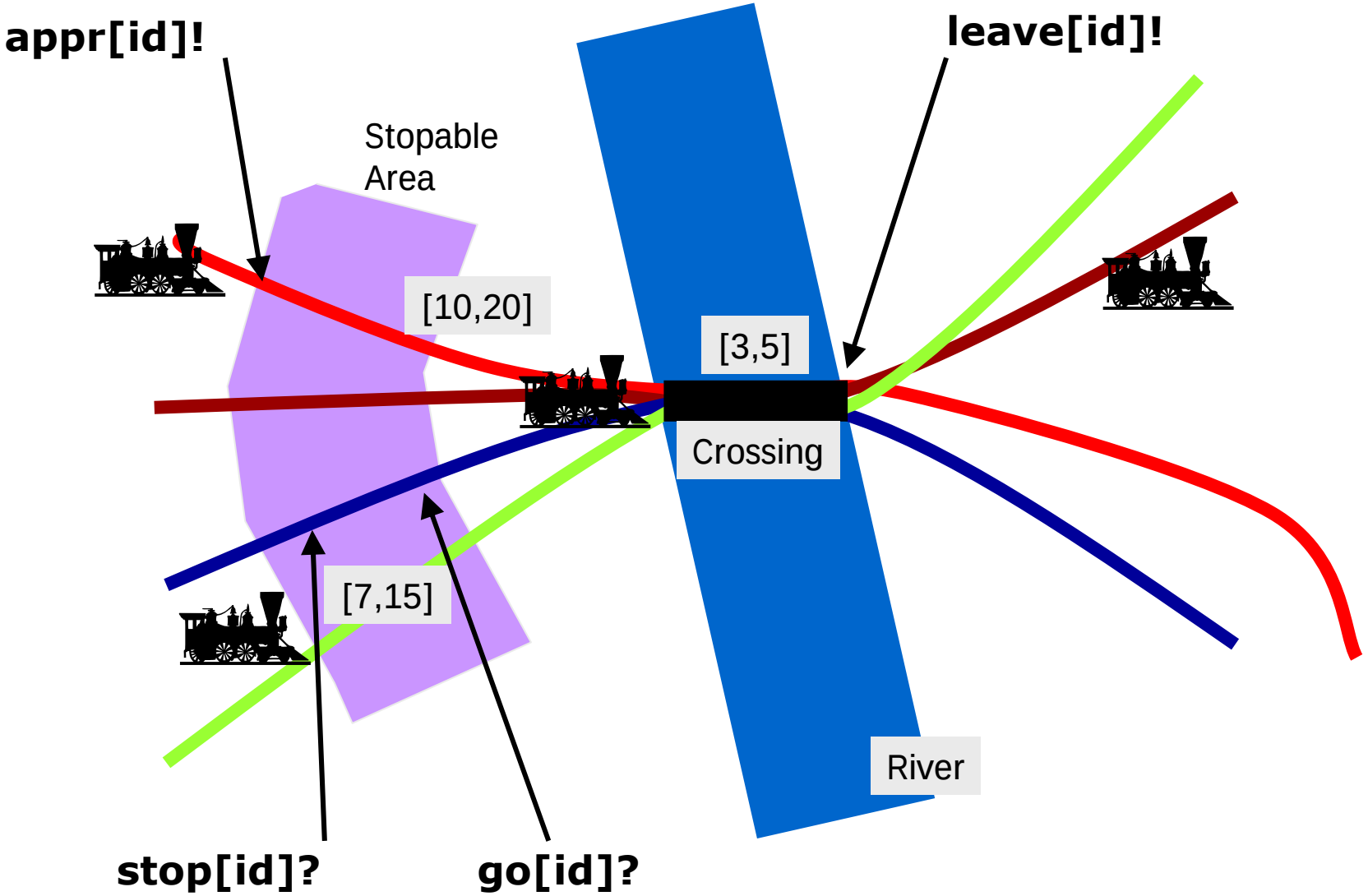
```
chan appr[N], stop[N], leave[N];
urgent chan go[N];
```

list

enqueue()
dequeue()
front()

- Scale the model:
  - const int N = 6; typedef int[0,N-1] id_t;
- Trains have their local clocks.
- The gate has its local list & functions.

Train-Gate Crossing



Scalar Sets

- Use: *typedef scalar[N] setA;*
  - defines a set of N scalars,
  - *typedef scalar[N] setB;* defines another set of N scalars,
  - it is very important to use the typedef.
  - *chan a[setA];* is an array of channels ranging over a scalar set – similarly for other types.
  - limited operations to keep scalars symmetric.
- A way to specify symmetries in the model.
  - UPPAAL uses symmetry reduction automatically.
  - Reduction: Project the current state to a representative of its equivalence class (w.r.t. symmetry).

Specification Language

Logical Specifications

- Validation Properties
  - Possibly: E<> *P*
- Safety Properties
  - Invariant: A[] *P*
  - Pos. Inv.: E[] *P*
- Liveness Properties
  - Eventually: A<> *P*
  - Leadsto: P → *Q*
- Bounded Liveness
  - Leads to within: $P \rightarrow_{\leq t} Q$

The expressions *P* and *Q* must be type safe, **side effect free**, and evaluate to a boolean.

Only references to integer variables, constants, clocks, and locations are allowed (and arrays of these).

Logical Specifications

- Validation Properties
  - Possibly: E<> *P*

- Safety Properties
  - Invariant: A[] *P*
  - Pos. Inv.: E[] *P*

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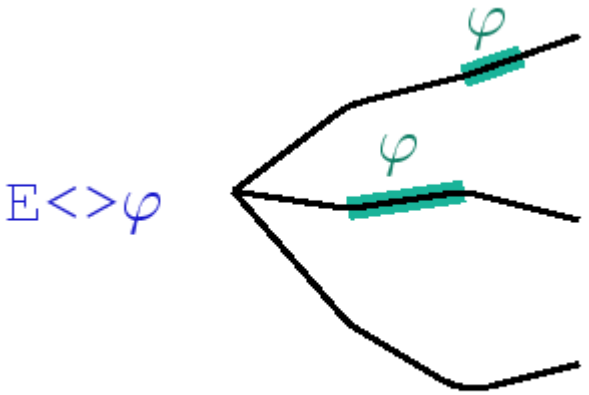

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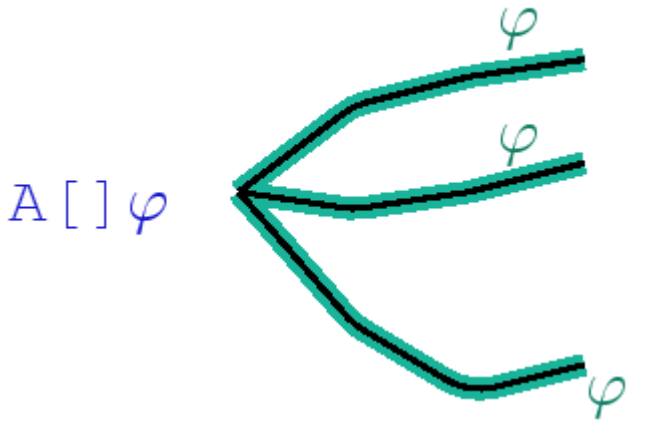

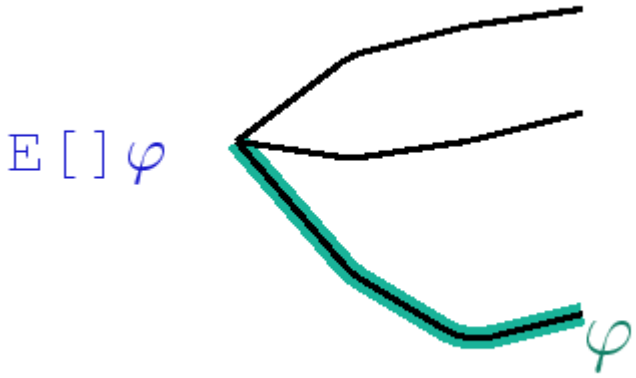

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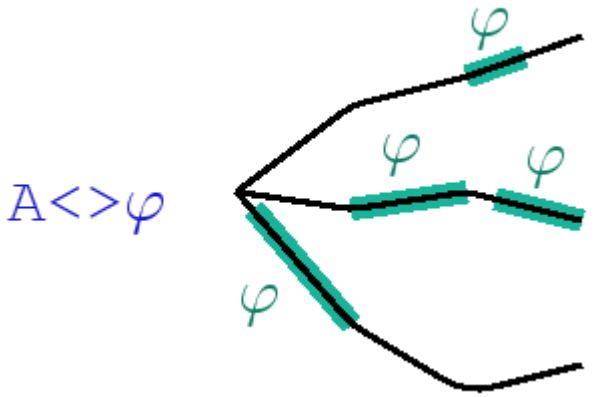

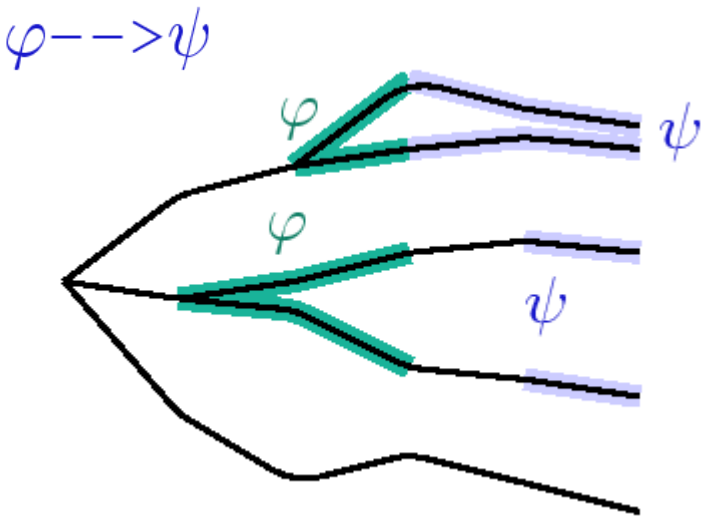

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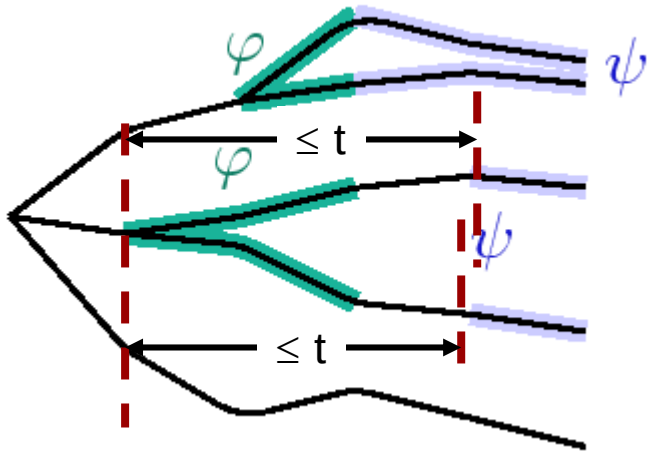


Jug Example

- Safety: Never overflow.
  - A[] forall(i:id_t) level[i] <= capa[i]

- Validation/Reachability: How to get 1 unit.
  - E<> exists(i:id_t) level[i] == 1

Train-Gate Crossing

- Safety: One train crossing.
  - A[] forall (i : id_t) forall (j : id_t)
    Train(i).Cross && Train(j).Cross imply i == j
- Liveness: Approaching trains eventually cross.
  - Train(0).Appr --> Train(0).Cross
  - Train(1).Appr --> Train(1).Cross
  - …
- No deadlock.
  - A[] not deadlock

UPPAAL Verification Engine

Overview – Intuition Only

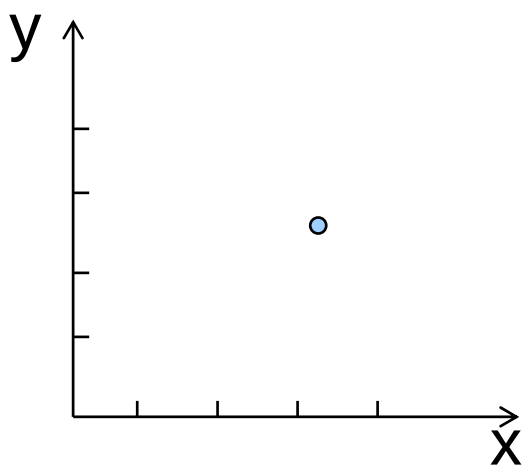
- Zones and DBMs
- Reachability algorithm revisited
- Minimal Constraint Form

Zones

From infinite to finite

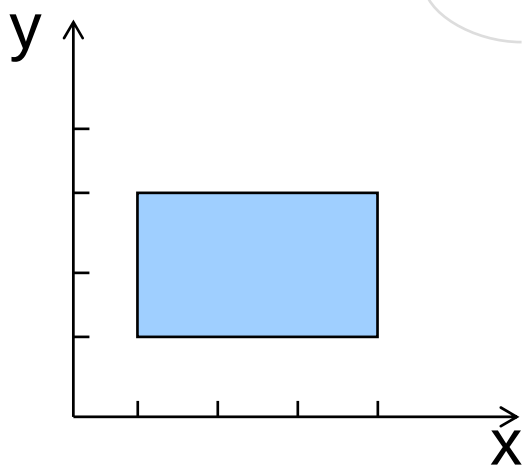
State

(n, x=3.2, y=2.5)



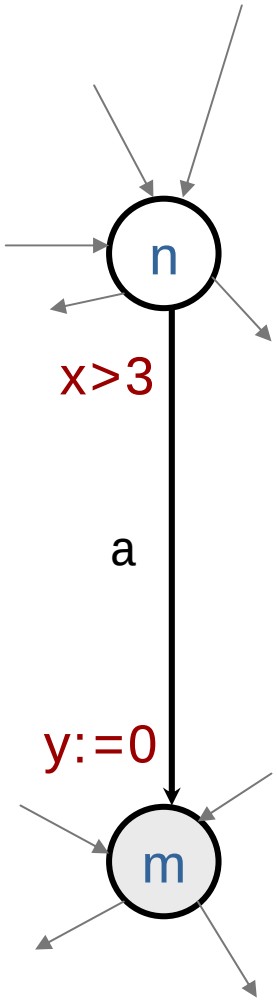
Symbolic state (set)

(n, $1 \leq x \leq 4$, $1 \leq y \leq 3$)

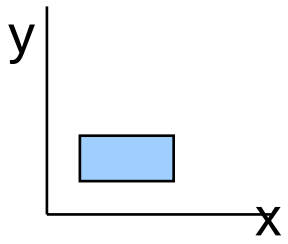


Zone:
conjunction of
x-y<=n,
x<=n,
x>=n

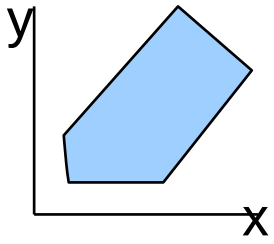
Symbolic Transitions



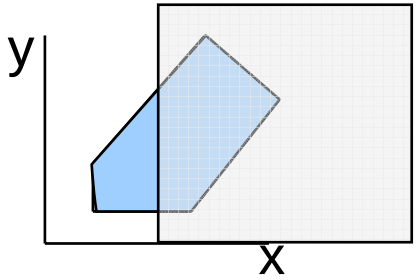
$1 \le x \le 4$
$1 \le y \le 3$



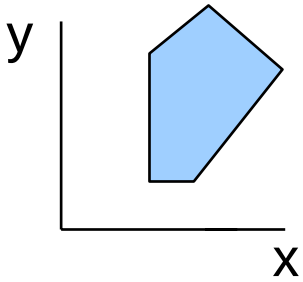
delays to



$1 \le x, 1 \le y$
$-2 \le x-y \le 3$



conjuncts to



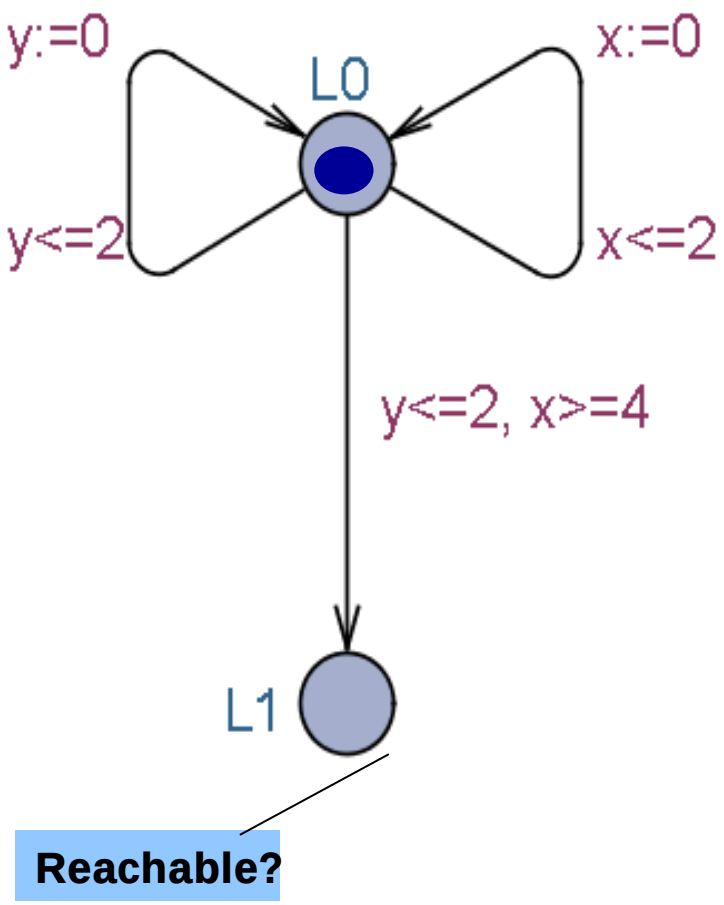
$3 < x, 1 \le y$
$-2 \le x-y \le 3$

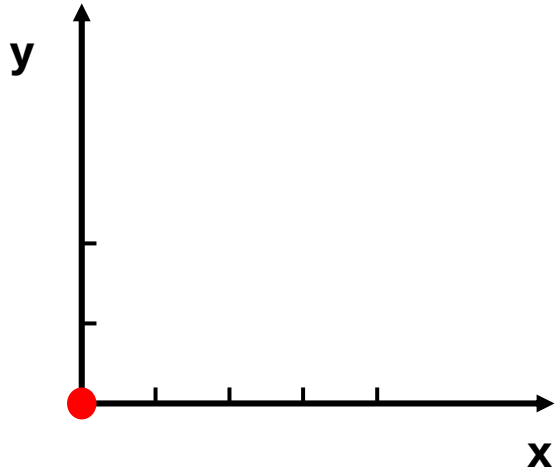
projects to

$3 < x, y=0$

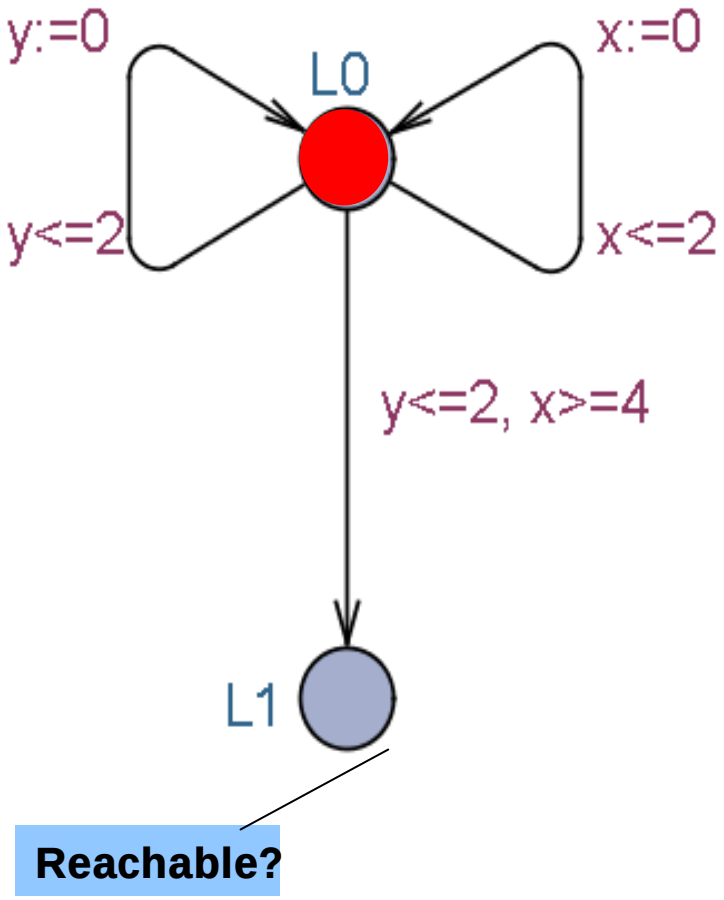
Thus $(n, 1 \le x \le 4, 1 \le y \le 3) \rightarrow^{a} (m, 3 < x, y=0)$

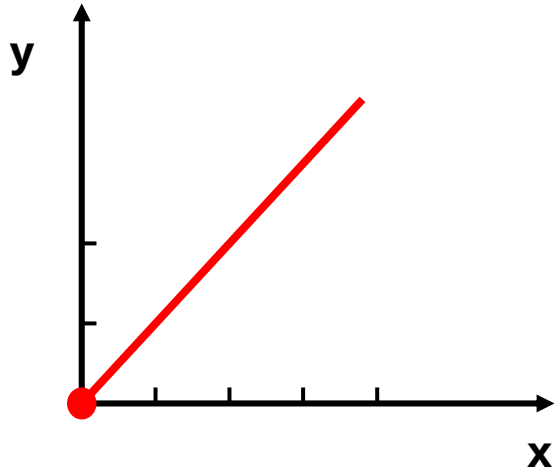
Symbolic Exploration





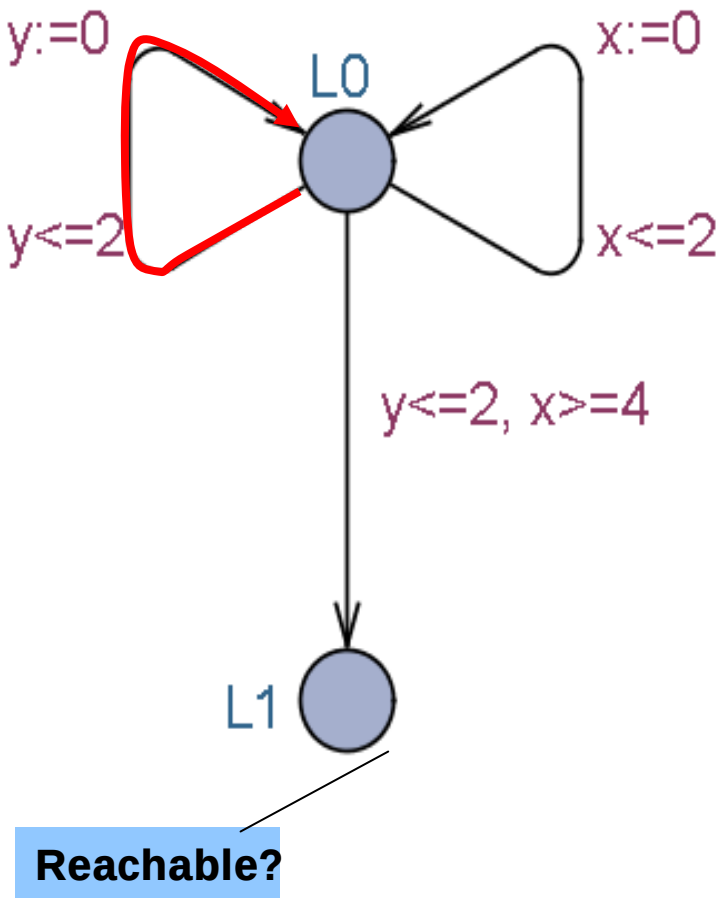
Symbolic Exploration

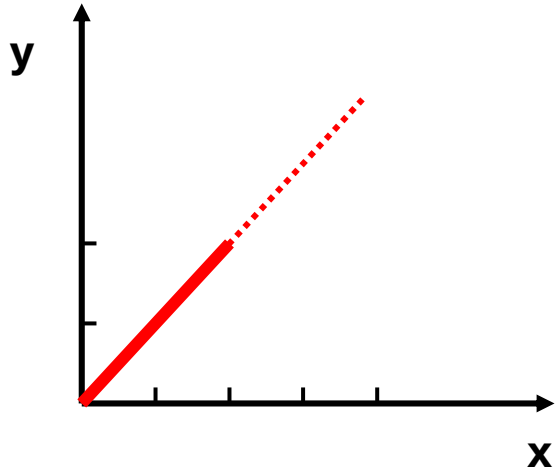




Delay

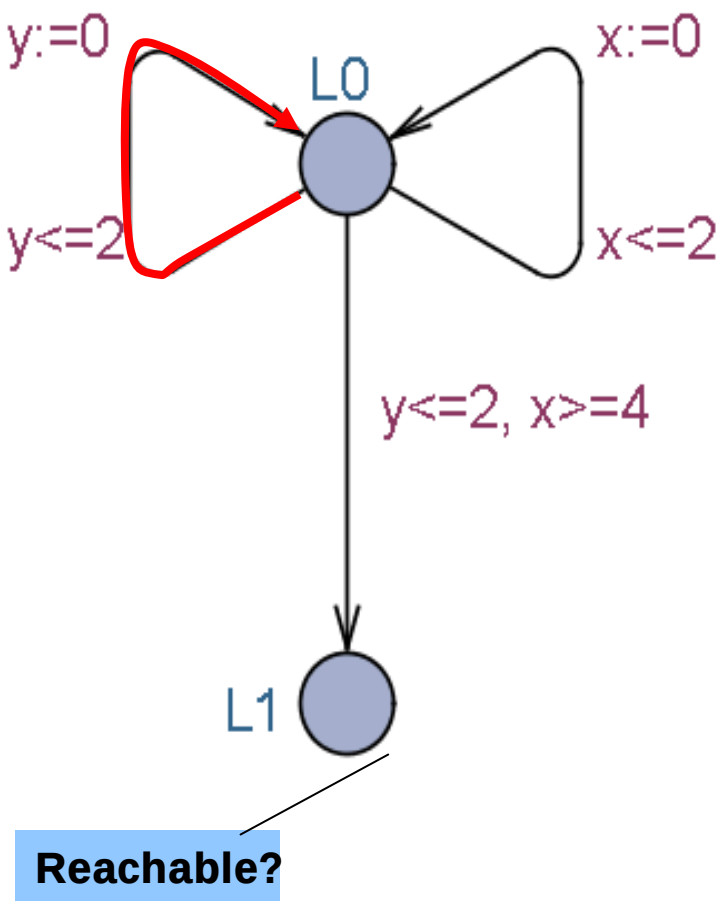
Symbolic Exploration

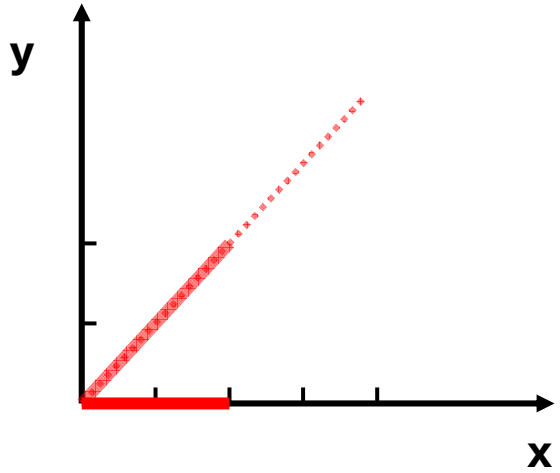




Left

Symbolic Exploration





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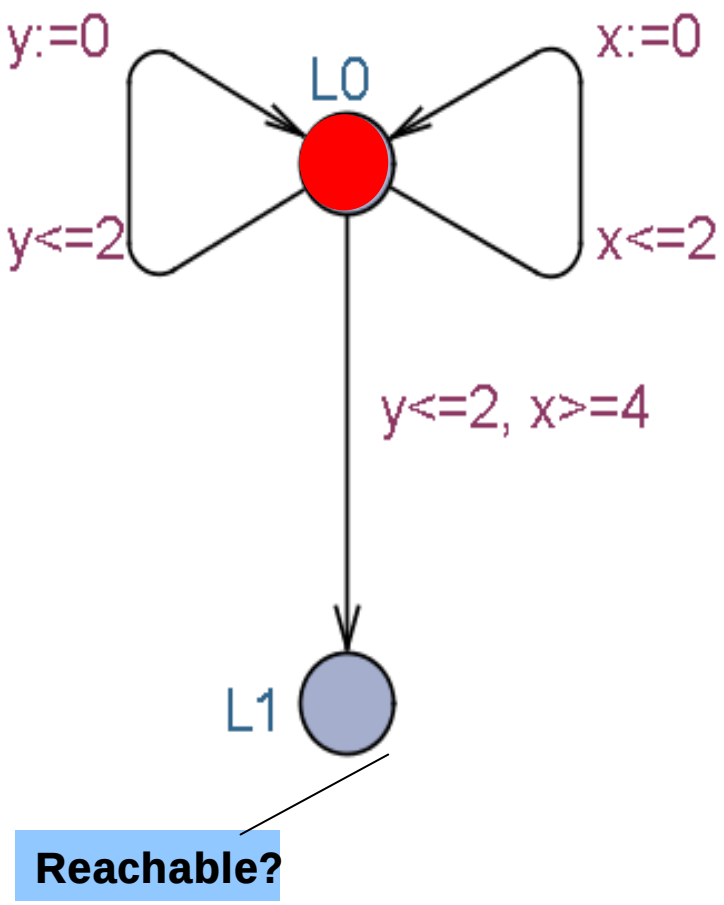
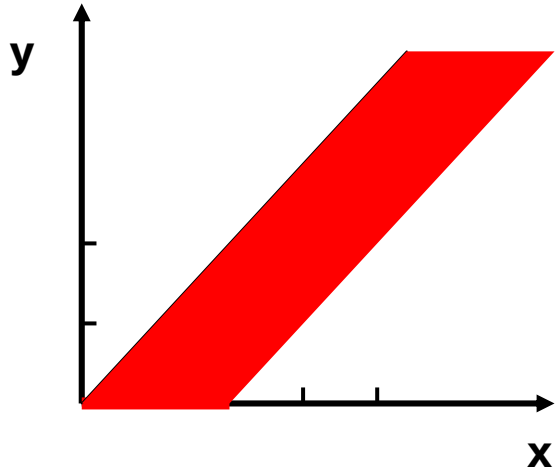
Symbolic Exploration





Delay

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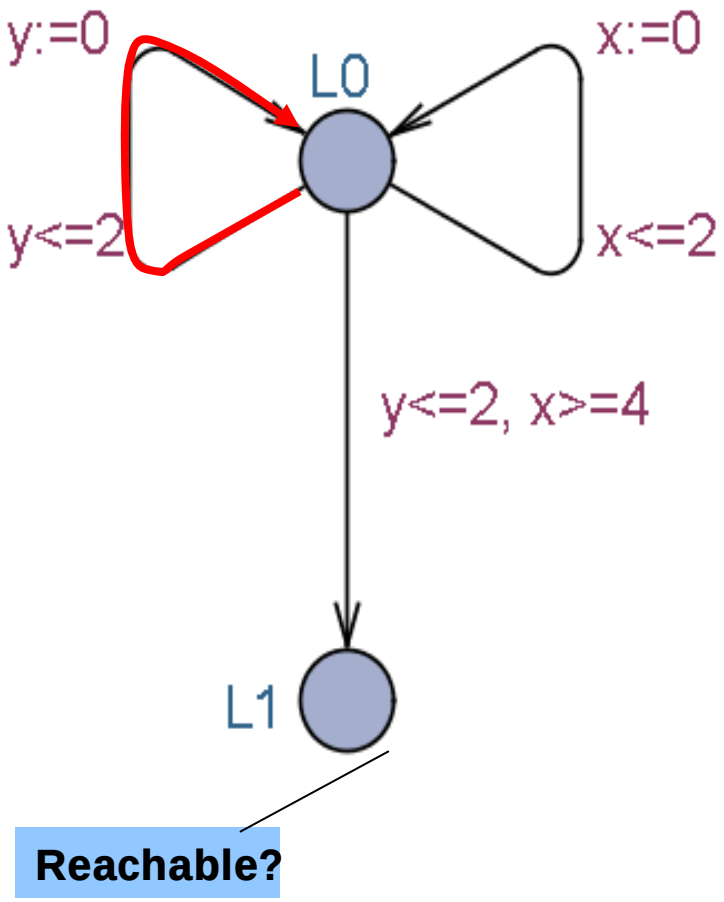
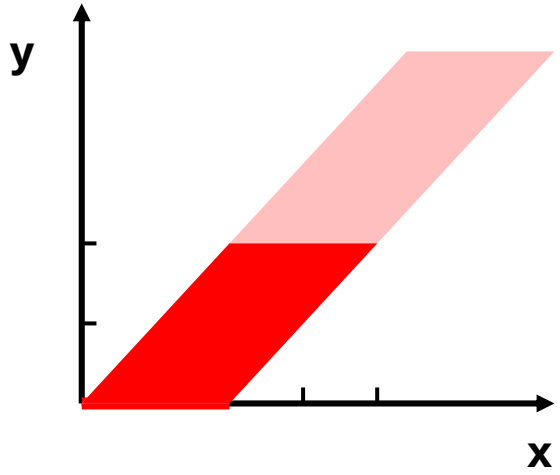
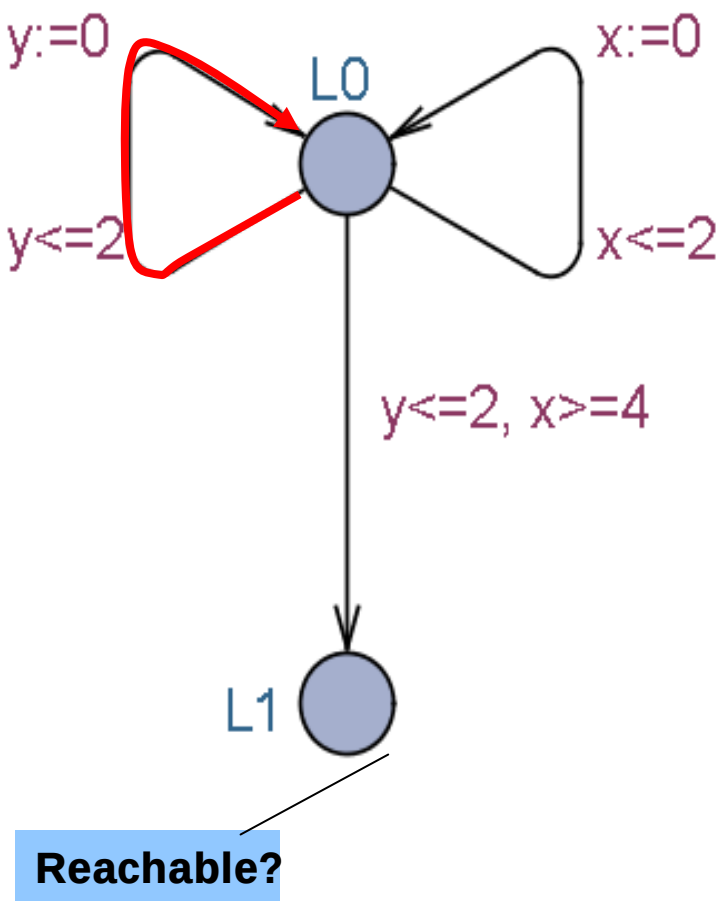
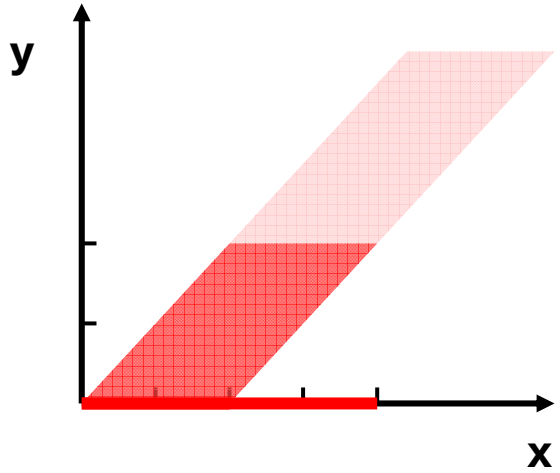




Left

Symbolic Exploration





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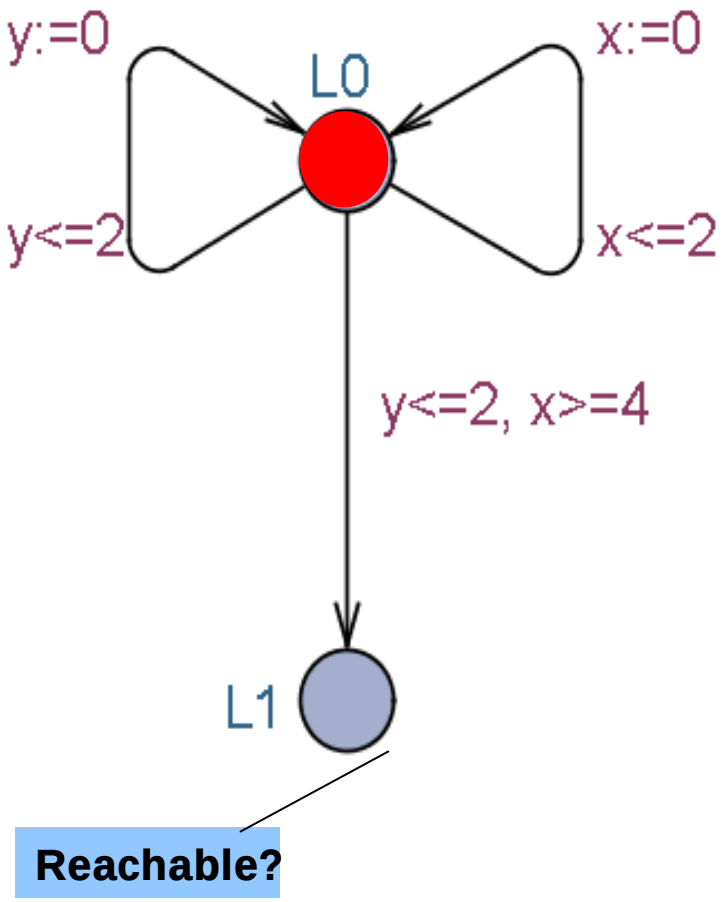

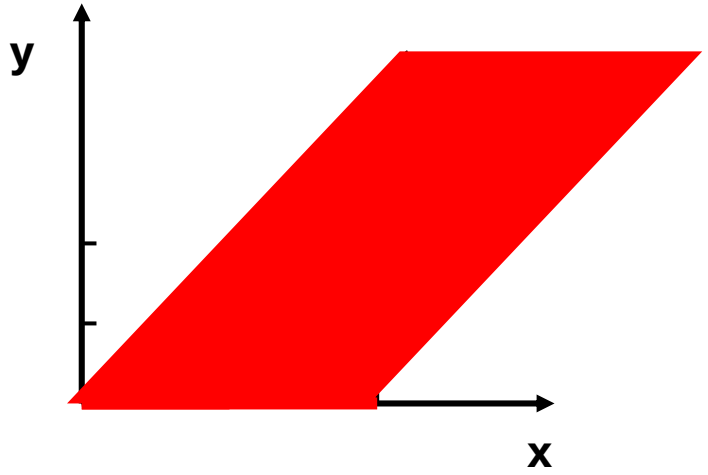

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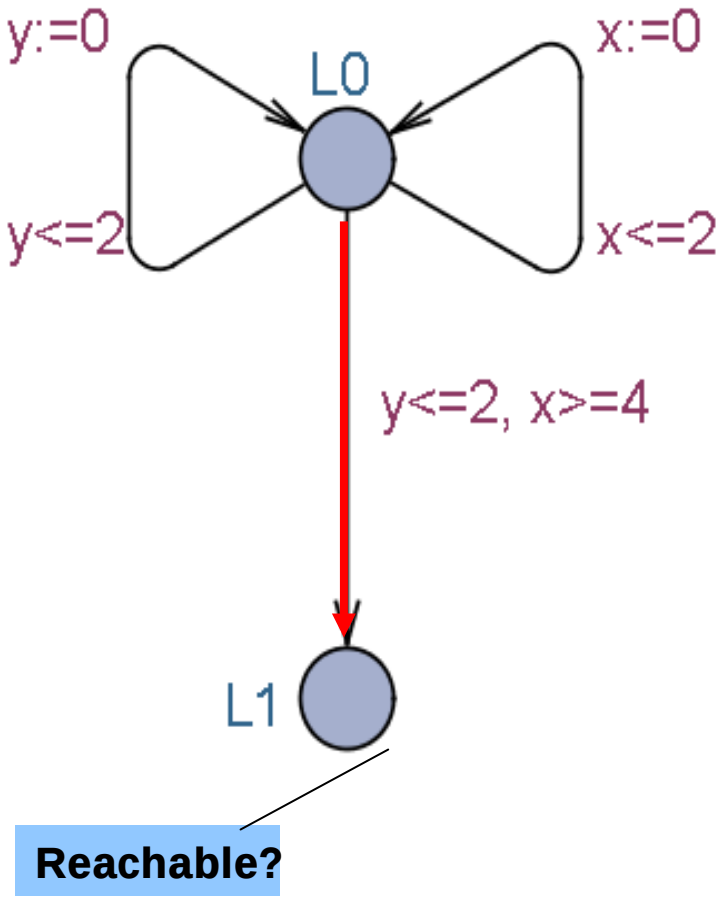
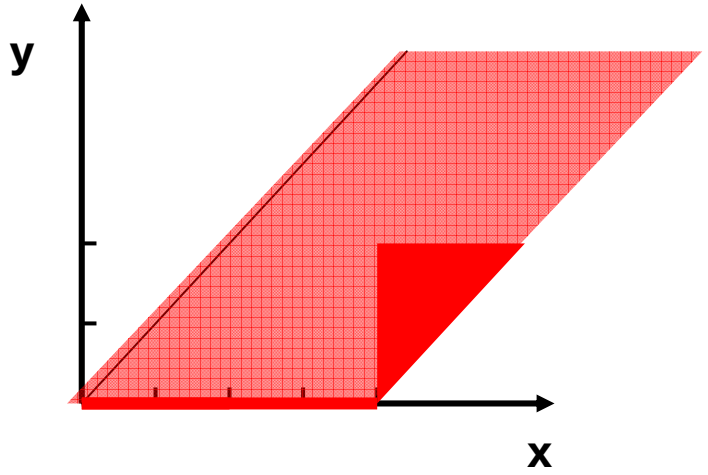


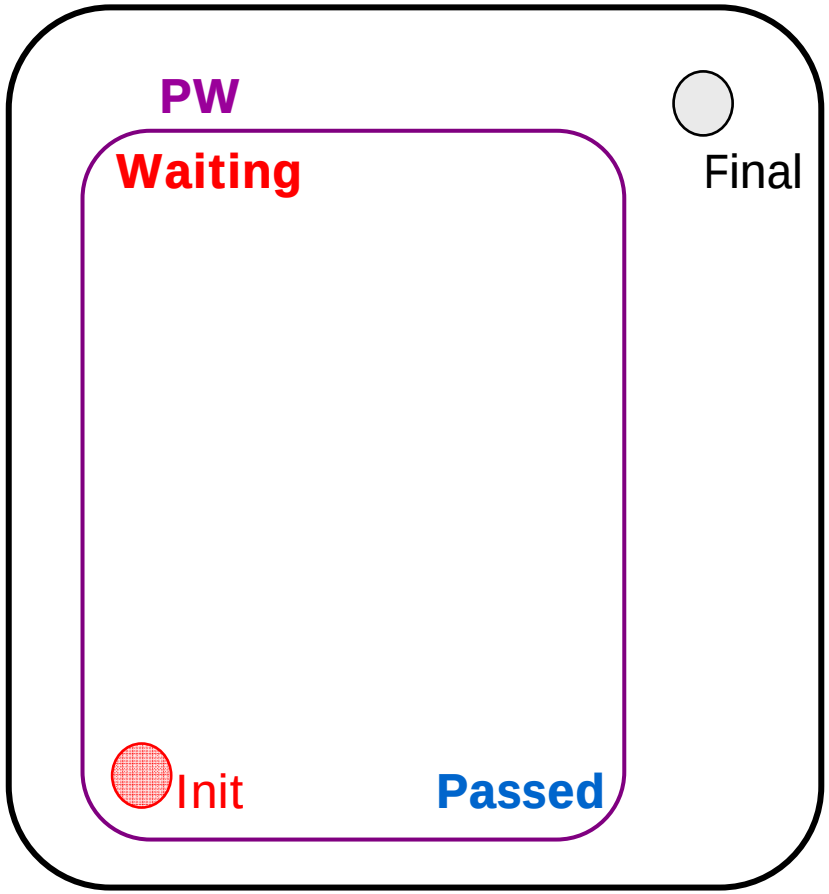


Down

The simulator shows you symbolic states!

Forward Reachability Algorithm

Init -> Final ?



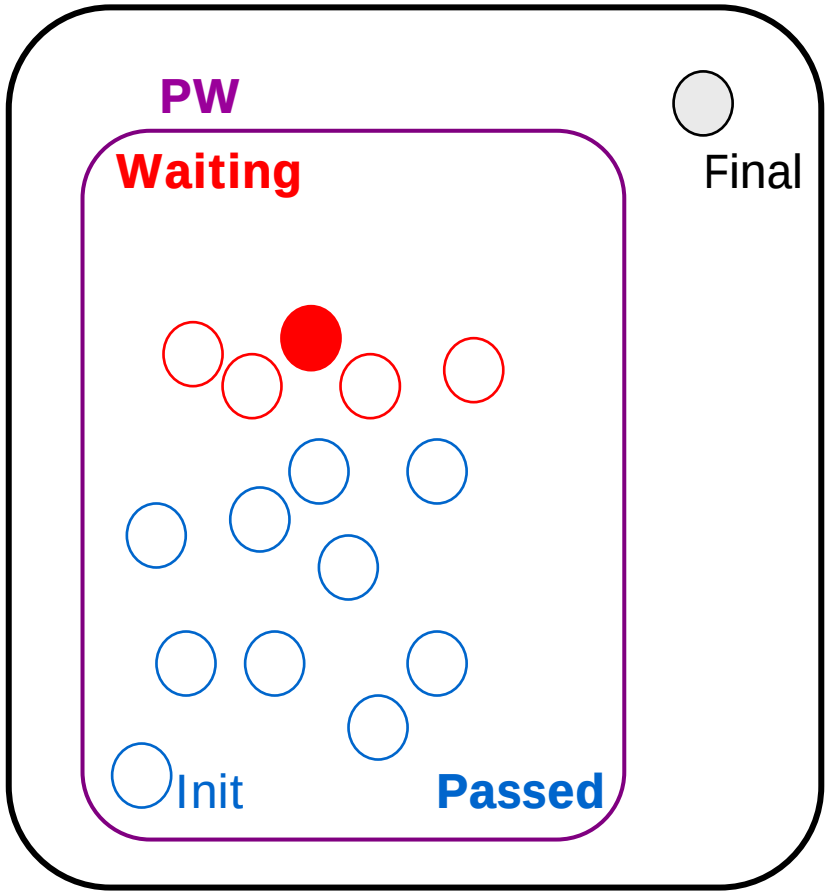
INITIAL **Passed** := Ø;
Waiting := $\{(n_0,Z_0)\}$

REPEAT

UNTIL **Waiting** = Ø
return false

Forward Reachability Algorithm

Init -> Final ?



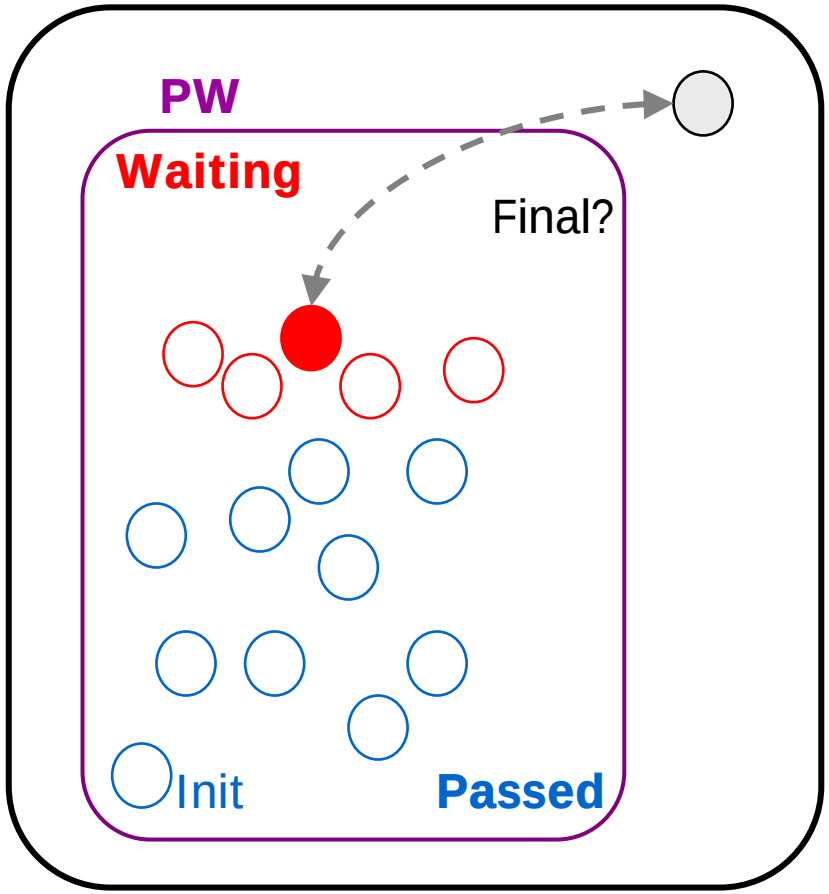
INITIAL **Passed** := Ø;
Waiting := $\{(n_0,Z_0)\}$

REPEAT
pick **(n,Z)** in **Waiting**

UNTIL **Waiting** = Ø
return false

Forward Reachability Algorithm

Init -> Final ?



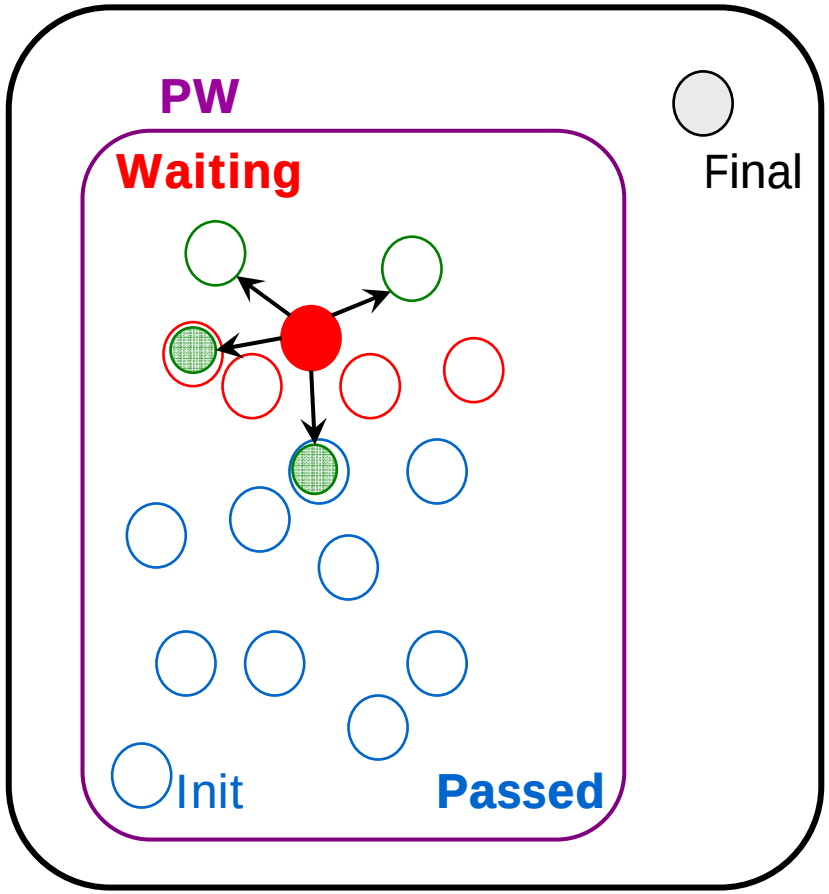
INITIAL **Passed** := Ø;
Waiting := $\{(n_0,Z_0)\}$

REPEAT
pick **(n,Z)** in **Waiting**
if (n,Z) = Final **return true**

UNTIL **Waiting** = Ø
return false

Forward Reachability Algorithm

Init -> Final ?



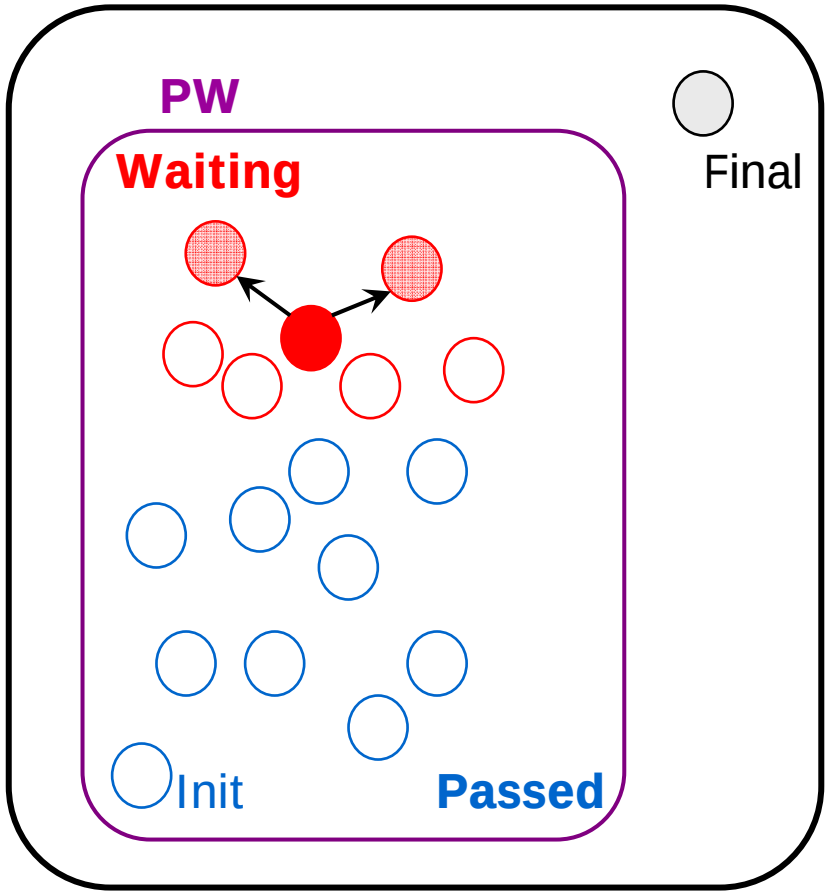
INITIAL **Passed** := Ø;
Waiting := $\{(n_0,Z_0)\}$

REPEAT
pick **(n,Z)** in **Waiting**
if (n,Z) = Final **return true**
for all (n,Z)→**(n',Z')**:
if for some (**n'**,Z'') **Z'⊆ Z''** **continue**

UNTIL **Waiting** = Ø
return false

Forward Reachability Algorithm

Init -> Final ?



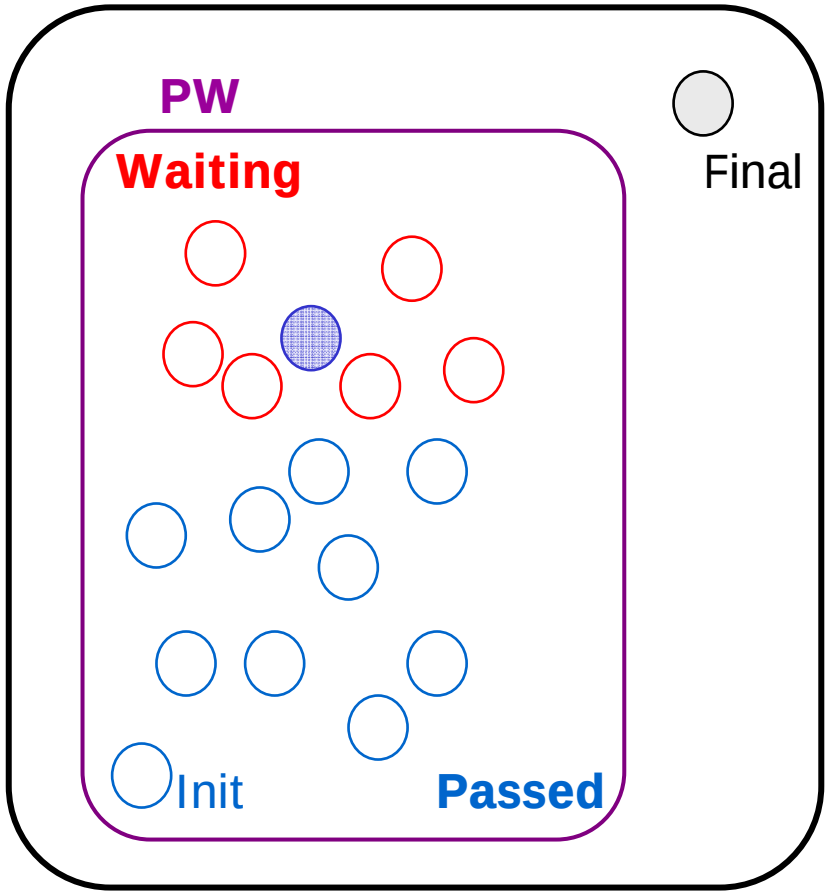
INITIAL **Passed** := Ø;
Waiting := $\{(n_0,Z_0)\}$

REPEAT
pick **(n,Z)** in **Waiting**
if (n,Z) = Final **return true**
for all (n,Z)→**(n',Z')**:
if for some (**n'**,Z'') **Z'⊆ Z''** **continue**
else add (n',Z') to **Waiting**

UNTIL **Waiting** = Ø
return false

Forward Reachability Algorithm

Init -> Final ?



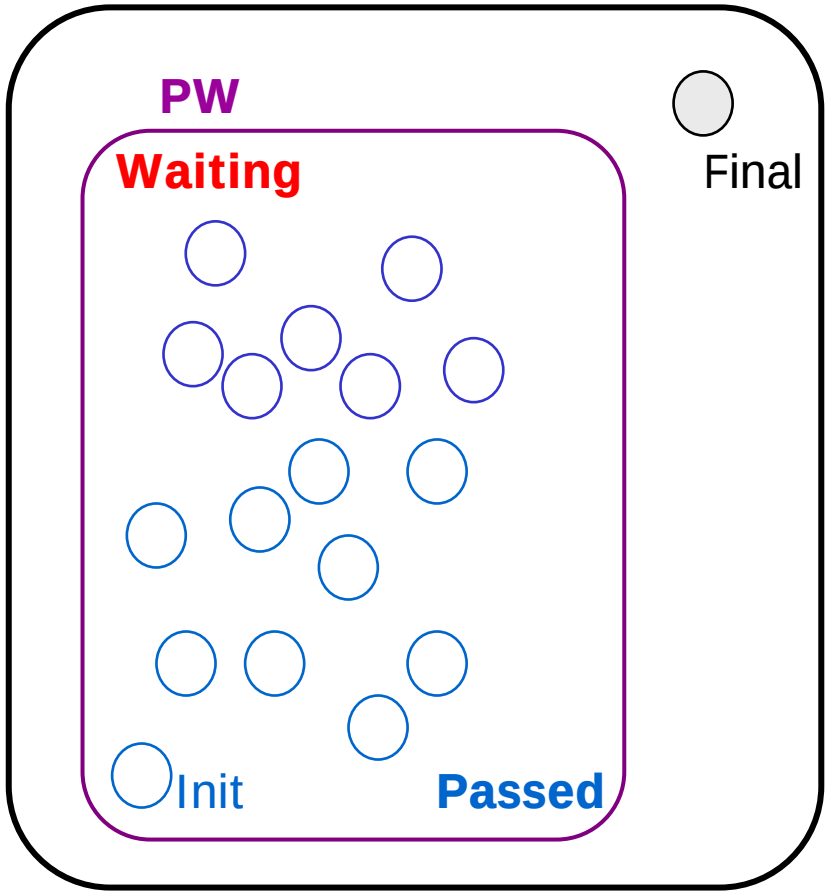
INITIAL **Passed** := Ø;
Waiting := $\{(n_0,Z_0)\}$

REPEAT
pick **(n,Z)** in **Waiting**
if (n,Z) = Final **return true**
for all (n,Z)→**(n',Z')**:
if for some (**n'**,Z'') **Z'⊆ Z''** **continue**
else add (n',Z') to **Waiting**
move (n,Z) to **Passed**

UNTIL **Waiting** = Ø
return false

Forward Reachability Algorithm

Init -> Final ?



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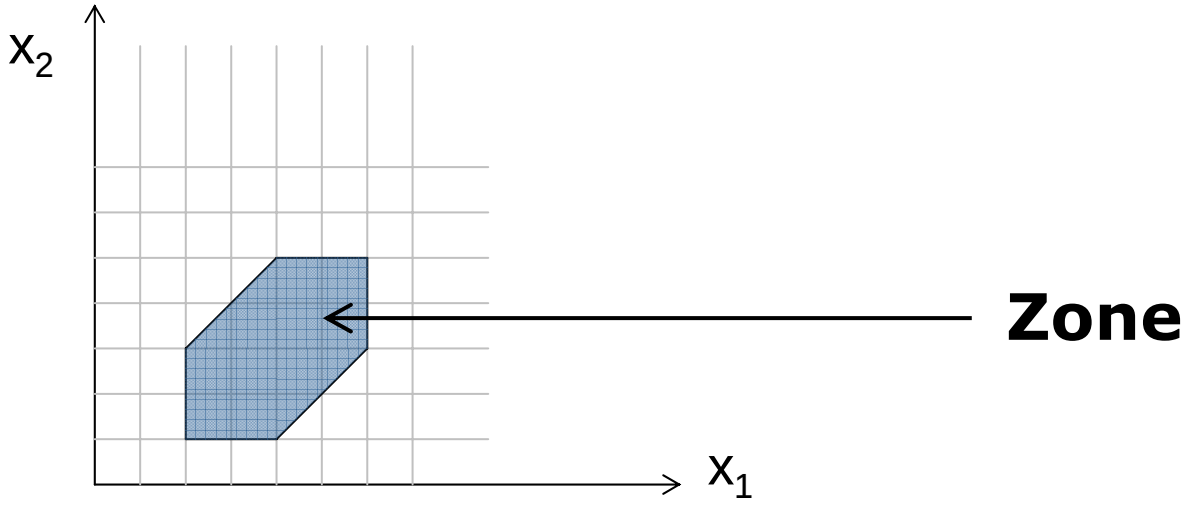
Difference Bound Matrices

$x_0-x_0<=0$	$x_0-x_1<=-2$	$x_0-x_2<=-1$
$x_1-x_0<=6$	$x_1-x_1<=0$	$x_1-x_2<=3$
$x_2-x_0<=5$	$x_2-x_1<=1$	$x_2-x_2<=0$

$$x_i - x_j <= c_{ij}$$



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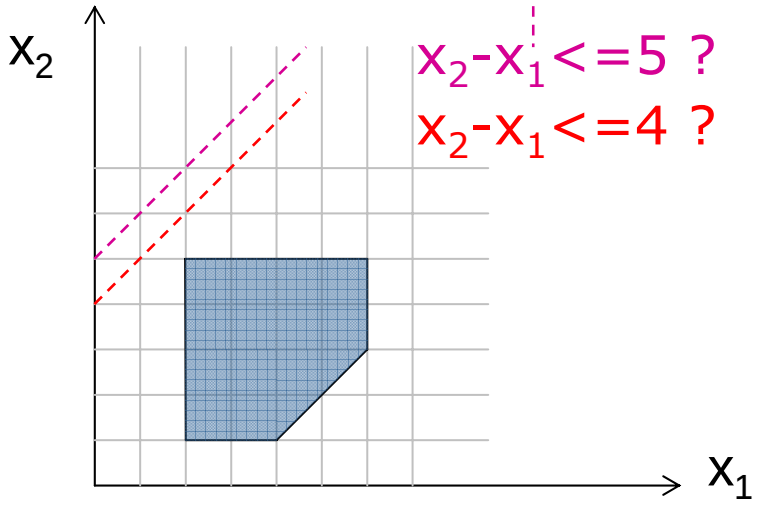
$$\mathbf{x_i-x_j<=c_{ij}}$$



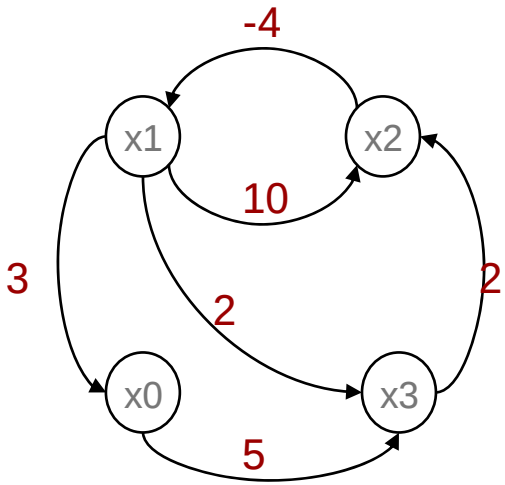
Canonical representation:
All constraints **as tight as possible**.
Needed for inclusion checking.
→ **Unique** DBM to represent a zone.

Canonical Datastructures for Zones

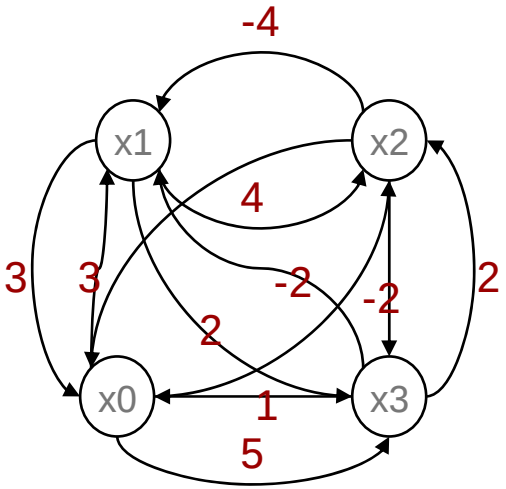
Minimal Constraint Form

RTSS 1997

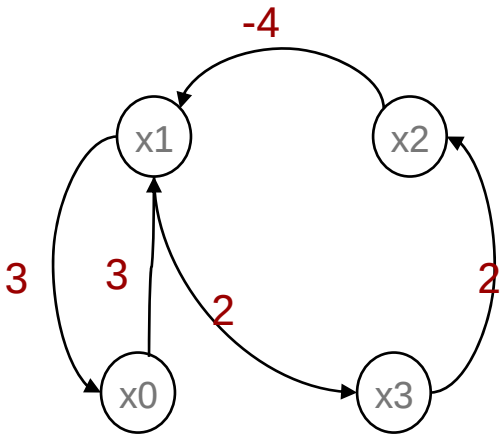
x1-x2<=4
x2-x1<=10
x3-x1<=2
x2-x3<=2
x0-x1<=3
x3-x0<=5



Shortest Path Closure O(n^3)



Shortest Path Reduction O(n^3)



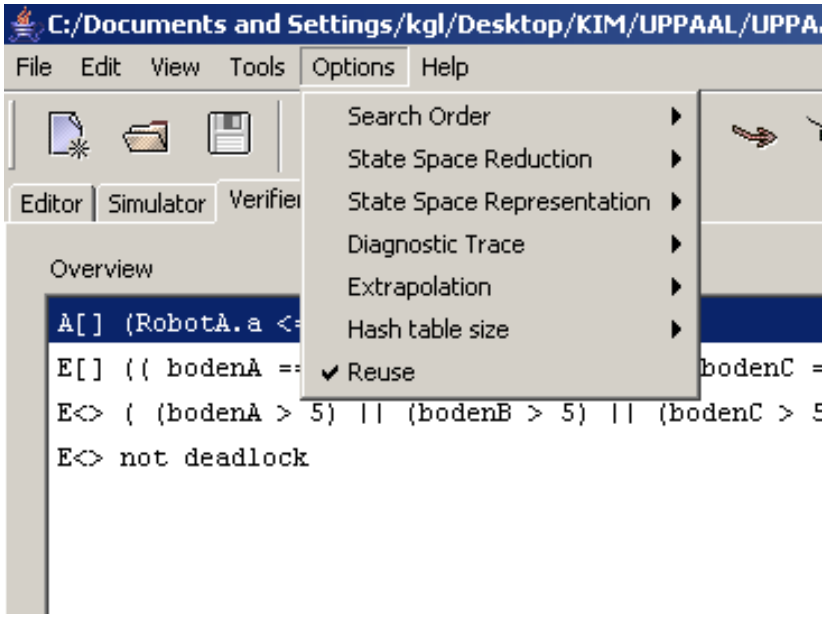
Space worst O(n^2)
practice O(n)

Large gain in space.
Small price in time.

Verification option "CDS".

Verification Options

Verification Options



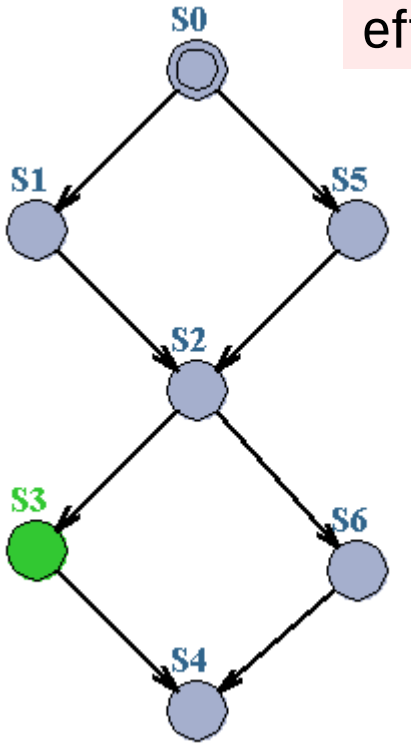
Search Order
- Depth First
- Breadth First

State Space Reduction
- None
- Conservative
- Aggressive

State Space Representation
- DBM
- Compact Form
- Under Approximation
- Over Approximation

Diagnostic Trace
- Some
- Shortest
- Fastest

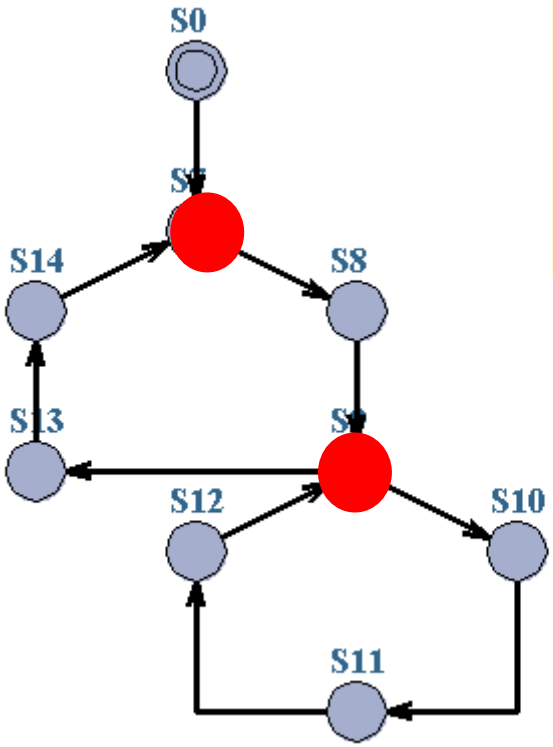
State Space Reduction



However,
Passed list useful for efficiency

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

State Space Reduction



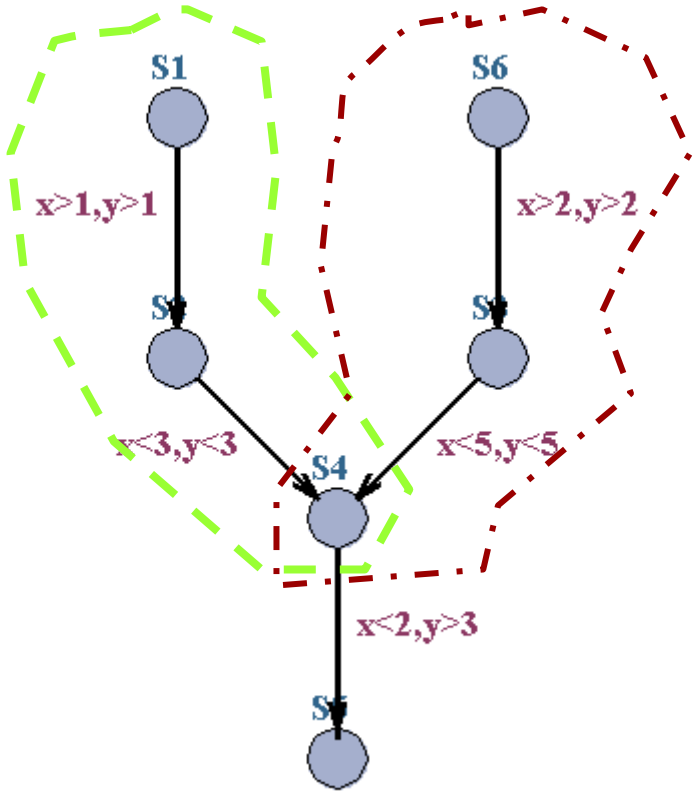
Cycles:

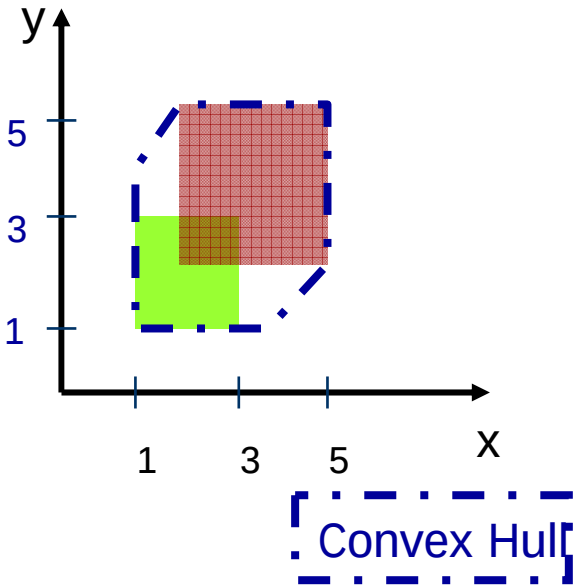
Only symbolic states involving loop-entry points need to be saved on **Passed** list

Over-approximation

Convex Hull

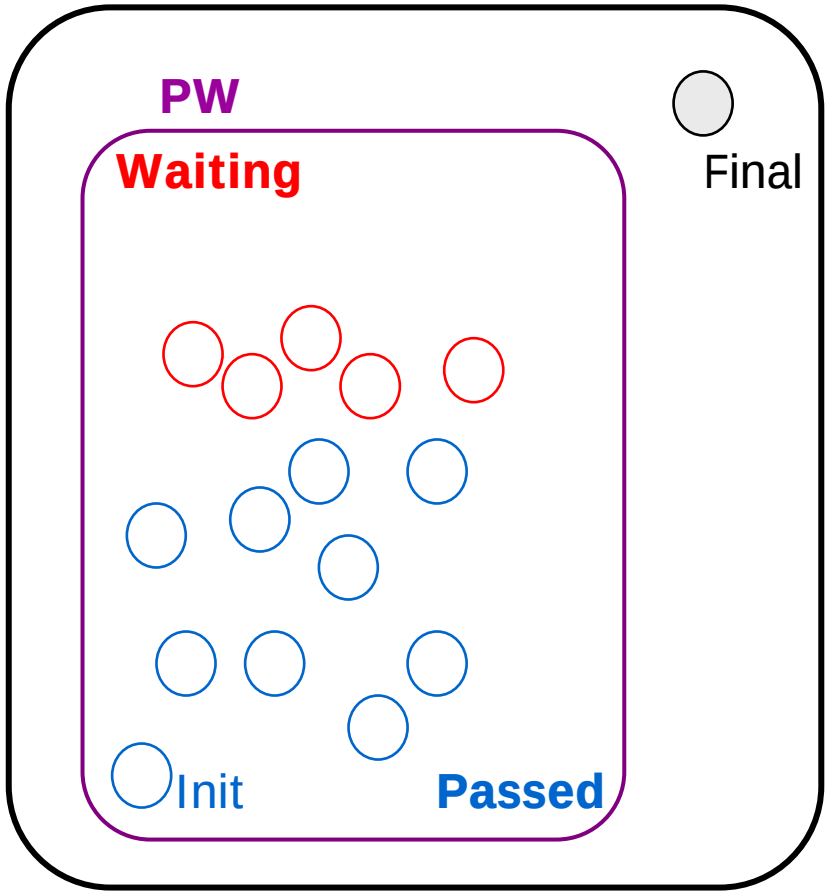
TACAS04: An **EXACT** method performing as well as Convex Hull has been developed based on abstractions taking max constants into account.





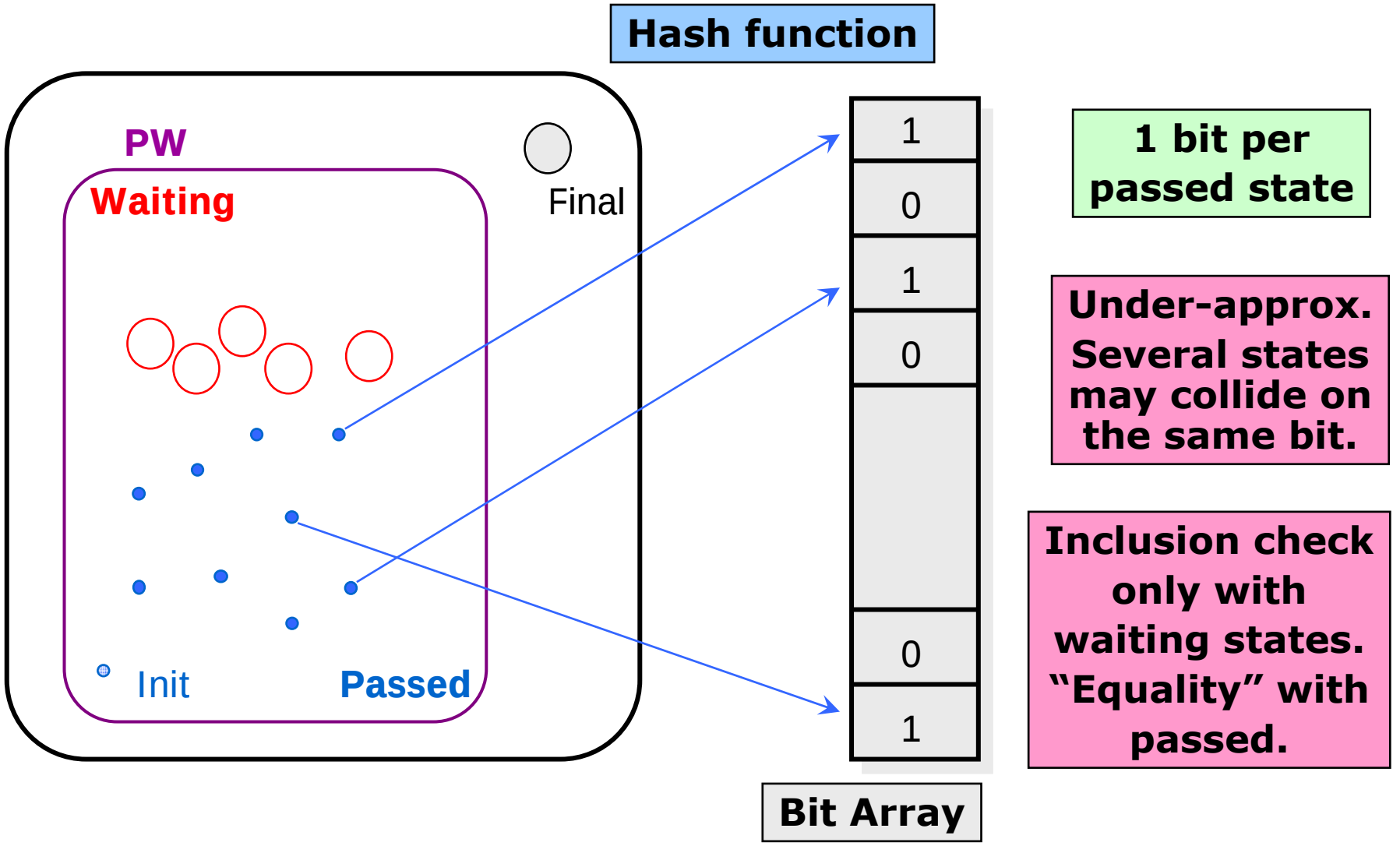
Under-approximation

Bitstate Hashing



Under-approximation

Bitstate Hashing



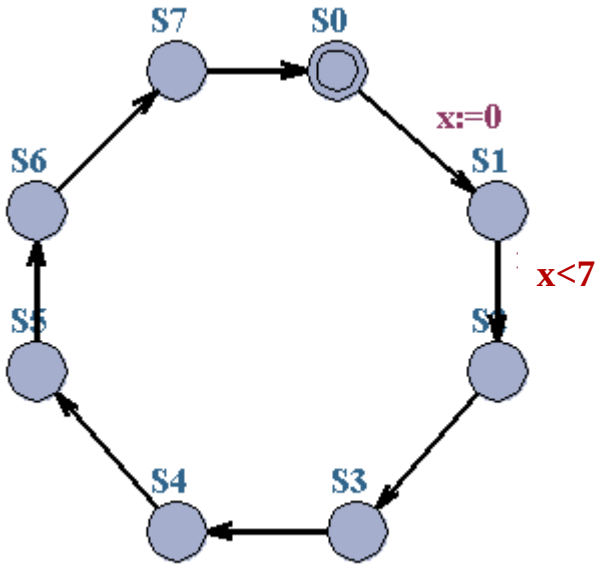
Modelling Patterns

Variable Reduction

- Reduce size of state space by explicitly resetting variables when they are not used!
- Automatically performed for clock variables (active clock reduction)

```
// Remove the front element of the queue
void dequeue()
{
        int i = 0;
        len -= 1;
        while (i < len)
        {
                list[i] = list[i + 1];
                i++;
        }
        list[i] = 0;
}
```

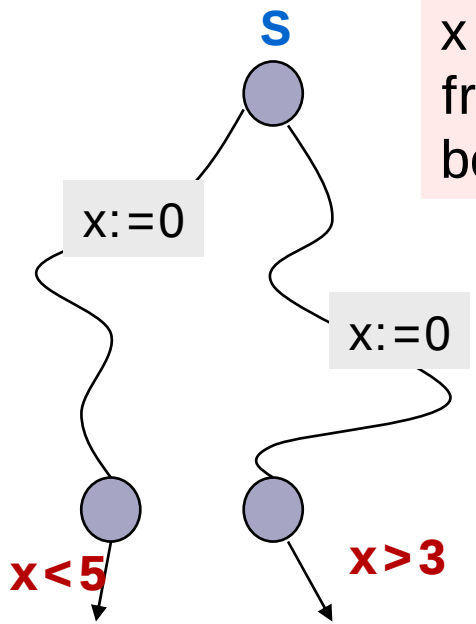
Clock Reduction (Automatic)



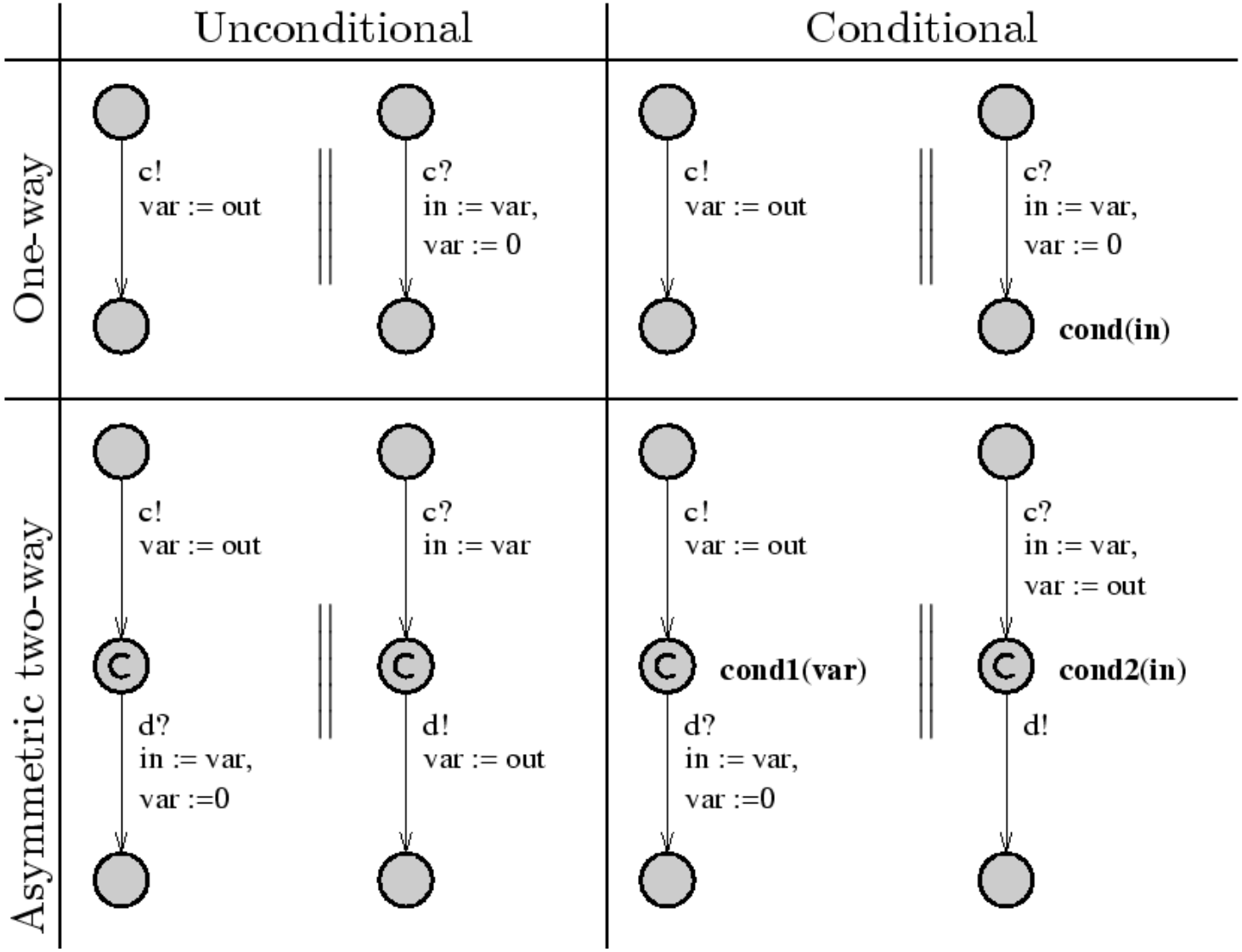
x is only ***active*** in location **S1**

Definition

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

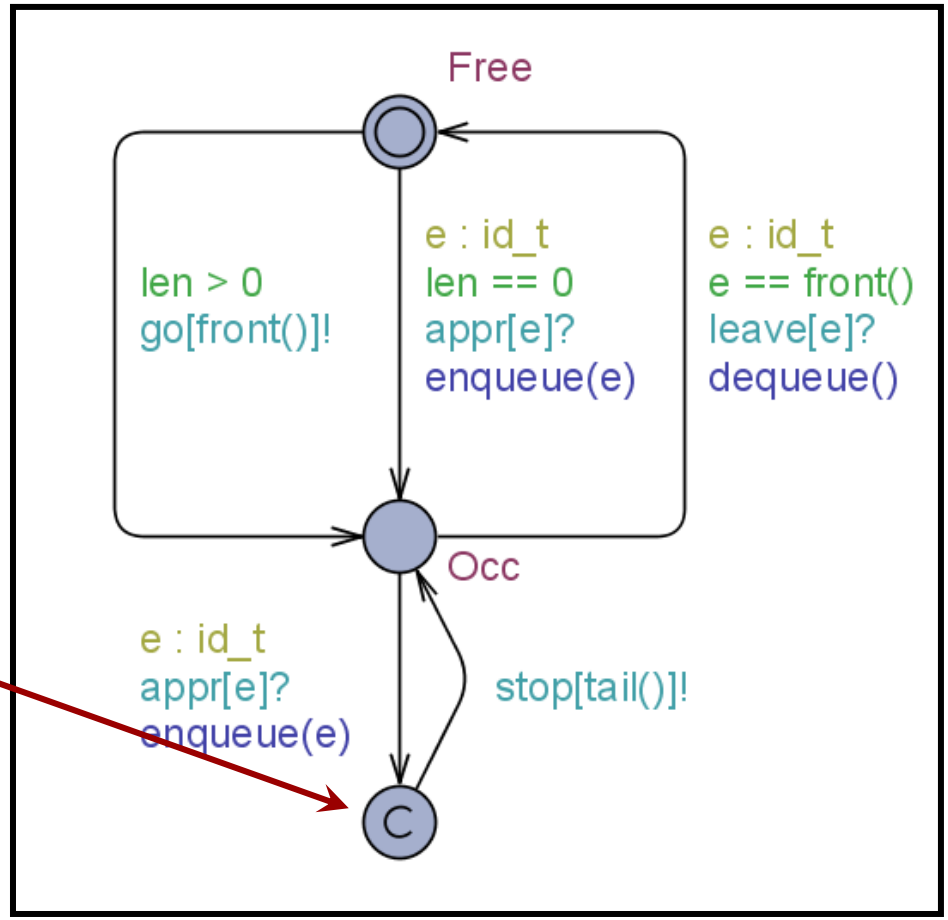


Synchronous Value Passing



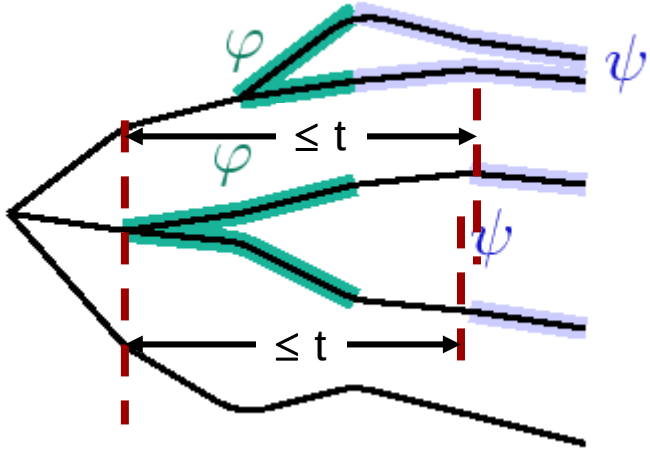
Atomicity

- Loops & complex control structures: C-functions.
- To allow encoding of multicasting.
- Committed locations.



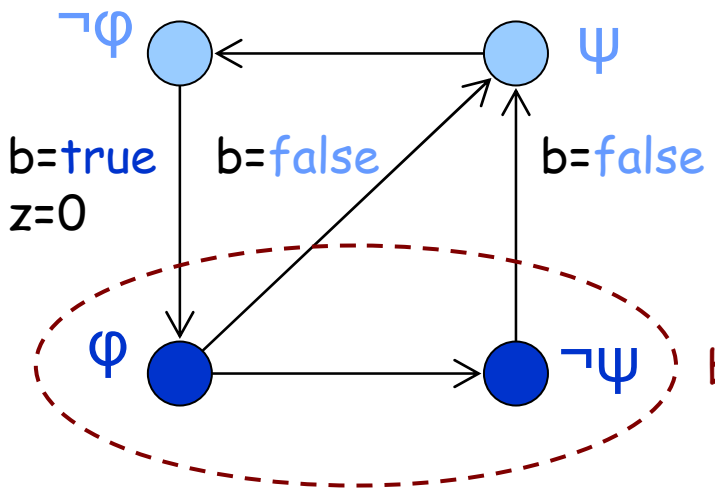
Bounded Liveness

- Leads to within: $\varphi \rightarrow_{\leq t} \psi$
  - More efficient than leadsto: φ leadsto$_{\leq t}$ ψ reduced to $A\Box(b \Rightarrow z \leq t)$ with
  - bool b set to true and clock z reset when φ holds.
  - When ψ holds set b to false.



Bounded Liveness

- The truth value of b indicates whether or not ψ should hold in the future.

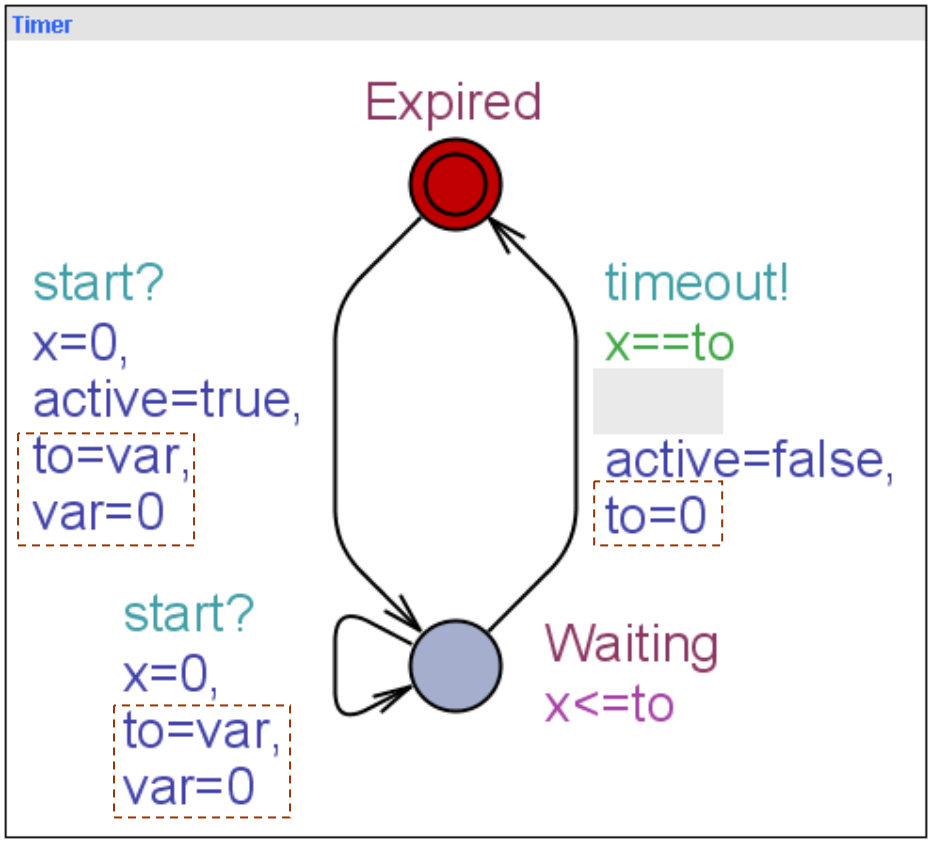


A[] (b imply z ≤ t)
E<> b (for meaningful check)

Timers

Parametric timer:

- (re-)start(value)
  `start! var=value`
- expired?
  `active` (bool)
  `active go?`
  (bool+urgent chan)
- time-out event
  `timeout?`



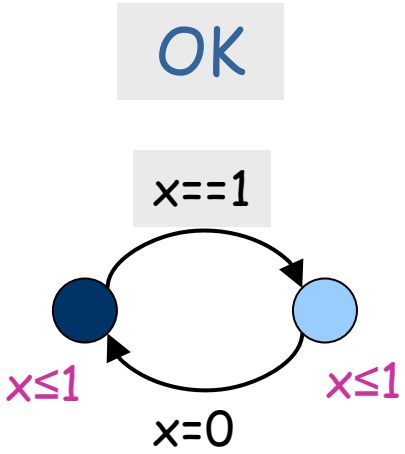
Declare 'to' with a tight range.

Zenoness

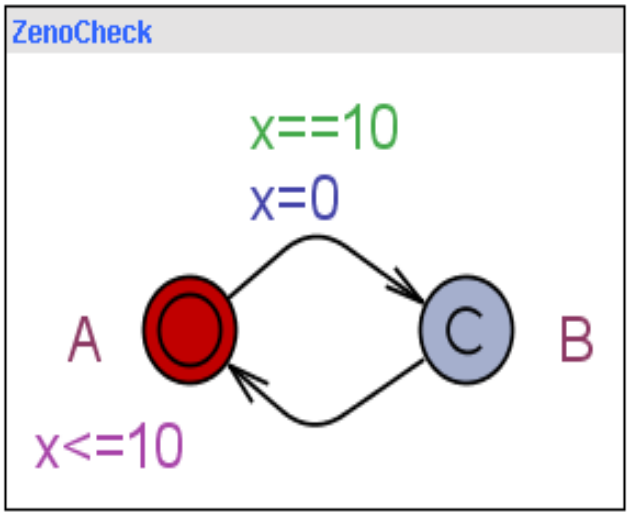
- Problem: UPPAAL does not check for zenoness directly.
  - A model has "zeno" behavior if it can take an infinite amount of actions in finite time.
  - That is usually not a desirable behavior in practice.
  - Zeno models may wrongly conclude that some properties hold though they logically should not.
  - Rarely taken into account.

- Solution: Add an observer automata and check for non-zenoness, i.e., that time will always pass.

Zenoness



Detect by
•adding the observer:



Constant (10) can be anything (>0), but choose it well w.r.t. your model for efficiency. Clocks 'x' are local.

•and check the property
`ZenoCheck.A --> ZenoCheck.B`