Parking Can Get You There Faster

Model Augmentation to Speed up Real-Time Model Checking

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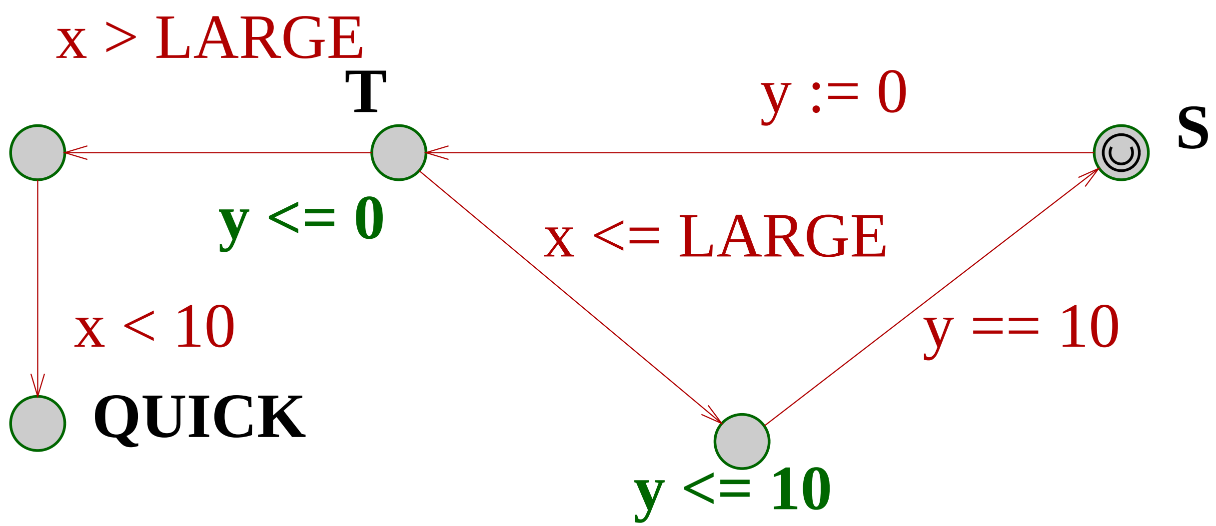
Timed Automata (UPPAAL Flavor)



clocks:	**x,y**
guards:	**y==10, x>LARGE, x<10**
invariants:	**y<=10**
urgency:	**location S**

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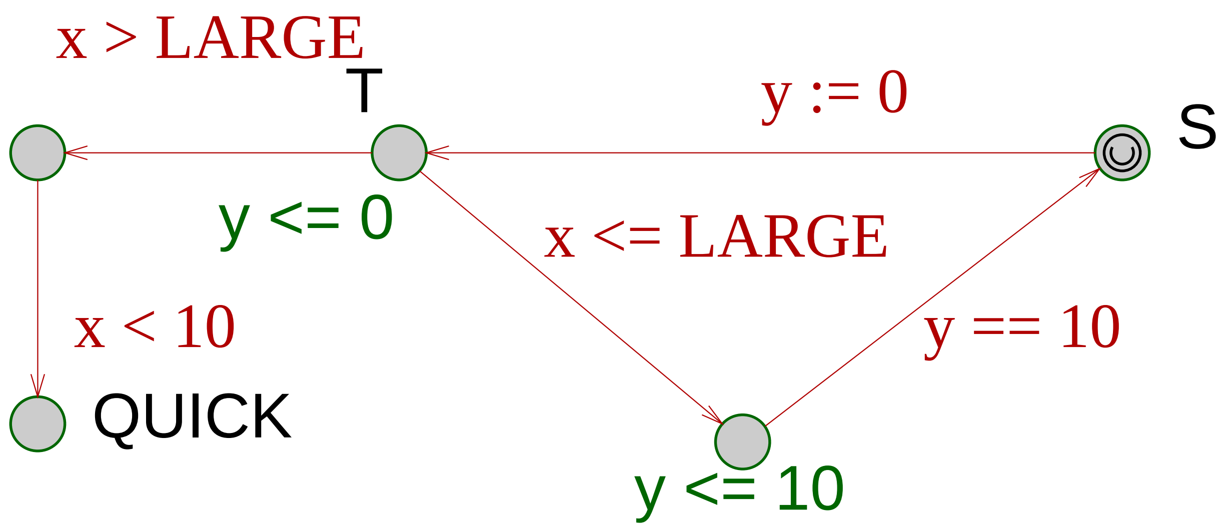

clocks:	**x,y**
guards:	**y==10, x>LARGE, x<10**
invariants:	**y<=10**
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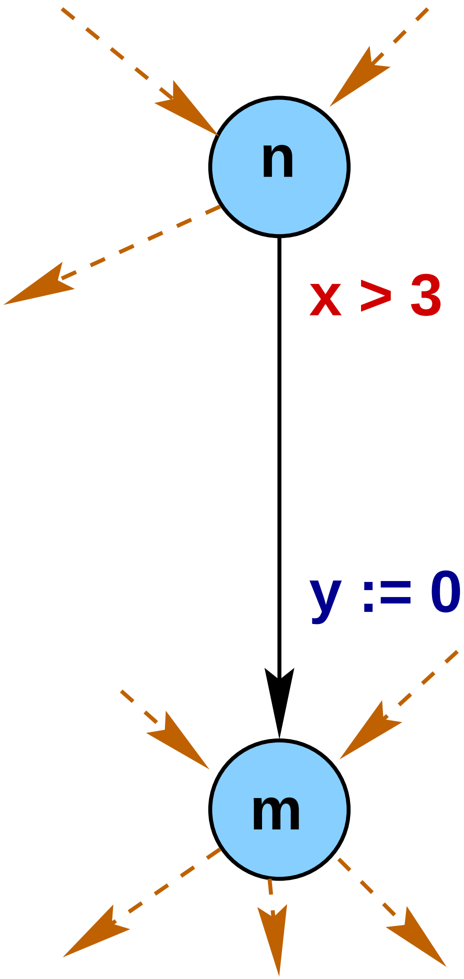
- network of timed automata
- hand-shake synchronization
- discrete data types
- ...

Symbolic Forward Reachability



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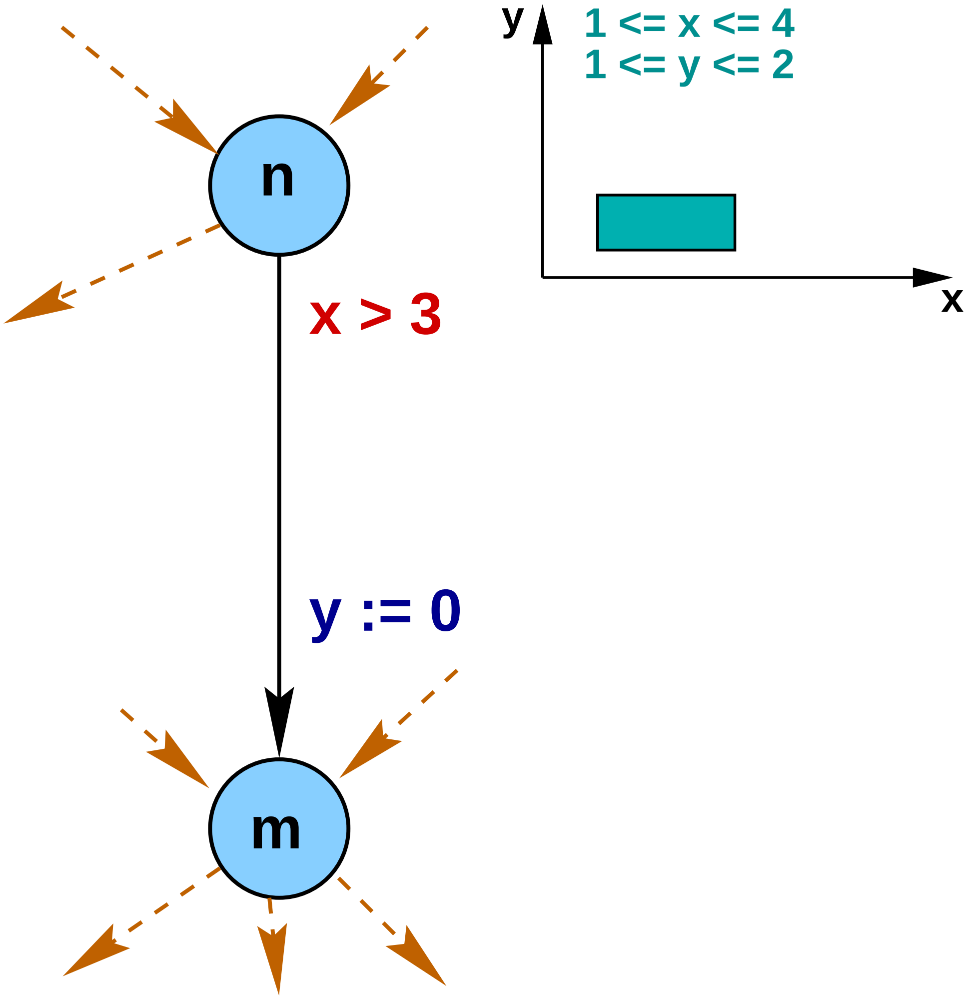

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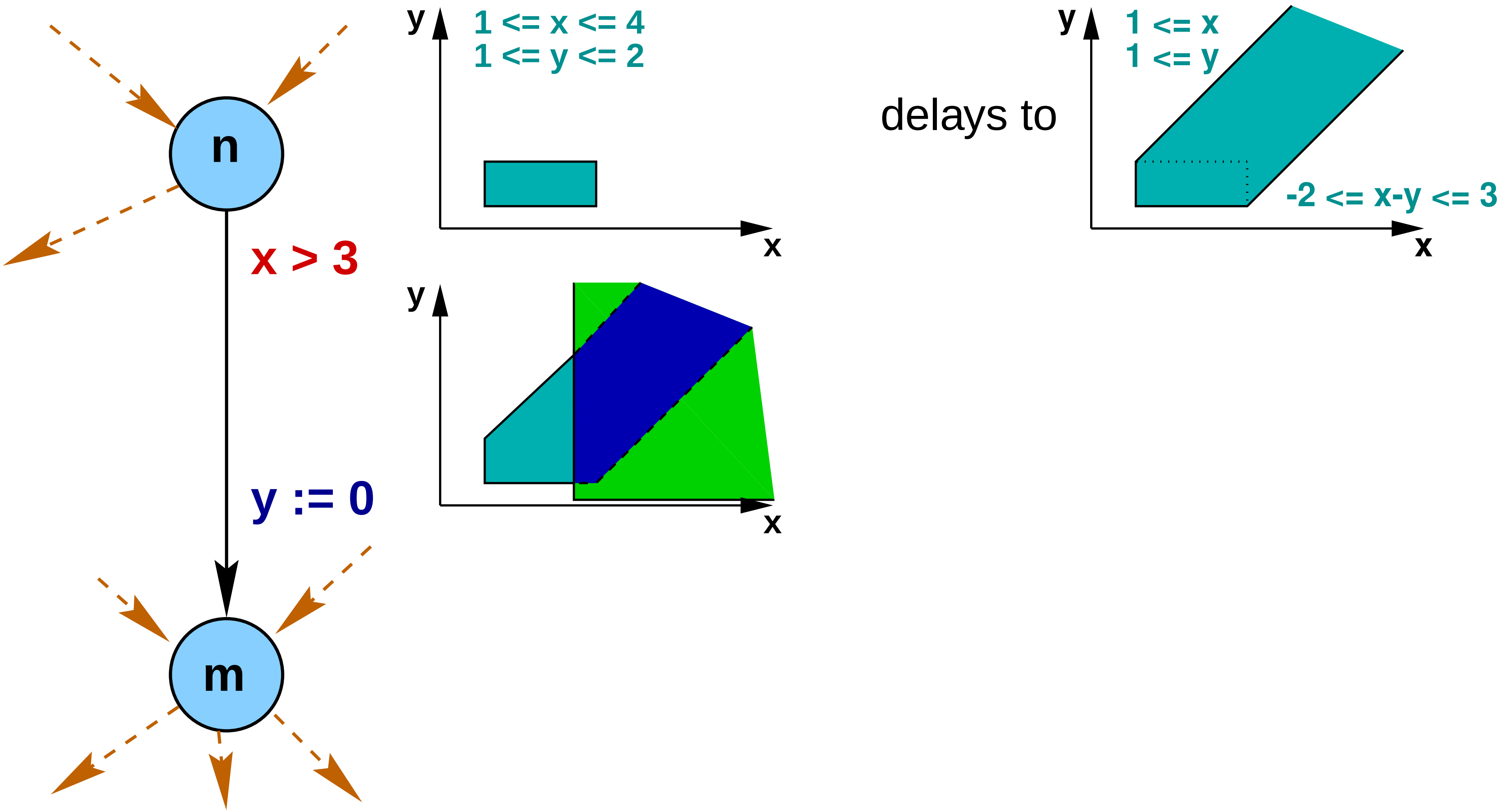

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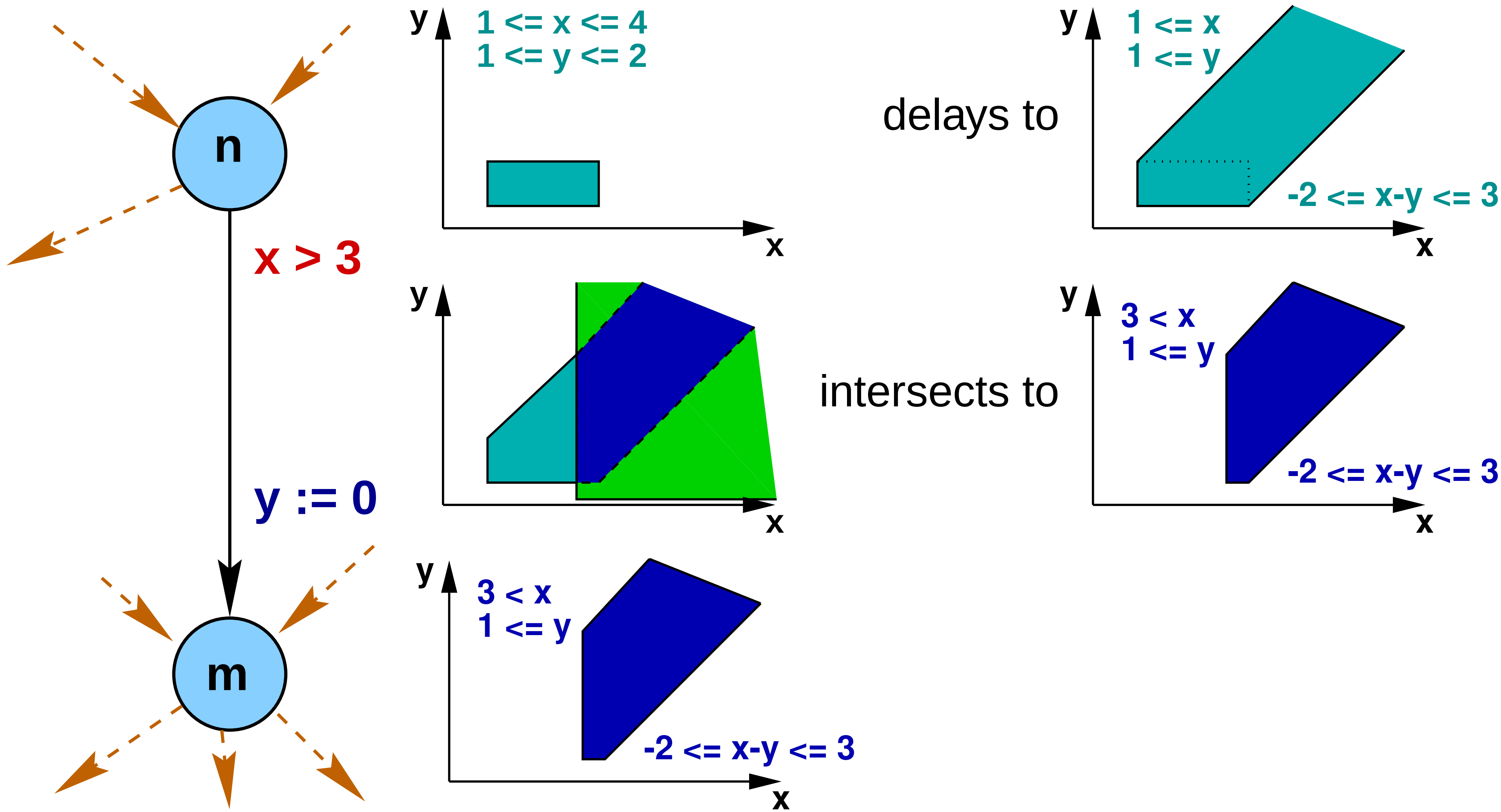

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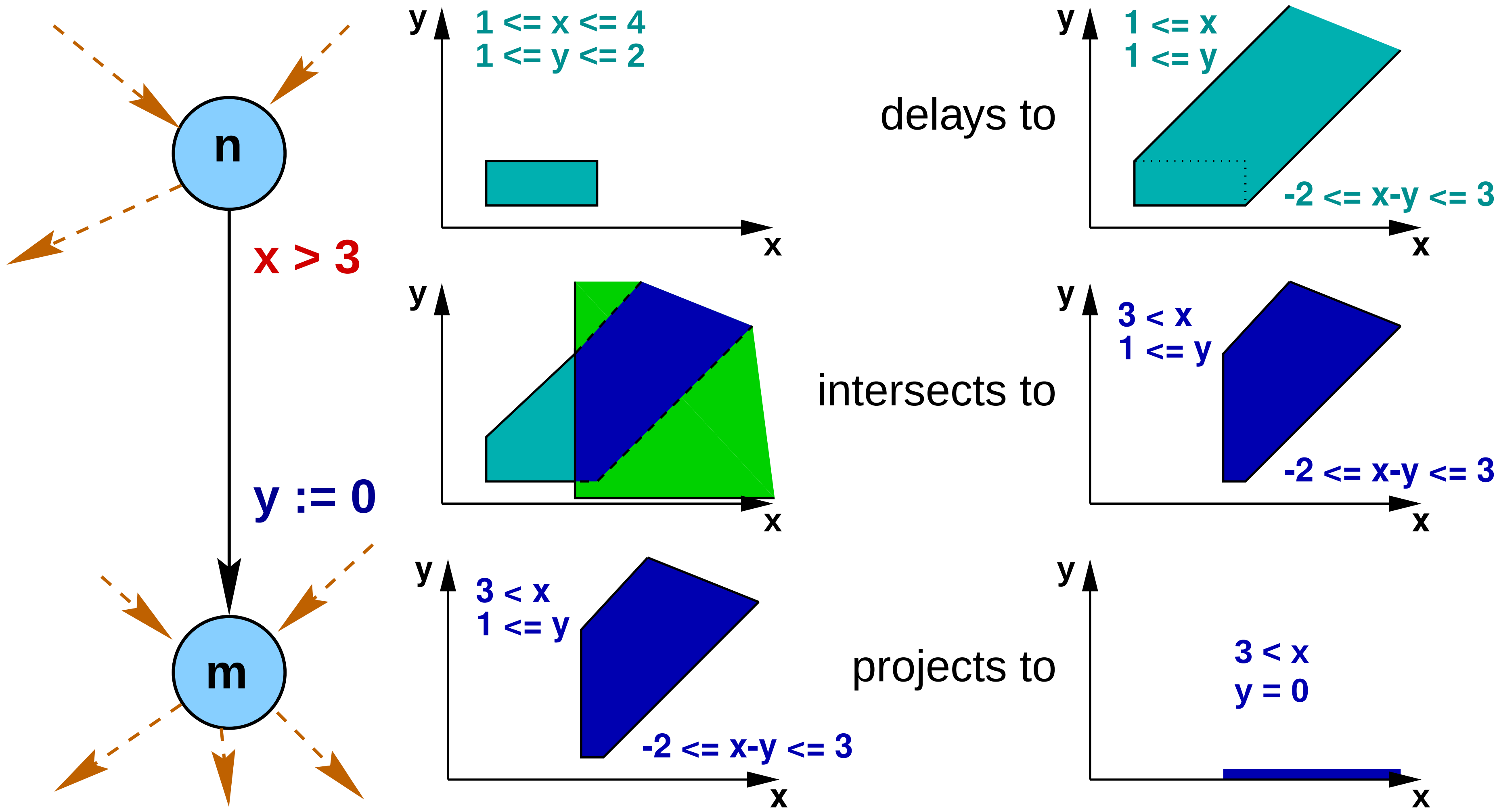


Forward State Space Exploration

Algorithm: *Reachability*

input: *Goal* : $(\vec{l}_g; v_g)$

Passed $:= \{\};$ *Waiting* $:= \{(\vec{l}_0; v_0^{\uparrow \vec{l}_0})\}$

REPEAT

FORALL $(\vec{l}; v) \in$ *Waiting*

IF $\forall(\vec{l}; v') \in$ *Passed*$.v \not\subseteq v'$ THEN

Passed $:=$ *Passed* $\cup (\vec{l}; v)$

FORALL $(\vec{l}'; v')$ with $\vec{l} \xrightarrow{g,r} \vec{l}'$

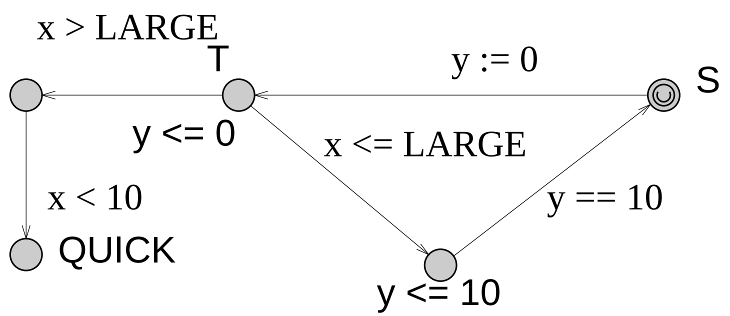
$v' := r(v \cap g)$

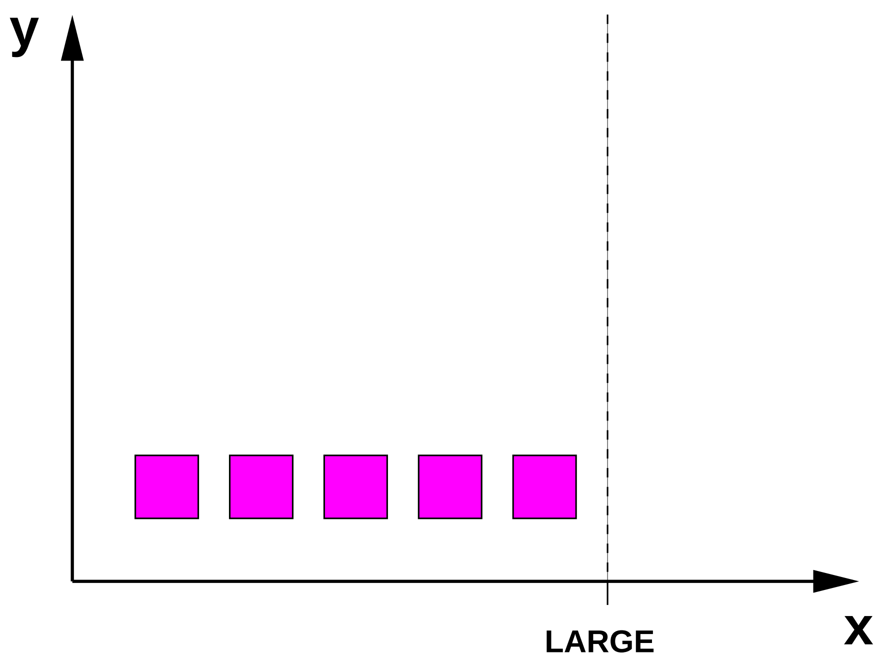
$v' \neq \emptyset$

Waiting $:=$ *Waiting* $\cup \{(\vec{l}'; v'^{\uparrow \vec{l}'})\}$

UNTIL *Waiting* $= \emptyset \vee \exists(\vec{l}, v) \in$ *Passed*$.\vec{l}_g \subseteq \vec{l} \wedge v_g \cap v \neq \emptyset$

Problem: Repetitions in the State-Space





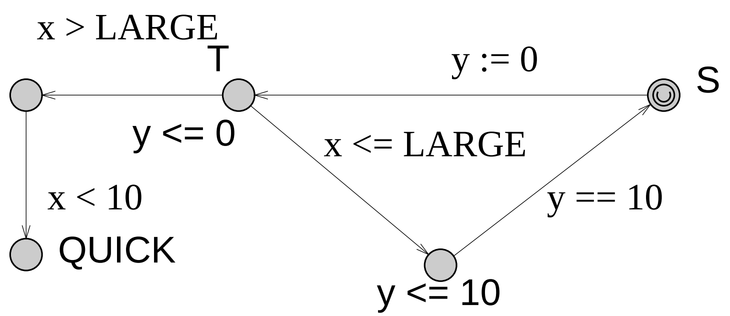
T is visited repeatedly

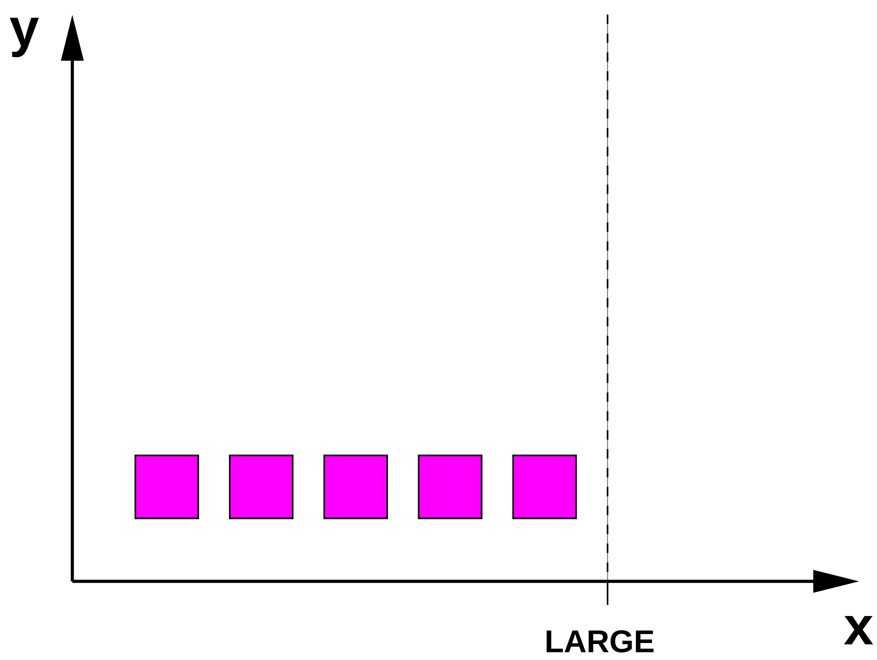
state space at control point **T**

Outline

1. Model Augmentation Technique
2. Application to RCX Bricks Sorter Model
3. Extension to Universal Path Properties

Idea: Subsume Many Small Steps by a Big One





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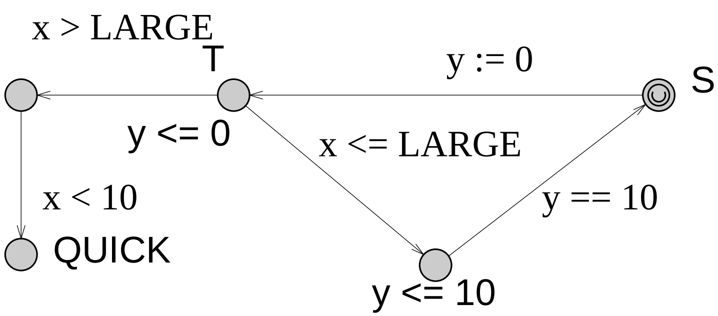

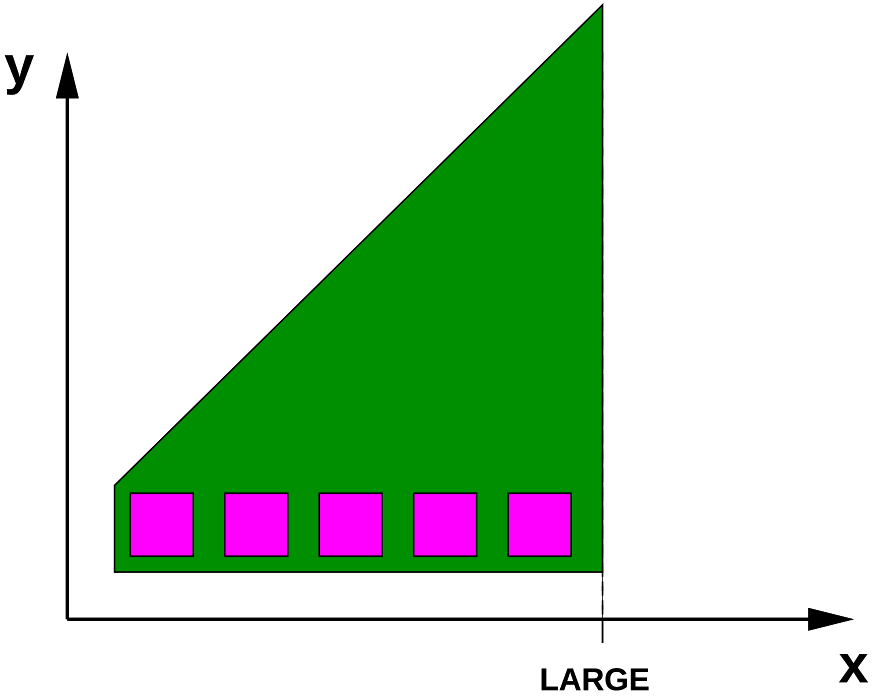

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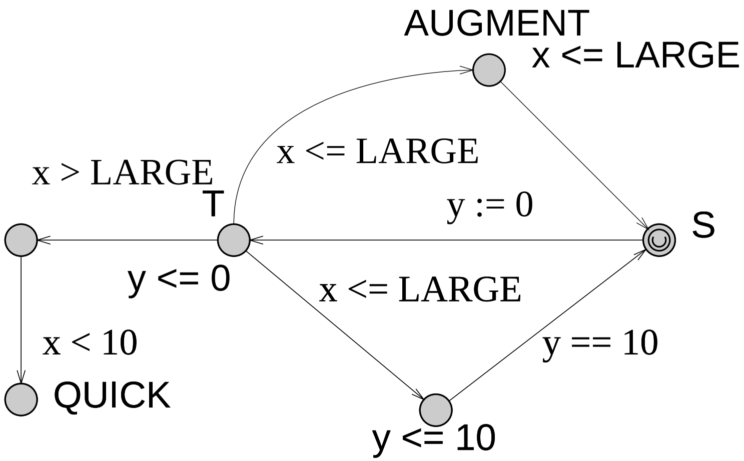
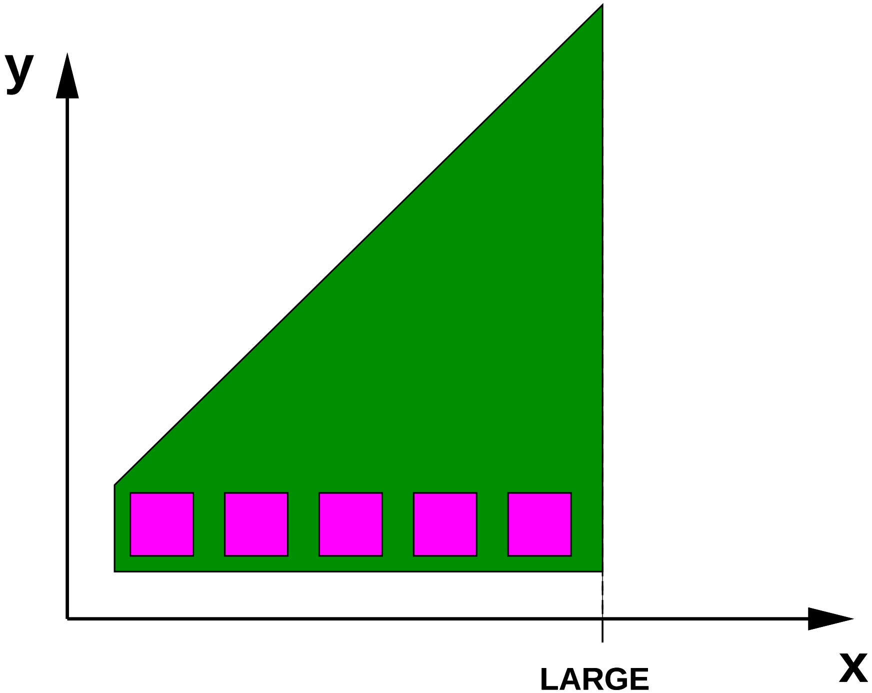
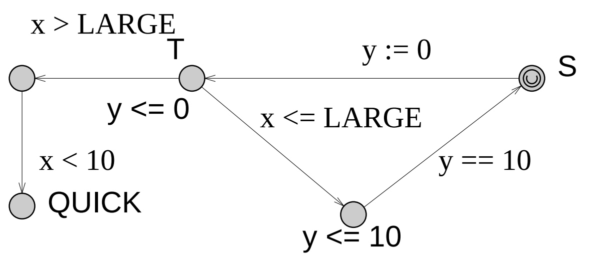


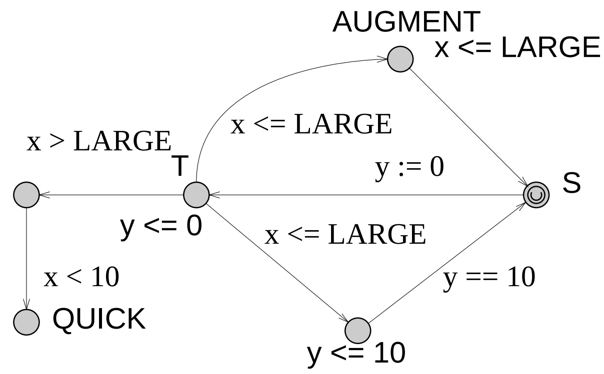
new way to reach **T**



state space at control point **T**

Effect: No Repetitions





LARGE	#states	time[sec]	memory[KB]	#states	time[sec]	memory[KB]
10	8	0.01	376	9	0.01	448
100	35	0.01	440	9	0.01	376
1000	305	0.04	424	9	0.01	440
10˙000	3˙005	1.51	1˙704	9	0.01	440
100˙000	30˙005	175.21	5˙440	9	0.02	416
1˙000˙000	300˙005	22˙449.94	42˙792	9	0.02	400

Model Checking: `QUICK` not reachable

Soundness for Safety

Crucial Observation:

every trace that was originally possible
is also possible after the modification

Therefore:

if a safety property $\texttt{A[]}\varphi$
can be established for the augmented model *Aug*$_{\mathfrak{A}}(M)$,
then it also holds for M.

Challenges for Beneficial Augmentation

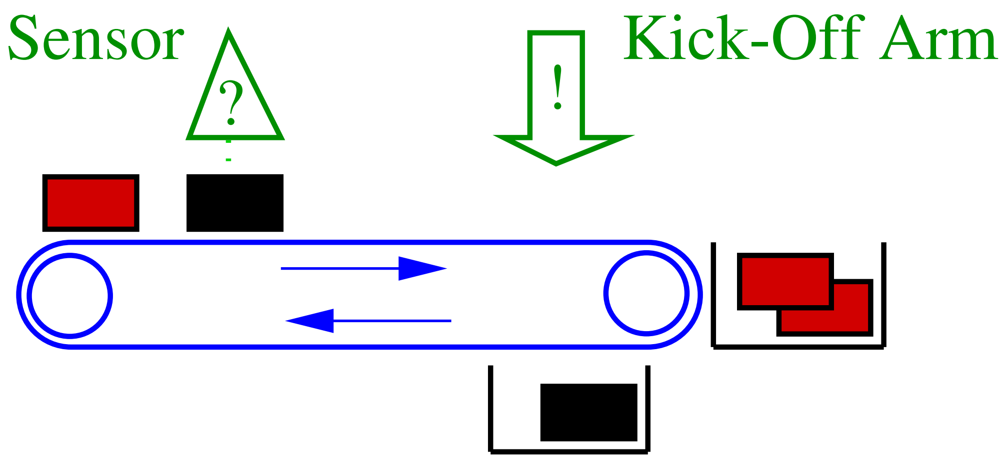
Prerequisites

- repetitions at one control point
- all processes can “park”
- return to the original control structure

What to do?

- find promising augmentation points
- identify suitable delays
- construct return conditions

Bricks Sorter Model



Processes of Sorter:

RCX_model	`Scheduler` `RCX0_main`*task* `RCX0_kick_off` *task*

Environment	`black_brick`
	`black_brick2`
	`kick_off_arm`

	`Hurry_Dummy`

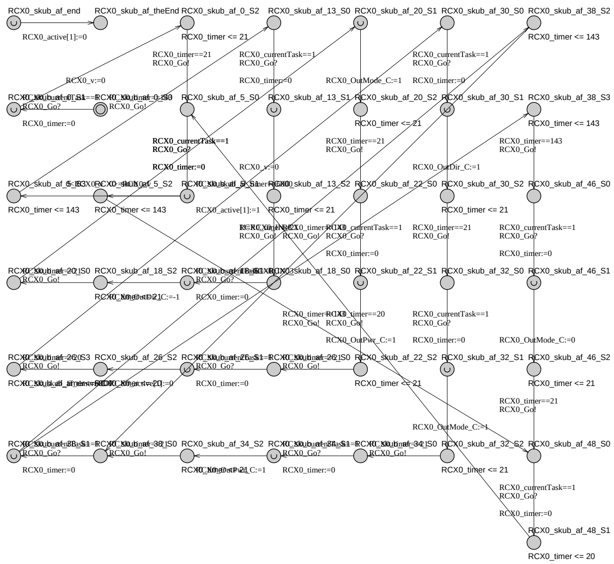
Objective: *Kick off all black bricks, but no red ones*

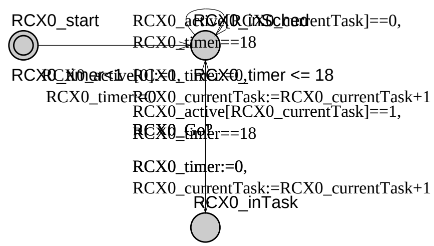
From RCX to UPPAAL

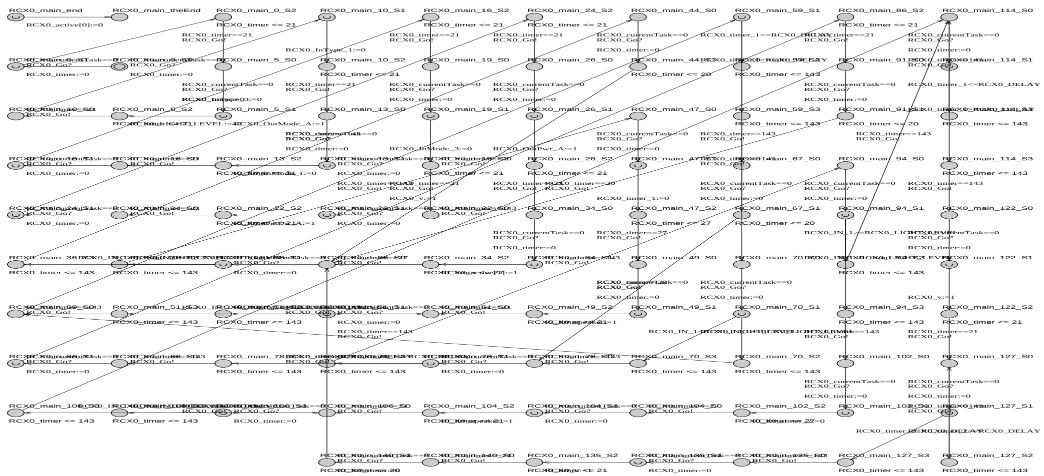
RCX program

```
*** Var 0 = v
*** Var 1 = DELAY
*** Var 2 = LIGHT_LEVEL

*** Task 0 = main
000 Set         var[1], 25             14 01 02 19 00
005 Set         var[2], 42             14 02 02 2a 00
010 InType      0, Light               32 00 03
013 InMode      0, Percent             42 00 80
016 InType      2, Switch              32 02 01
019 InMode      2, Boolean             42 02 20
022 OutDir      A, Fwd                 e1 81
024 OutMode     A, On                  21 81
026 OutPwr      A, 1                   13 01 02 01
030 Display     1                      33 02 01 00
034 StartTask   1                      71 01
036 Test        Input(0) <= var[2], 47 95 09 00 00 00 02 05 00
044 Jump        36                     72 89 00
047 ClearTimer  1                      a1 01
049 PlaySound   1                      51 01
051 Test        Input(0) <= var[2], 51 95 09 00 00 00 02 fa ff
059 Test        Timer(1) <= var[1], 70 95 01 00 01 00 01 05 00
067 Jump        78                     72 0a 00
070 Test        Input(0) >= var[2], 59 95 49 00 00 00 02 ef ff
078 Test        Timer(1) <= var[1], 94 95 01 00 01 00 01 0a 00
086 Set         var[0], 1              14 00 02 01 00
091 Jump        36                     72 b8 00
094 Test        Input(0) >= var[2], 114 95 49 00 00 00 02 0e 00
102 ClearTimer  2                      a1 02
104 PlaySound   1                      51 01
106 Test        Input(0) <= var[2], 106 95 09 00 00 00 02 fa ff
114 Test        Timer(1) <= var[1], 114 95 01 00 01 00 01 fa ff
122 Set         var[0], 1              14 00 02 01 00
127 Test        Timer(2) <= var[1], 127 95 01 00 02 00 01 fa ff
135 Set         var[0], 1              14 00 02 01 00
140 Jump        36                     72 e9 00

*** Task 1 = skub_af
000 Set         var[0], 0              14 00 02 00 00
005 Test        0 >= var[0], 48        95 42 00 00 00 00 25 00
013 Set         var[0], 0              14 00 02 00 00
018 OutDir      C, Rev                 e1 04
020 OutMode     C, On                  21 84
022 OutPwr      C, 1                   13 04 02 01
026 Delay       6                      43 02 06 00
030 OutDir      C, Fwd                 e1 84
032 OutMode     C, On                  21 84
034 OutPwr      C, 1                   13 04 02 01
038 Test        1 != Input(2), 38      95 82 09 01 00 02 fa ff
046 OutMode     C, Off                 21 44
048 Jump        5                      72 ac 00
```

(automatic) translation to UPPAAL

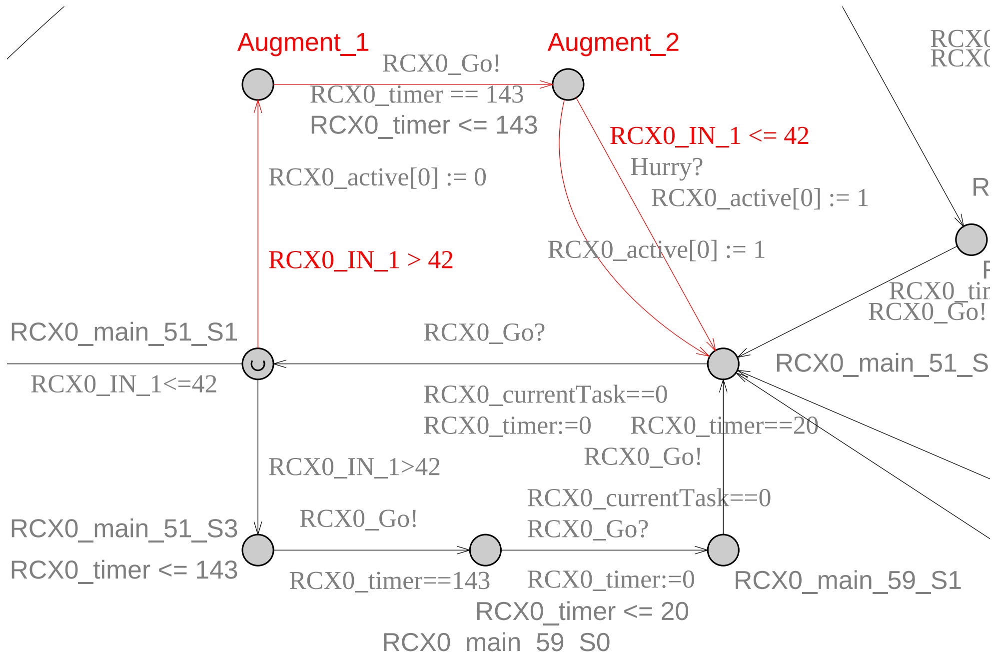






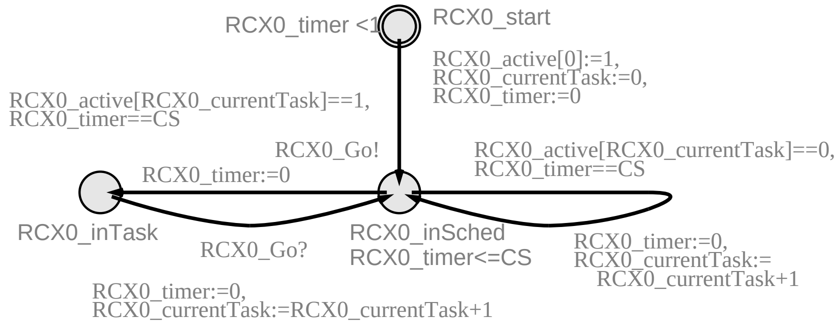
Augmentation of Wait Loops

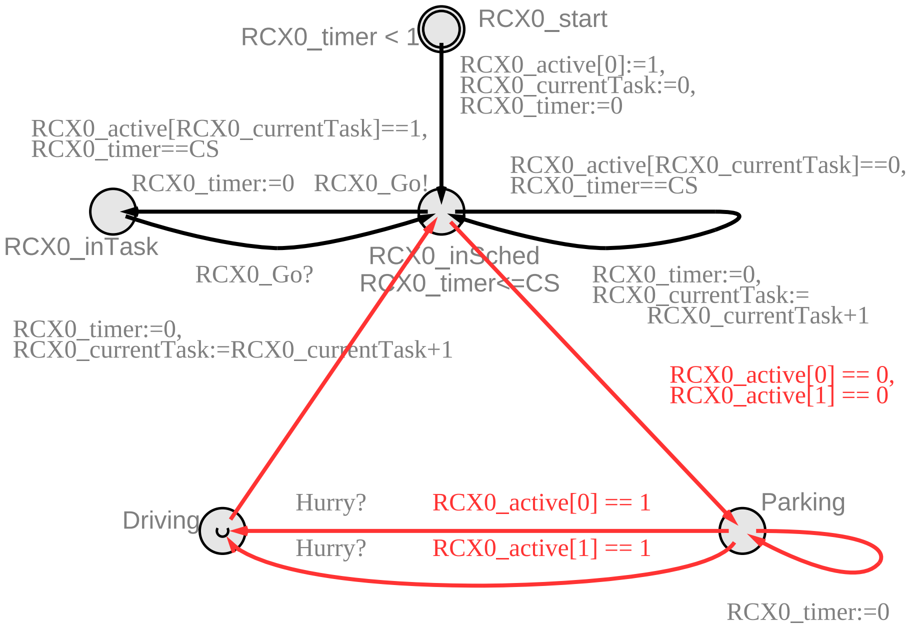
```
*** Task 0 = main
...
031 InType      2, Switch
034 InMode      2, Boolean
037 OutDir      A, Fwd
039 OutMode     A, On
041 OutPwr      A, 1
045 OutDir      B, Fwd
047 OutMode     B, On
049 OutPwr      B, 6
053 Display     1
057 StartTask   1
059 Test        Input(0) <= var[4], 70
067 Jump        59
070 ...
```



waiting for an input **’jumping’ to this input**

Augmenting the Scheduler





Original Scheduler Process

Augmented Scheduler Process

Augmentations in Total

- **9** model augmentations: 6 input / 3 time condition
- **16** new locations
- **34** new transitions

- **NO** locations/transitions removed
- **NO** new variables or clocks

Model Checking a (True) Safety Property

	#explored states	successors (average)	#deadlocks	time [sec]	memory [KB]
Sorter	151˙103	1.28	0	86.84	1˙840
$Aug^{*}_{\mathfrak{A}}(Sorter)$	22˙966	2.09	20	21.15	2˙512

- both runs used *convex hull* over-approximation
- number of symbolic states changes significantly
- higher non-determinism
- deadlocks necessarily spurious

Universal Path Properties

$$\zeta ::= \texttt{A[]}\zeta \;\mid\; \texttt{A<>}\zeta \;\mid\; \zeta \vee \zeta \;\mid\; \zeta \wedge \zeta \;\mid\; \varphi$$

φ is a *local property*, i.e., depends only on the current con£guration.

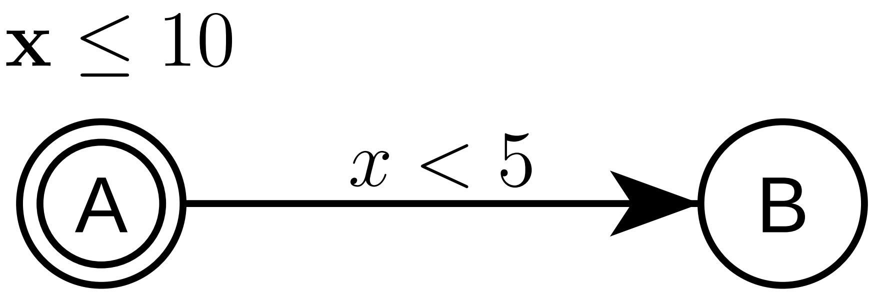
A trace $\sigma = (\mathbf{s}_0, \mathbf{s}_1, \ldots)$ satisfies ζ at position i iff:

$$\begin{array}{lcllcl}
(\sigma, i) & \models & \texttt{A[]}\zeta & \Longleftrightarrow & \forall j \geq i.(\sigma, j) \models \zeta \\
(\sigma, i) & \models & \texttt{A<>}\zeta & \Longleftrightarrow & \exists j \geq i.(\sigma, j) \models \zeta \\
(\sigma, i) & \models & \zeta_1 \vee \zeta_2 & \Longleftrightarrow & (\sigma, i) \models \zeta_1 \text{ or } (\sigma, i) \models \zeta_2 \\
(\sigma, i) & \models & \zeta_1 \wedge \zeta_2 & \Longleftrightarrow & (\sigma, i) \models \zeta_1 \text{ and } (\sigma, i) \models \zeta_2 \\
(\sigma, i) & \models & \varphi & \Longleftrightarrow & \mathbf{s}_i \models \varphi
\end{array}$$

A timed automata model satisfies ζ, if all traces satisfy ζ at position 0.

Problem: Augmentation Can Remove Deadlocks

Process P**:**



Formula: `A<>` $P.B$ (inevitably **B**)

not true: could get stuck at **A**

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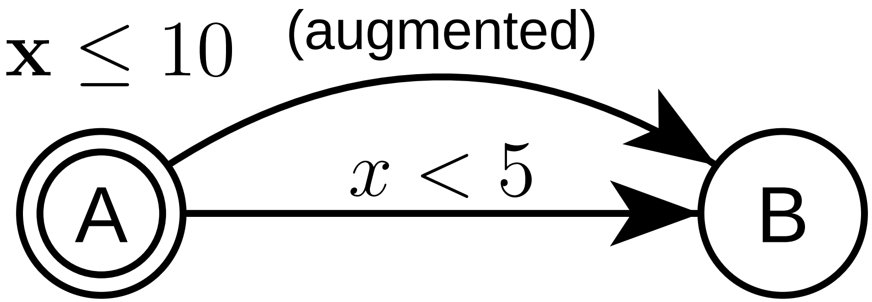

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SUDDENLY HOLDS IN AUGMENTED MODEL

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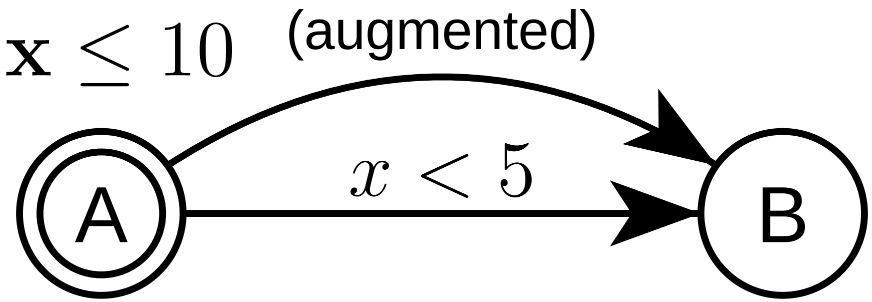

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SUDDENLY HOLDS IN AUGMENTED MODEL

Solution: *change step semantics*

Allow augmented transitions *only* if another (non-augmented) transition is enabled

Modified Step Semantics

M: UPPAAL timed automata model

$\mathfrak{A}$: $\langle l_i \xrightarrow{g,\vec{a}} l', L_{\mathfrak{A}}, T_{\mathfrak{A}}, \mathit{Type}_{\mathfrak{A}} \rangle$ a model augmentation of M

- define the *weak traces* of $\mathit{Aug}_{\mathfrak{A}}(M)$ as the those where

> in a $(\vec{l}, e, \nu)$ with $l_i \in \vec{l}$,
> the action transition $l_i \xrightarrow{g,\vec{a}} l'$ is only taken,
> if another action transition is enabled

- this yields $\mathcal{T}^{\mathfrak{A}}(\mathit{Aug}_{\mathfrak{A}}(M)) \subseteq \mathcal{T}(\mathit{Aug}_{\mathfrak{A}}(M))$
- $\mathit{Aug}_{\mathfrak{A}}(M) \models^{\mathfrak{A}} \zeta$ if and only if
  $\forall$ traces $\sigma = (\mathbf{s}_0, \mathbf{s}_1, \ldots) \in \mathcal{T}^{\mathfrak{A}}(\mathit{Aug}_{\mathfrak{A}}(M)).\quad (\sigma, 0) \models \zeta$

Theorem:

$$\mathit{Aug}_{\mathfrak{A}}(M) \models^{\mathfrak{A}} \zeta \quad \Rightarrow \quad M \models \zeta$$

Conclusions

- over-approximation
  → *sound* but inherently *not complete*
- shifted-clock repetition seems to be specific to *real-time*
- technique has potential in special scenarios
- automation highly desirable
  (and possible, but not done)