Optimal & Real Time Scheduling

using

Model Checking Technology

- **Academic partners:**
  - Nijmegen
  - Aalborg
  - Dortmund
  - Grenoble
  - Marseille
  - Twente
  - Weizmann

- **Industrial Partners**
  - Axxom
  - Bosch
  - Cybernetix
  - Terma

AMETIST

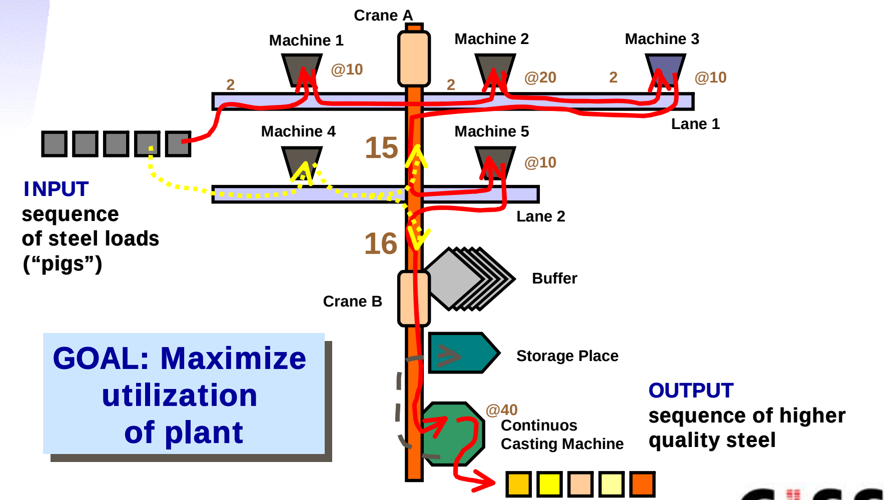
advanced methods for timed systems

OBJECTIVES

- powerful, unifying mathematical modelling
- efficient computerized problem-solving tools
- distributed real-time systems
- time-dependent behaviour and dynamic resource allocation
- **TIMED AUTOMATA**

BRICS
Basic Research
in Computer Science

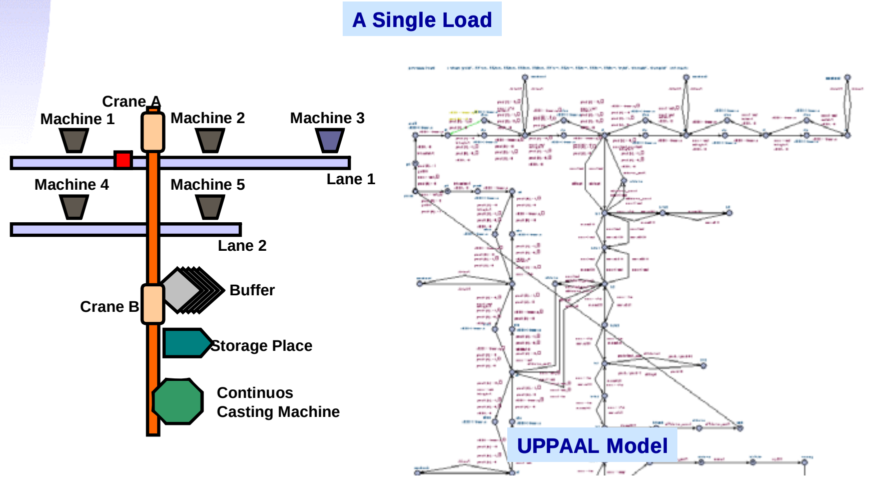
SIDMAR Overview



CISS

LTR Project VHS (Verification of Hybrid systems)

SIDMAR Modelling



CISS

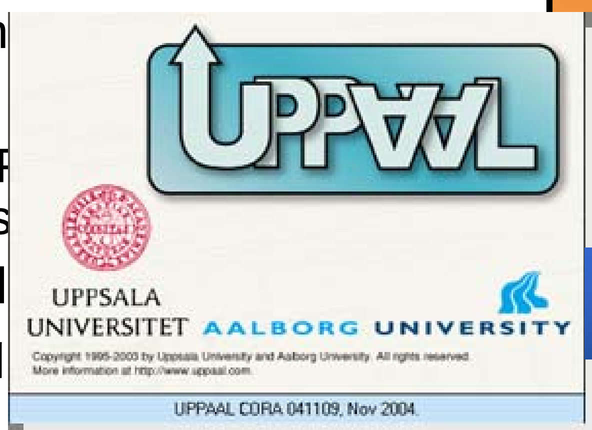
AMETIST

advanced methods f

Case S

- Cybern
  - Sma
    Pers
- Terma:
  - Mem
- Bosch:
  - Car P
    Sens
- AXXOM
  - Lacq
- Benchmarks

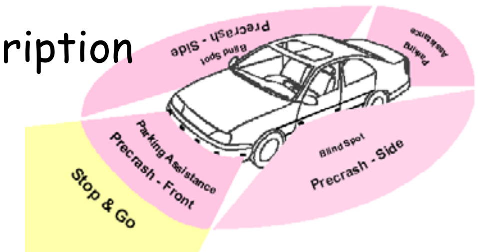
CLASSIC



CORA

BRICS
Basic Research
in Computer Science

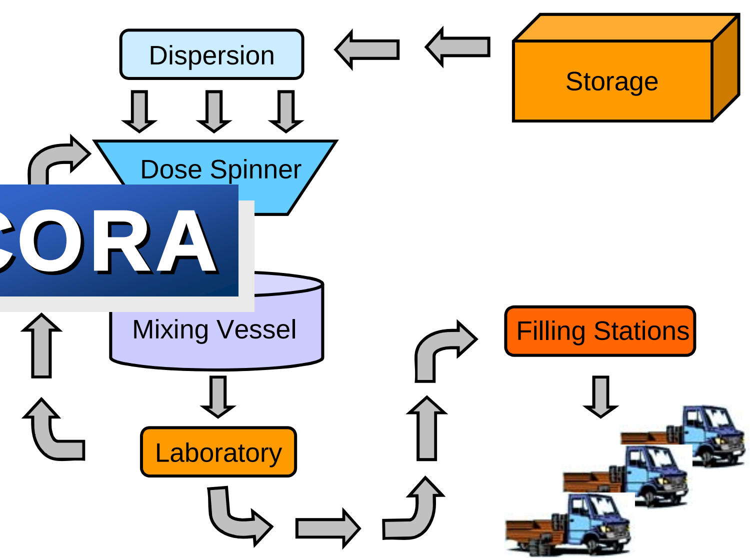
CPS: Informal description

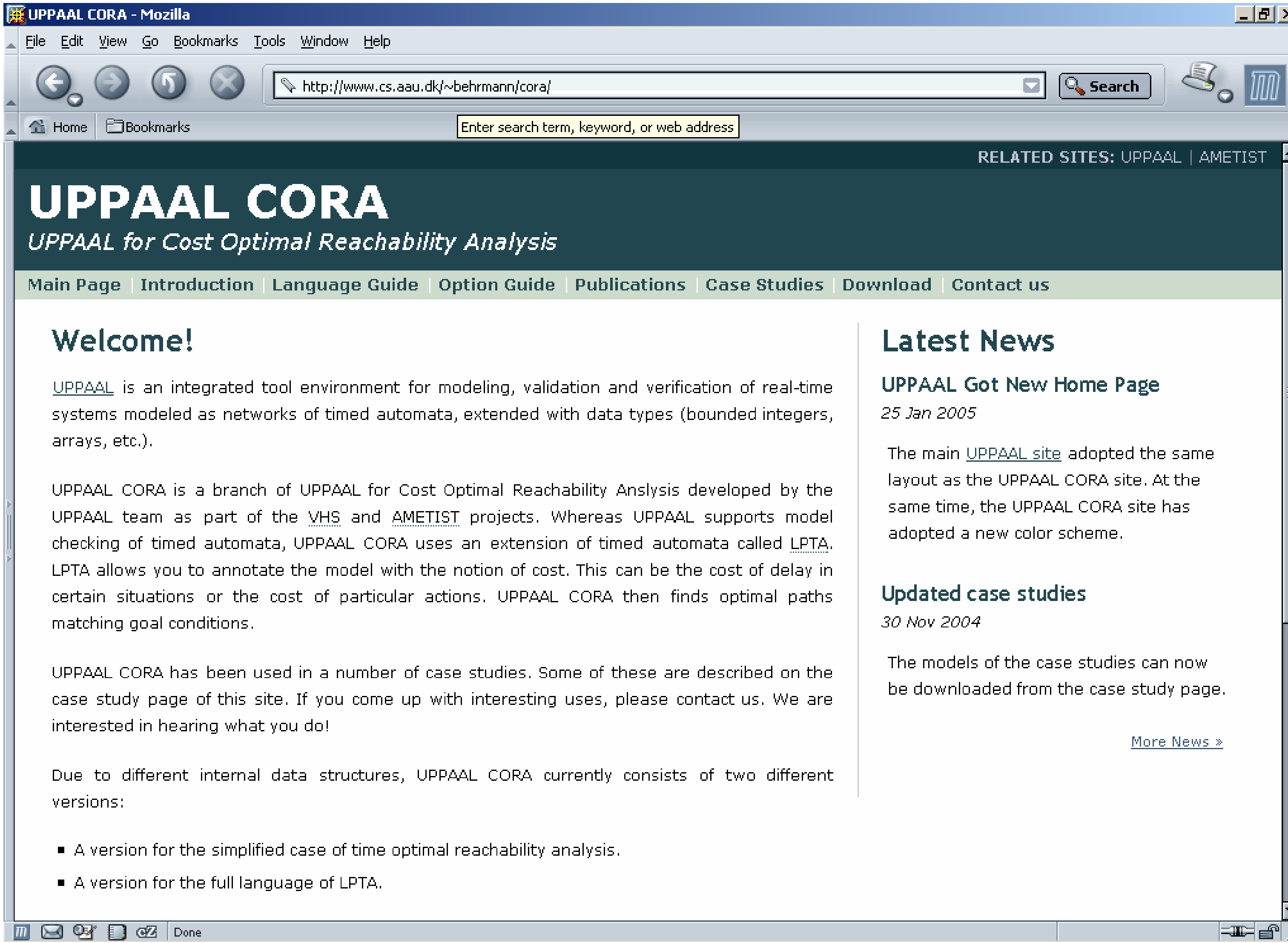


- CPS obtains and makes available for other systems information about environment of a car. This information may be used for:
  - Parking assistance
  - Pre-crash detection
  - Blind spot supervision
  - Lane change assistance
  - Stop & go
  - Etc
- The CPS considered in this case study
  - One sensor group only (currently 2 sensors)
  - Only the front sensors and corresponding controllers
  - Application: pre-crash detection, parking assistance, stop & go

Product flow of a Product

axxom





UPPAAL CORA - Mozilla

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http://www.cs.aau.dk/~behrmann/cora/

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Home Bookmarks Enter search term, keyword, or web address

RELATED SITES: UPPAAL | AMETIST

UPPAAL CORA

UPPAAL for Cost Optimal Reachability Analysis

Main Page | Introduction | Language Guide | Option Guide | Publications | Case Studies | Download | Contact us

Welcome!

UPPAAL is an integrated tool environment for modeling, validation and verification of real-time systems modeled as networks of timed automata, extended with data types (bounded integers, arrays, etc.).

UPPAAL CORA is a branch of UPPAAL for Cost Optimal Reachability Anslysis developed by the UPPAAL team as part of the VHS and AMETIST projects. Whereas UPPAAL supports model checking of timed automata, UPPAAL CORA uses an extension of timed automata called LPTA. LPTA allows you to annotate the model with the notion of cost. This can be the cost of delay in certain situations or the cost of particular actions. UPPAAL CORA then finds optimal paths matching goal conditions.

UPPAAL CORA has been used in a number of case studies. Some of these are described on the case study page of this site. If you come up with interesting uses, please contact us. We are interested in hearing what you do!

Due to different internal data structures, UPPAAL CORA currently consists of two different versions:

- A version for the simplified case of time optimal reachability analysis.
- A version for the full language of LPTA.

Latest News

UPPAAL Got New Home Page

25 Jan 2005

The main UPPAAL site adopted the same layout as the UPPAAL CORA site. At the same time, the UPPAAL CORA site has adopted a new color scheme.

Updated case studies

30 Nov 2004

The models of the case studies can now be downloaded from the case study page.

More News »

Done

CISS
CENTER FOR INDLEJREDE SOFTWARE SYSTEMER

Overview

- Timed Automata & Scheduling
- Priced Timed Automata and Optimal Scheduling
- Optimal Infinite Scheduling
-
- Scheduling and Off-Line Test Generation

> Optimal Scheduling Using Priced Timed Automata.
> G. Behrmann, K. G. Larsen, J. I. Rasmussen,
> ACM SIGMETRICS Performance Evaluation Review

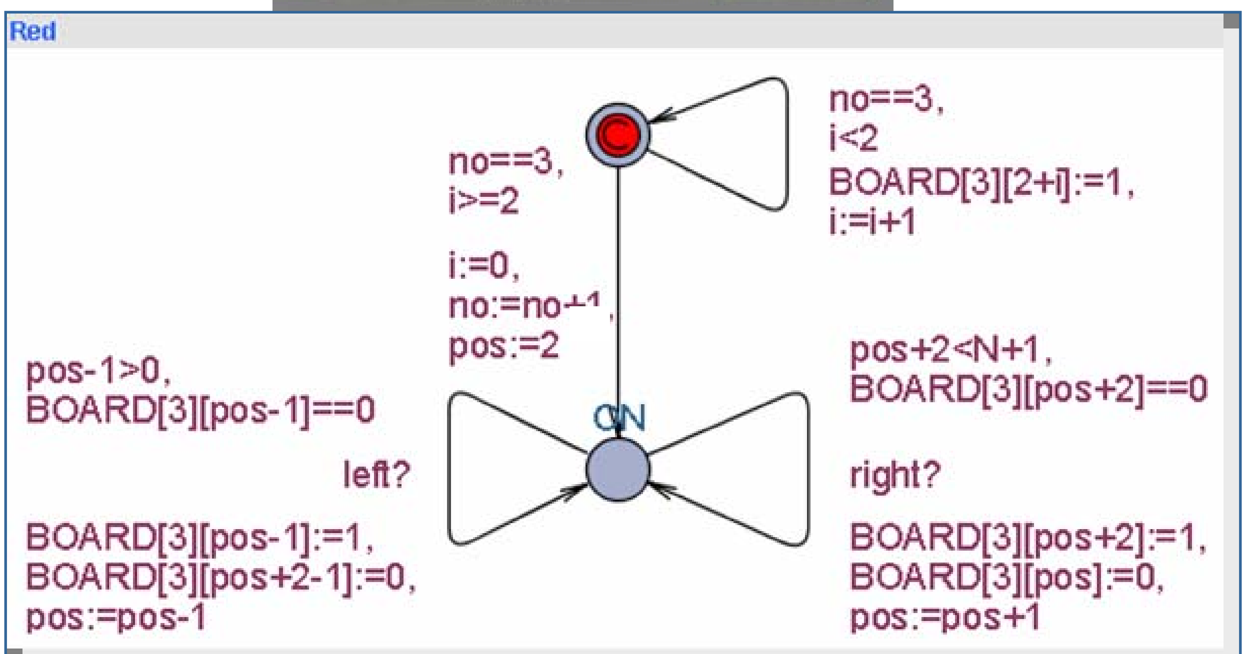
BRICS
Basic Research
in Computer Science

Rush Hour

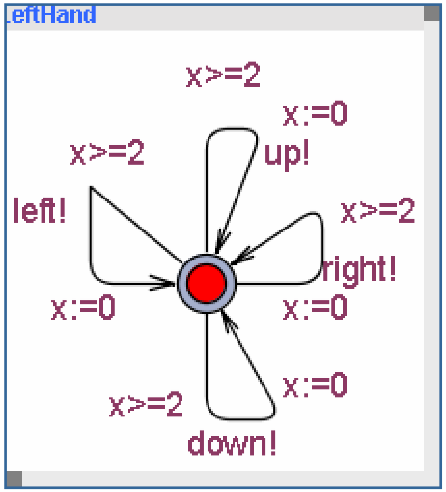
OBJECTIVE:
Get your CAR out

Rush Hour

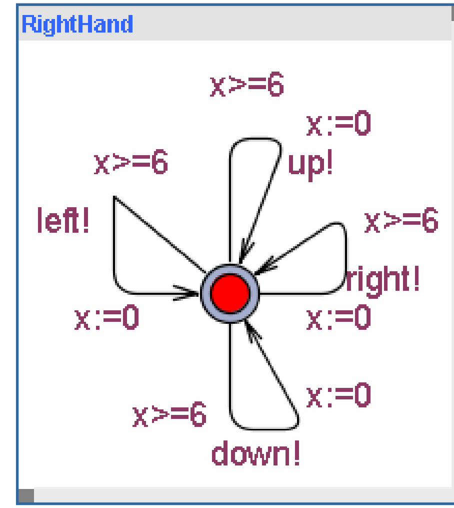

RUSH HOUR
BINARY ARTS

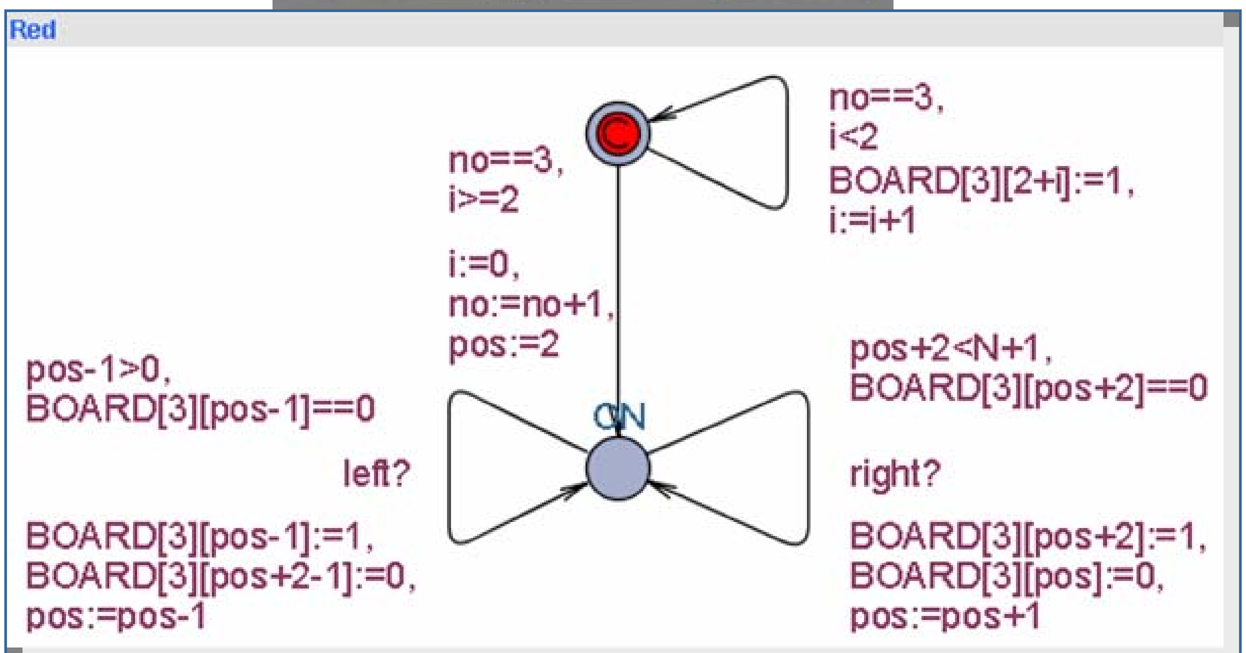

Red
no==3,
i<2
BOARD[3][2+i]:=1,
i:=i+1
no==3,
i>=2
i:=0,
no:=no+1,
pos:=2
ON
pos-1>0,
BOARD[3][pos-1]==0
left?
BOARD[3][pos-1]:=1,
BOARD[3][pos+2-1]:=0,
pos:=pos-1
pos+2<N+1,
BOARD[3][pos+2]==0
right?
BOARD[3][pos+2]:=1,
BOARD[3][pos]:=0,
pos:=pos+1

Rush Hour


LeftHand
x>=2
x:=0
up!
x>=2
left!
x>=2
right!
x:=0
x:=0
x:=0
x>=2
down!


RUSH HOUR

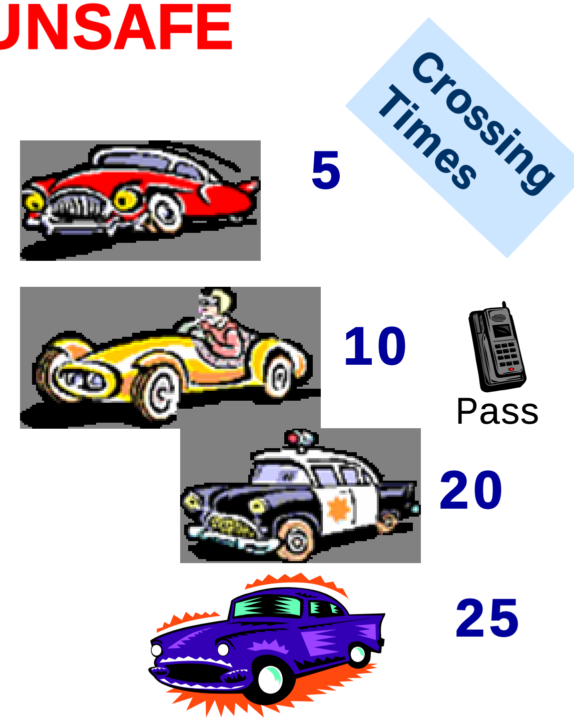

RightHand
x>=6
x:=0
up!
x>=6
left!
x>=6
right!
x:=0
x:=0
x:=0
x>=6
down!

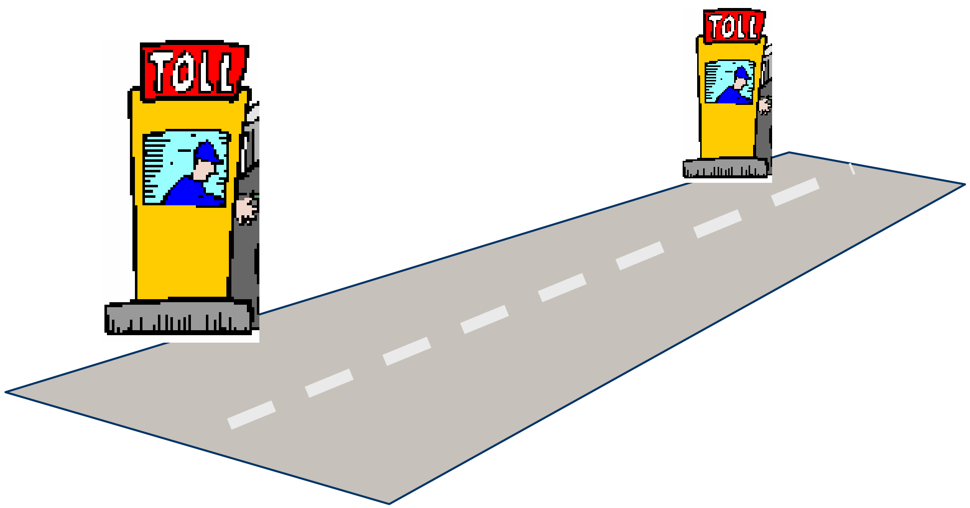

Red
no==3,
i>=2
no==3,
i<2
BOARD[3][2+i]:=1,
i:=i+1
i:=0,
no:=no+1,
pos:=2
pos-1>0,
BOARD[3][pos-1]==0
left?
BOARD[3][pos-1]:=1,
BOARD[3][pos+2-1]:=0,
pos:=pos-1
ON
pos+2<N+1,
BOARD[3][pos+2]==0
right?
BOARD[3][pos+2]:=1,
BOARD[3][pos]:=0,
pos:=pos+1

Real Time Scheduling

- Only 1 “Pass”
- Cheat is possible
  (drive close to car with “Pass”)

UNSAFE





SAFE

CAN THEY MAKE IT TO SAFE WITHIN 70 MINUTES ???

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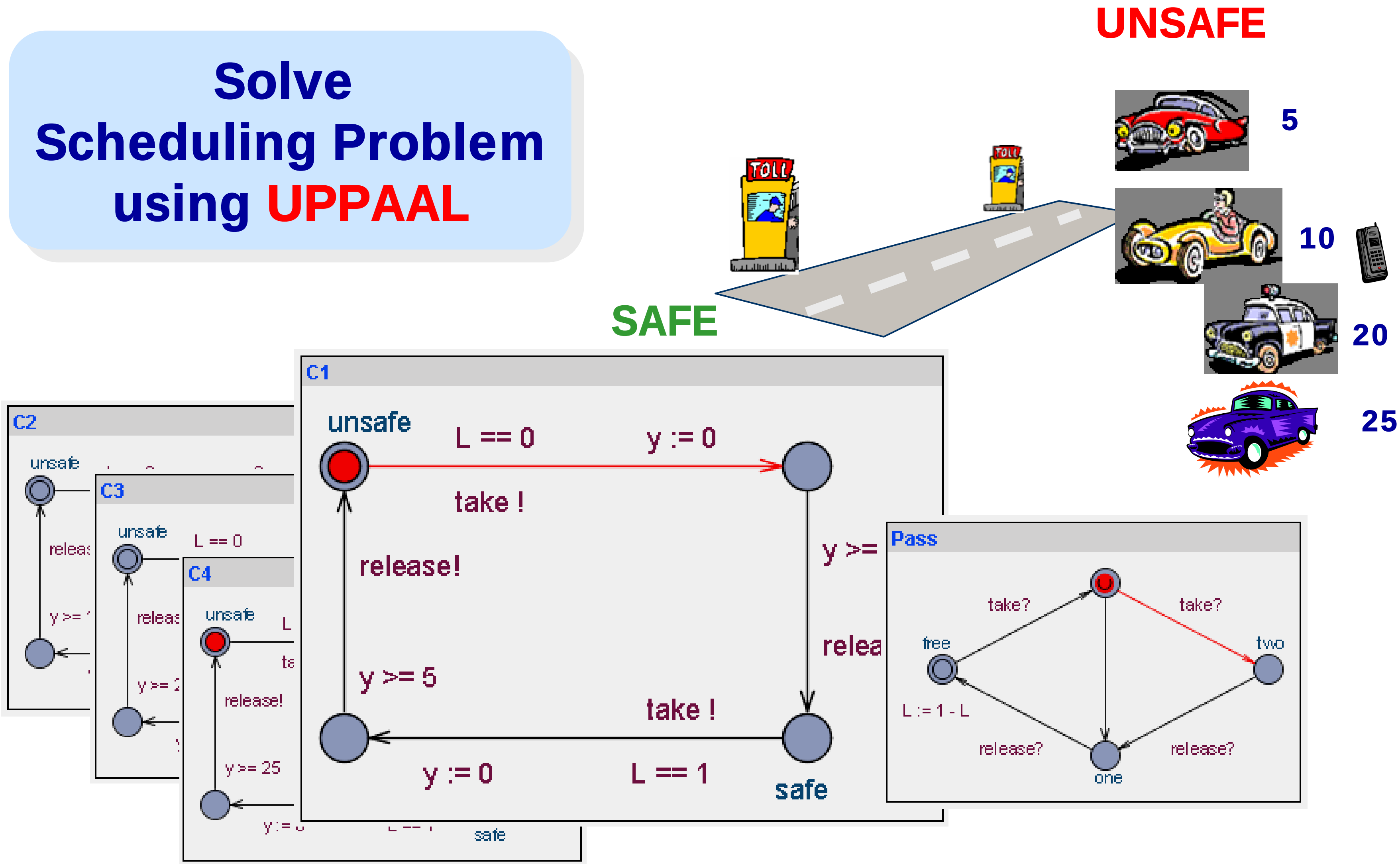
Real Time Scheduling

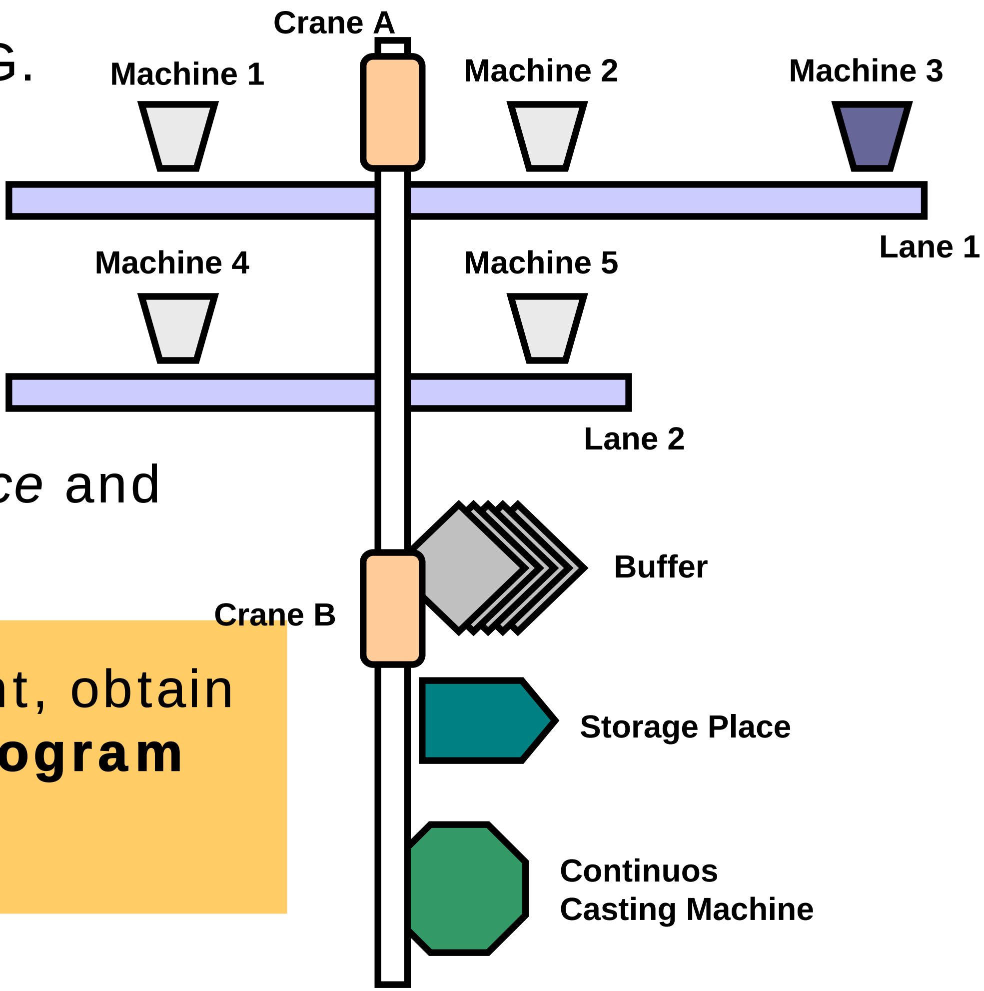
Solve Scheduling Problem using UPPAAL



BRICS
Basic Research
in Computer Science

Steel Production Plant

- A. Fehnker, T. Hune, K. G. Larsen, P. Pettersson
- Case study of Esprit-LTR project 26270 VHS
- Physical plant of SIDMAR located in Gent, Belgium.
- Part between *blast furnace* and *hot rolling mill*.



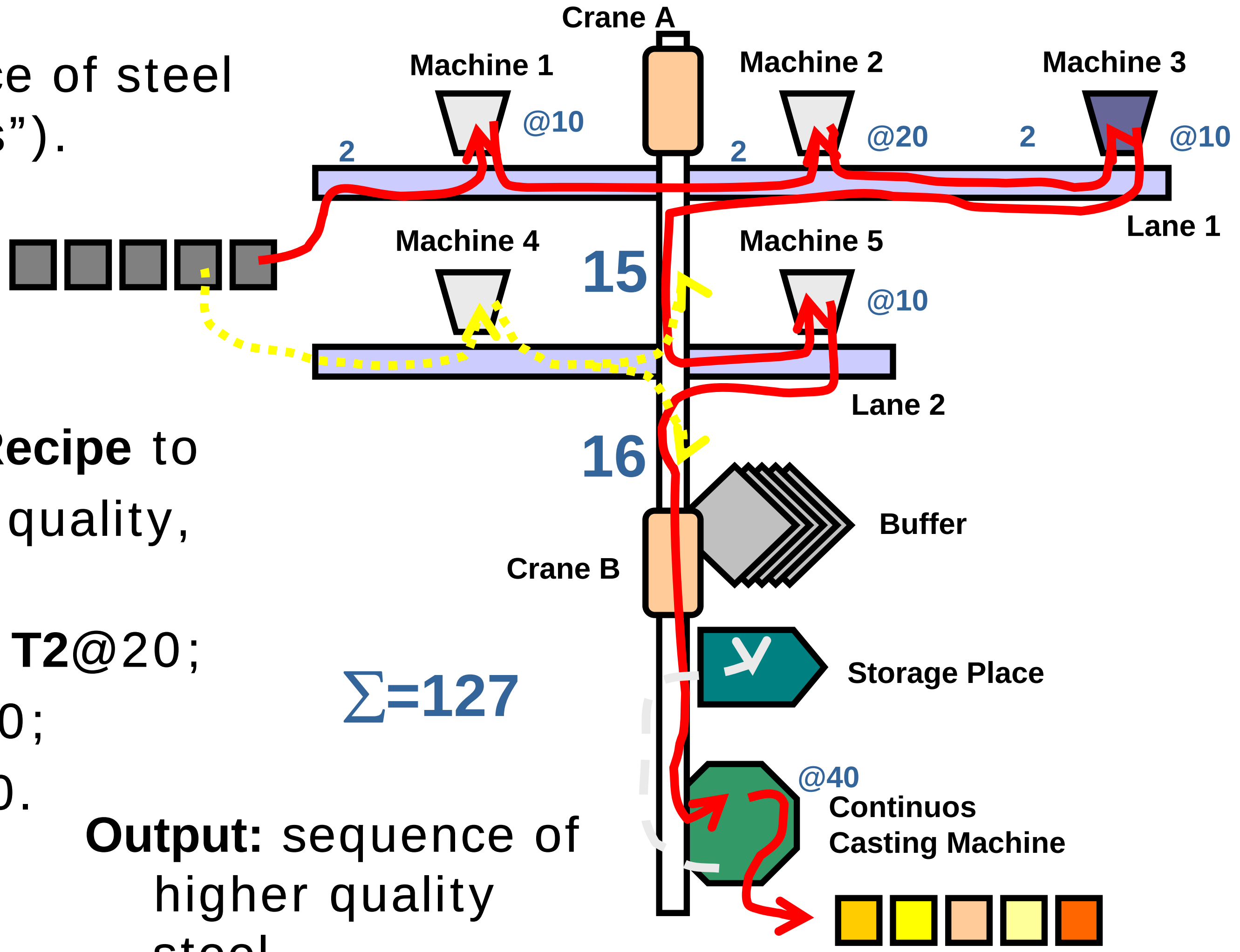
Objective: model the plant, obtain **schedule** and control **program** for plant.

Steel Production Plant

Input: sequence of steel loads ("pigs").

Load follows **Recipe** to obtain certain quality, e.g:

start; **T1**@10; **T2**@20; **T3**@10; **T2**@10; end within 120.



Output: sequence of higher quality steel.

CISS
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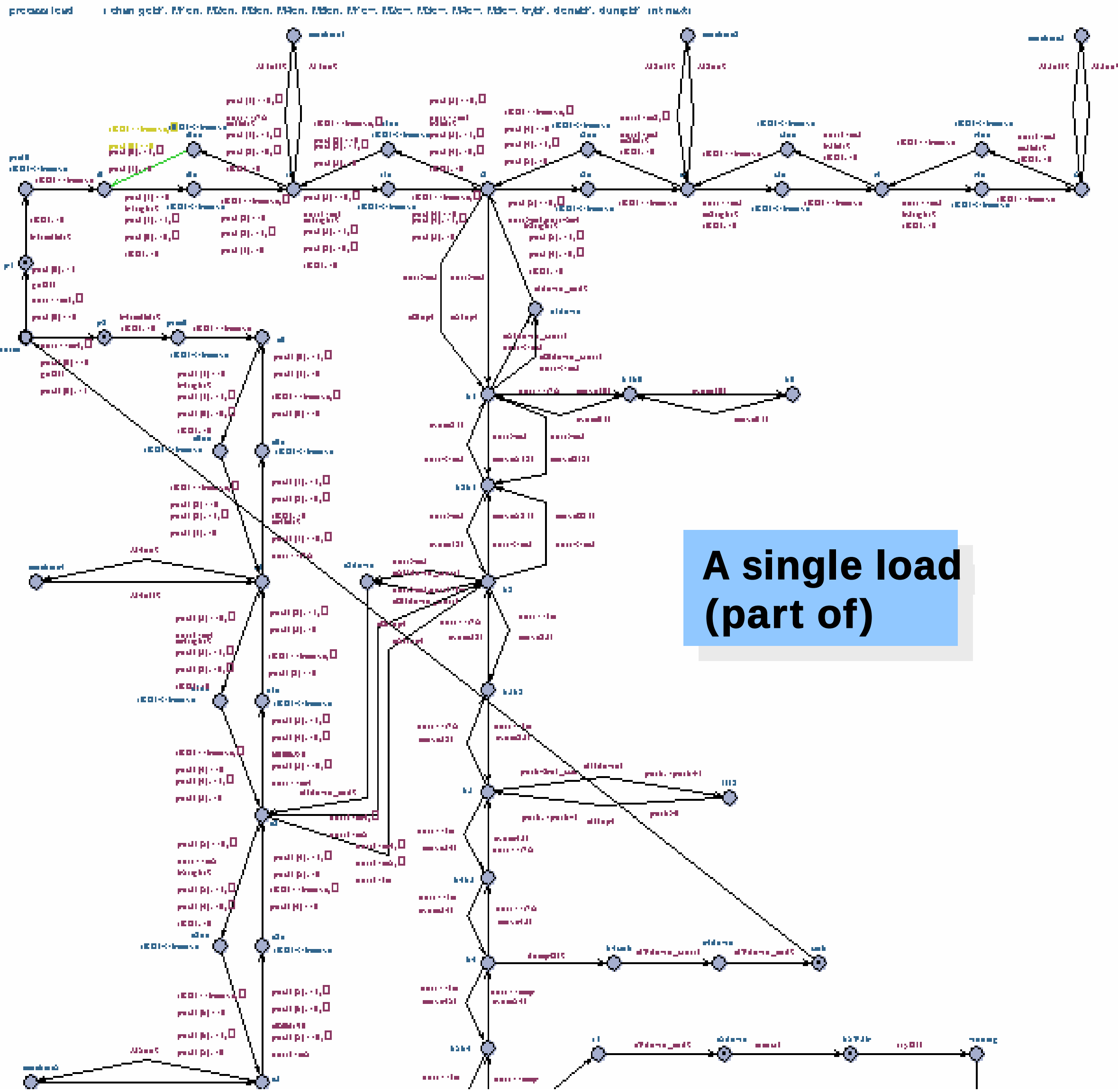
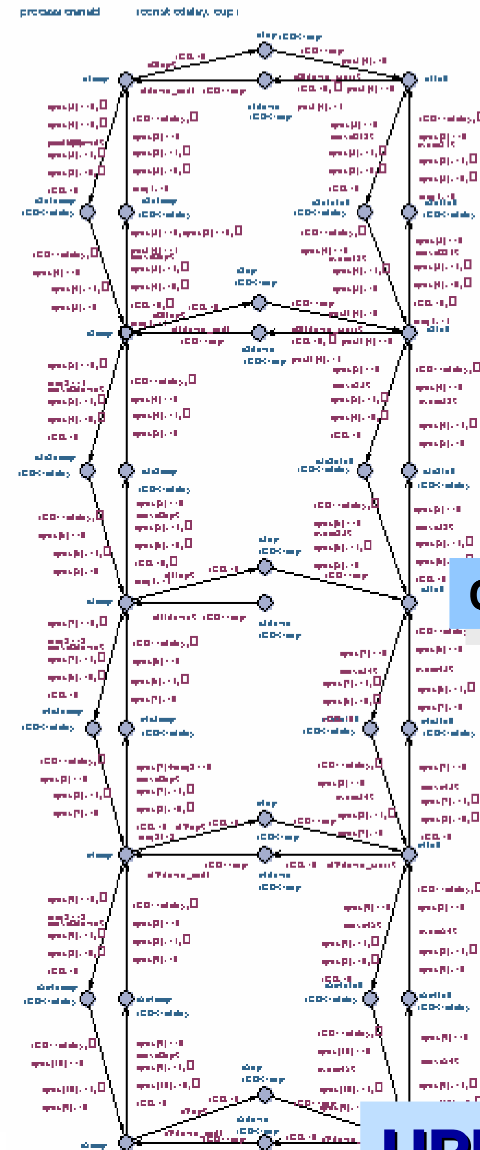


A single load (part of)



Crane B

UPPAAL

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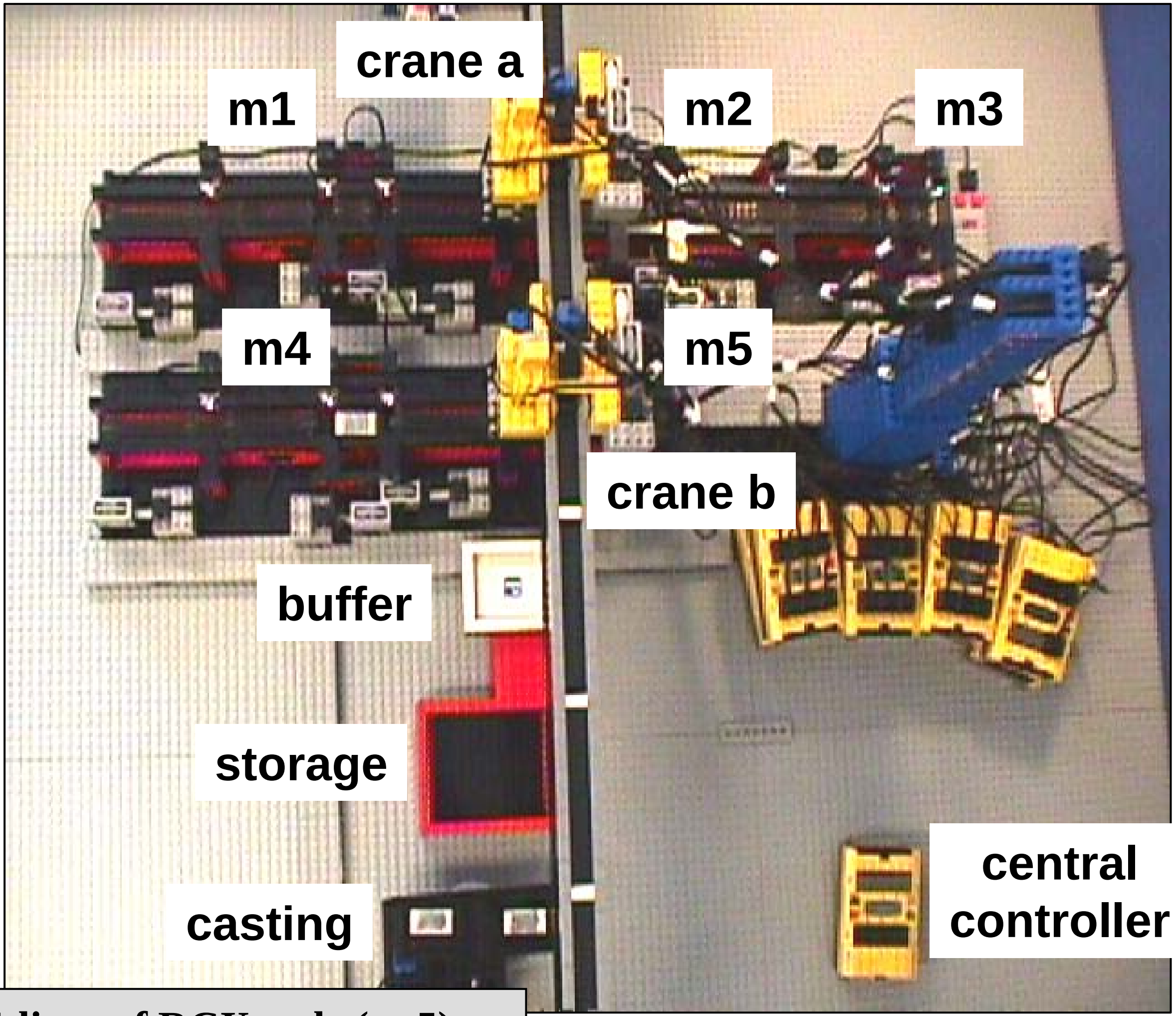
Basic Research
in Computer Science

Controller Synthesis for LEGO Model

- LEGO RCX Mindstorms.
- Local controllers with control programs.
- IR protocol for remote invocation of programs.
- Central controller.

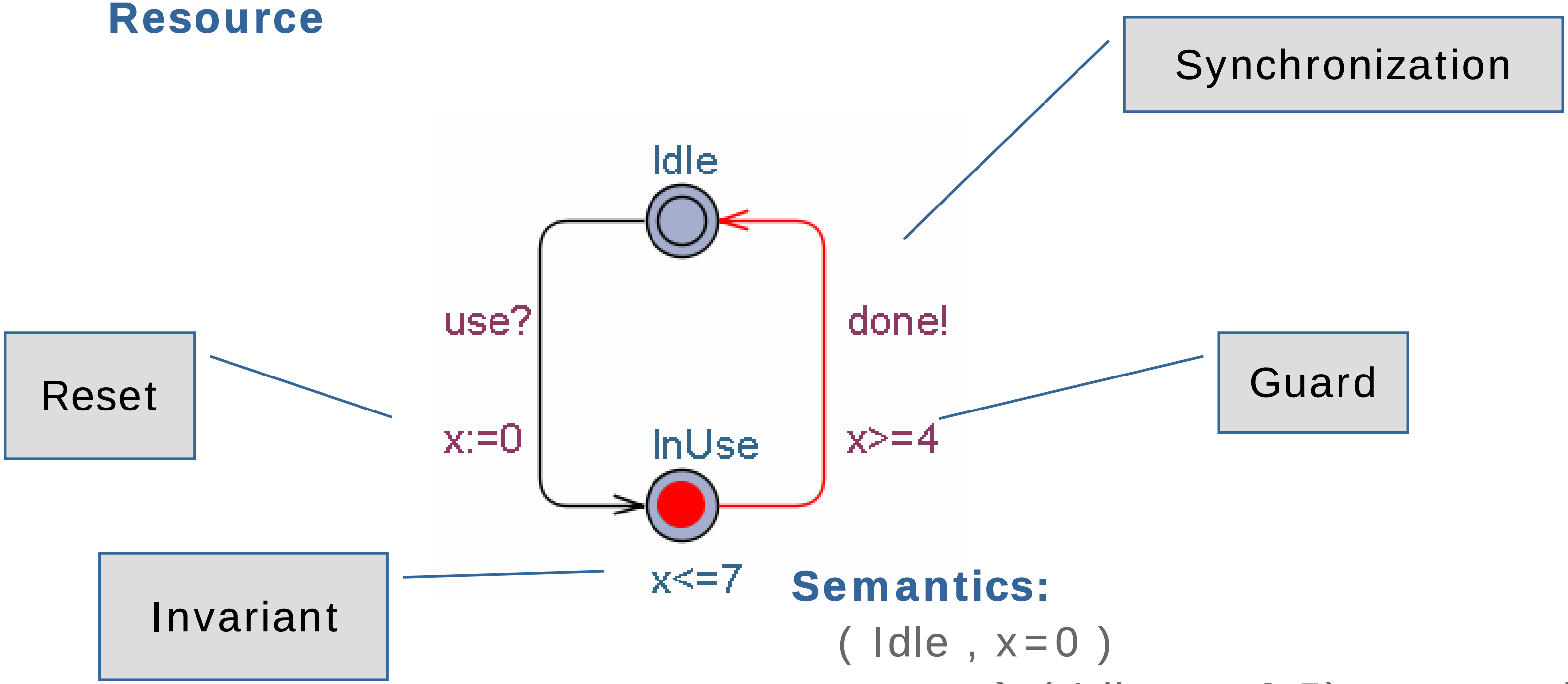


1971 lines of RCX code (n=5),
24860 - “ - (n=60).

Synthesis

Timed Automata [Alur & Dill'89]

Resource

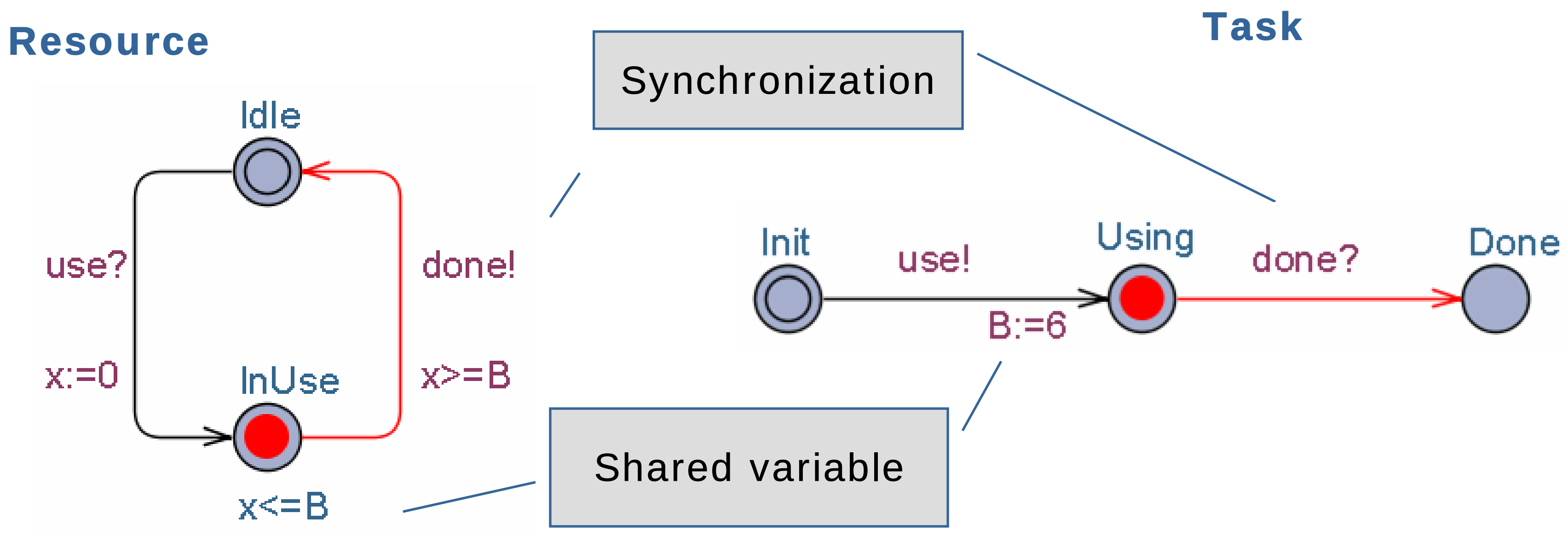


Semantics:

(Idle , x=0)

→ (Idle , x=2.5)	d(2.5)
→ (InUse , x=0)	use?
→ (InUse , x=5)	d(5)
→ (Idle , x=5)	done!
→ (Idle , x=8)	d(3)
→ (InUse , x=0)	use?

Composition



Semantics:

(Idle , Init , B=0, x=0)

→ (Idle , Init , B=0 , x=3.1415)   d(3)

→ (InUse , Using , B=6, x=0)   use

→ (InUse , Using , B=6, x=6)   d(6)

→ (Idle , Done , B=6 , x=6)   done

Jobshop Scheduling

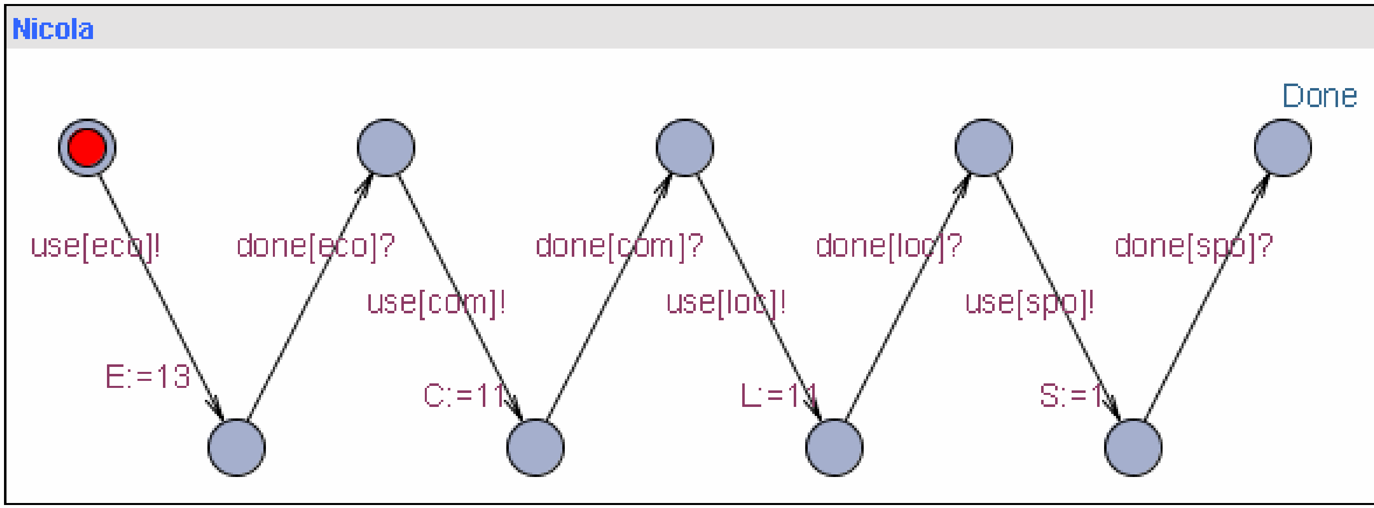
RE SOURCES

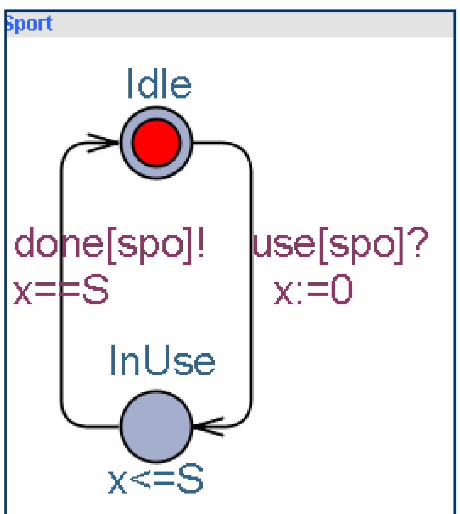
JOBS

	Sport	Economy	Local News	Comic Stip
Kim	2. 5 min	4. 1 min	3. 3 min	1. 10 min
Maria	1. 10 min	2. 20 min	3. 1 min	4. 1 min
Nicola	4. 1 min	1. 13 min	3. 11 min	2. 11 min

Problem: compute the minimal **MAKESPAN**

Jobshop Scheduling in UPPAAL





	Sport	Economy	Local News	Comic Stip
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Maria	1. 10 min	2. 20 min	3. 1 min	4. 1 min
Nicola	4. 1 min	1. 13 min	3. 11 min	2. 11 min

Experiments

[TACAS'2001]

B-&-B algorithm running for 60 sec.

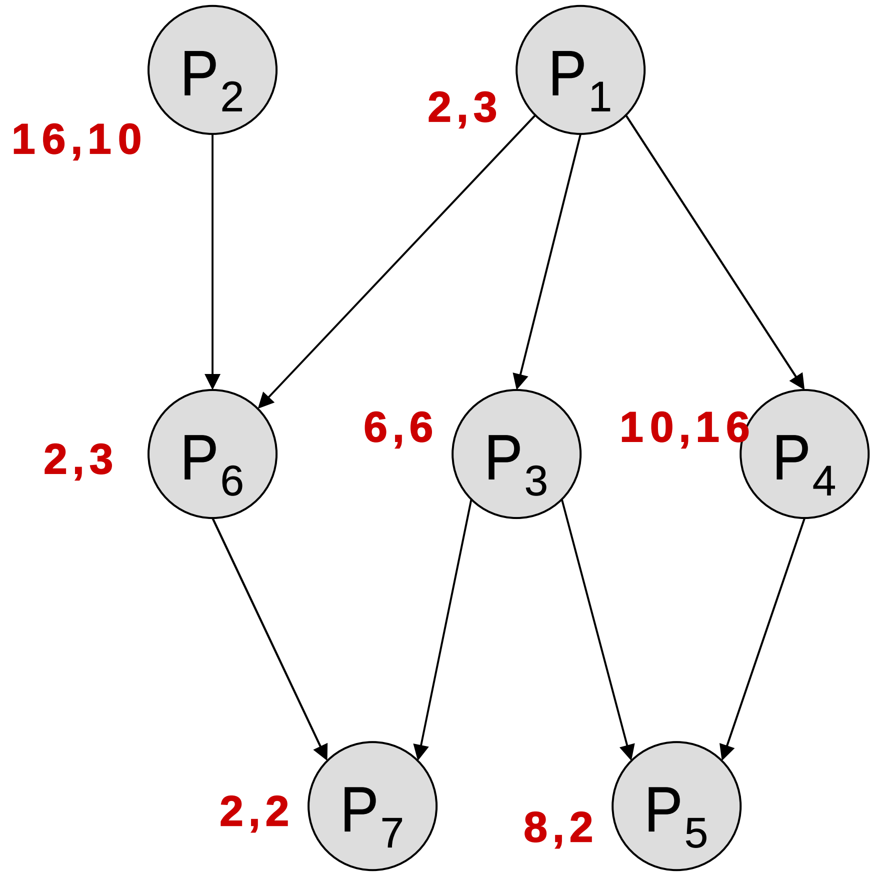
		problem instance	BF cost	BF states	MC cost	MC states	MC+ cost	MC+ states	DF cost	DF states	RDF cost	RDF states	comb. heur. cost	comb. heur. states	minimal makespan
m=5	j=10	la01	-	-	-	-	-	-	2466	-	842	-	666	292	666
		la02	-	-	-	-	-	-	2360	-	806	-	672	-	655
		la03	-	-	-	-	-	-	2094	-	769	-	626	-	597
		la04	-	-	-	-	-	-	2212	-	783	-	639	-	590
		la05	-	-	-	-	593	9791	1955	-	696	-	593	284	593
	j=15	la06	-	-	-	-	-	-	3656	-	1076	-	926	480	926
		la07	-	-	-	-	-	-	3410	-	1113	-	890	-	890
		la08	-	-	-	-	-	-	3520	-	1009	-	863	400	863
		la09	-	-	-	-	-	-	3984	-	1154	-	951	425	951
		la10	-	-	-	-	-	-	3681	-	1063	-	958	454	958
	j=20	la11	-	-	-	-	-	-	4974	-	1303	-	1222	642	1222
		la12	-	-	-	-	-	-	4557	-	1271	-	1039	633	1039
		la13	-	-	-	-	-	-	4846	-	1227	-	1150	662	1150
		la14	-	-	-	-	1292	10653	5145	-	1377	-	1292	688	1292
		la15	-	-	-	-	-	-	5264	-	1459	-	1289	-	1207
m=10	j=10	la16	-	-	-	-	-	-	4849	-	1298	-	1022	-	945
		la17	-	-	-	-	-	-	4299	-	938	-	786	-	784
		la18	-	-	-	-	-	-	4763	-	1034	-	922	-	848
		la19	-	-	-	-	-	-	4566	-	1140	-	904	-	842
		la20	-	-	-	-	-	-	5056	-	1378	-	964	-	902
	j=15	la21	-	-	-	-	-	-	7608	-	1326	-	1149	-	(1040,1053)
		la22	-	-	-	-	-	-	6920	-	1413	-	1047	-	927
		la23							7676	-	1357	-	1075	-	1032
		la24							7237	-	1346	-	1061	-	935
		la25	-	-	-	-	-	-	7141	-	1290	-	1070	-	977

Lawrence Job Shop Problems

Task Graph Scheduling

Optimal Static Task Scheduling

- Task **P** = { P_1,.., P_m }
- Machines **M** = { M_1,..,M_n }
- Duration Δ : $(\mathbf{P}\times\mathbf{M}) \rightarrow \mathbf{N}_\infty$
- < : p.o. on **P** (pred.)



M = { M_1,M_2 }

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Task Graph Scheduling

Optimal Static Task Scheduling

- Task $\mathbf{P} = \{P_1, .., P_m\}$
- Machines $\mathbf{M} = \{M_1, .., M_n\}$
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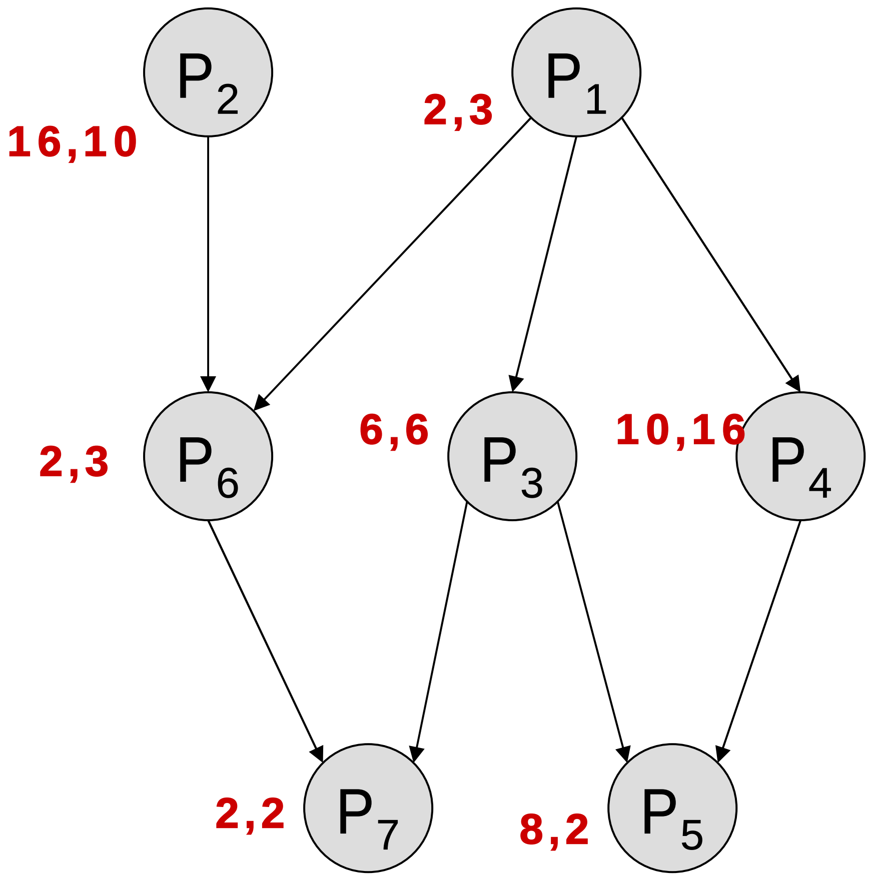

- A task can be executed only if all predecessors have completed
- Each machine can process at most one task at a time
- Task cannot be preempted.

$\mathbf{M} = \{M_1, M_2\}$

Task Graph Scheduling

Optimal Static Task Scheduling

- Task $\mathbf{P} = \{P_1, .., P_m\}$
- Machines $\mathbf{M} = \{M_1,..,M_n\}$
- Duration $\Delta : (\mathbf{P} \times \mathbf{M}) \rightarrow \mathbf{N}_\infty$
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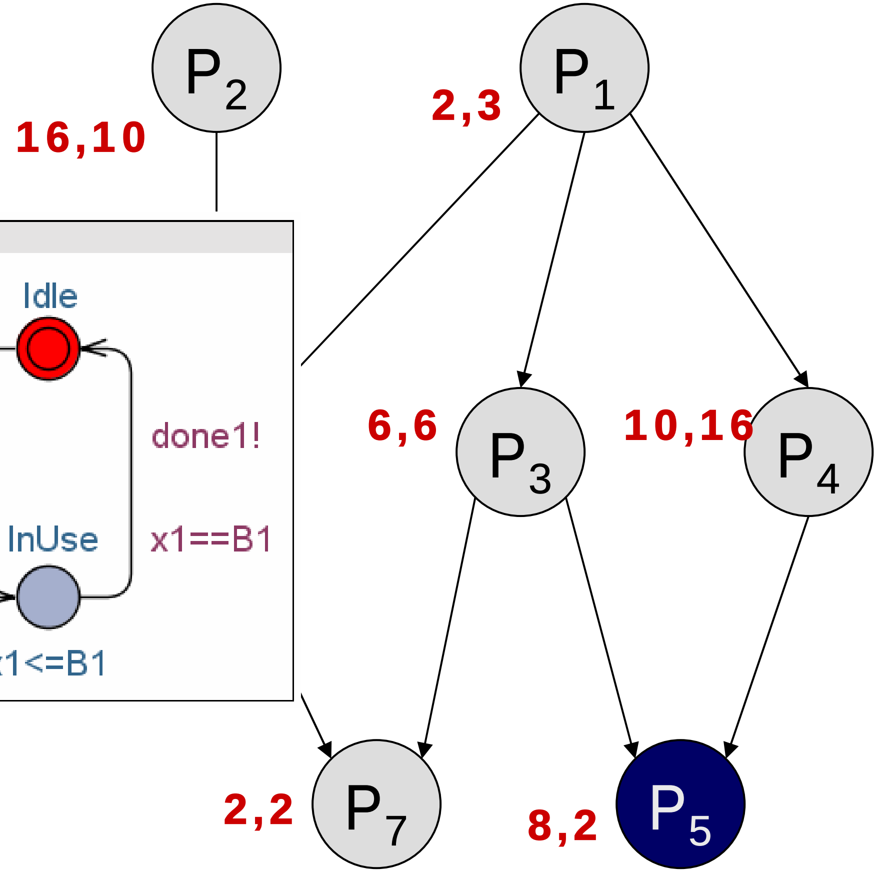
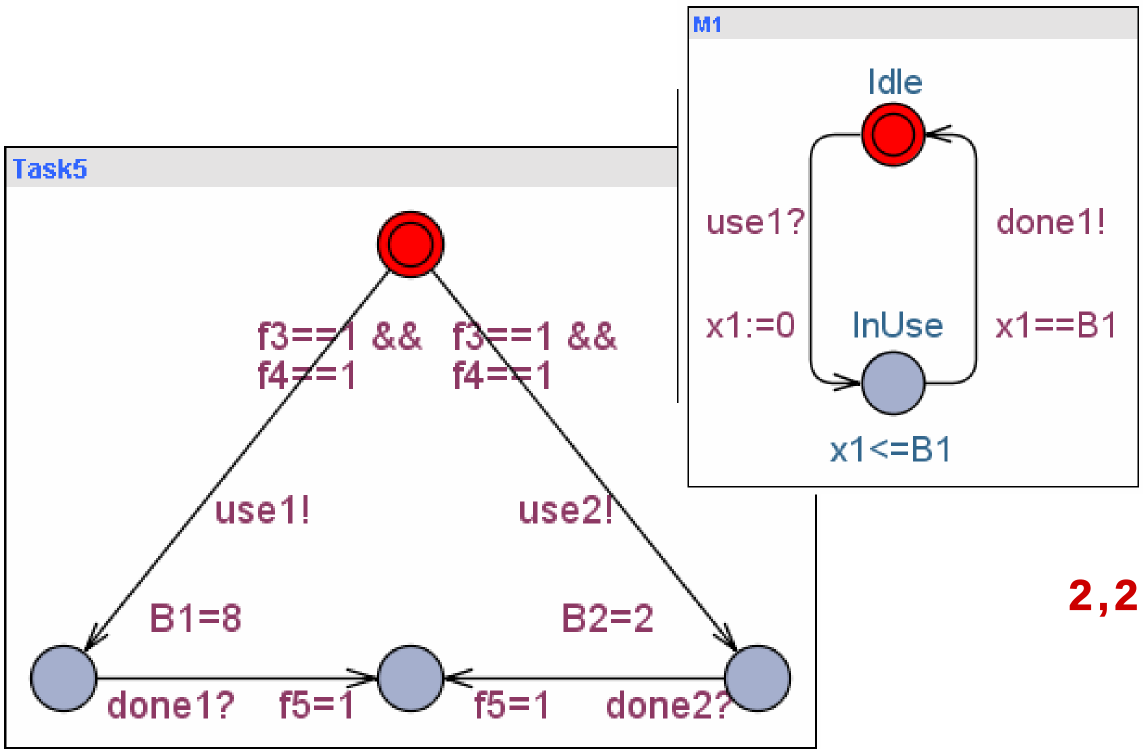




$\mathbf{M} = \{M_1, M_2\}$

Experimental Results

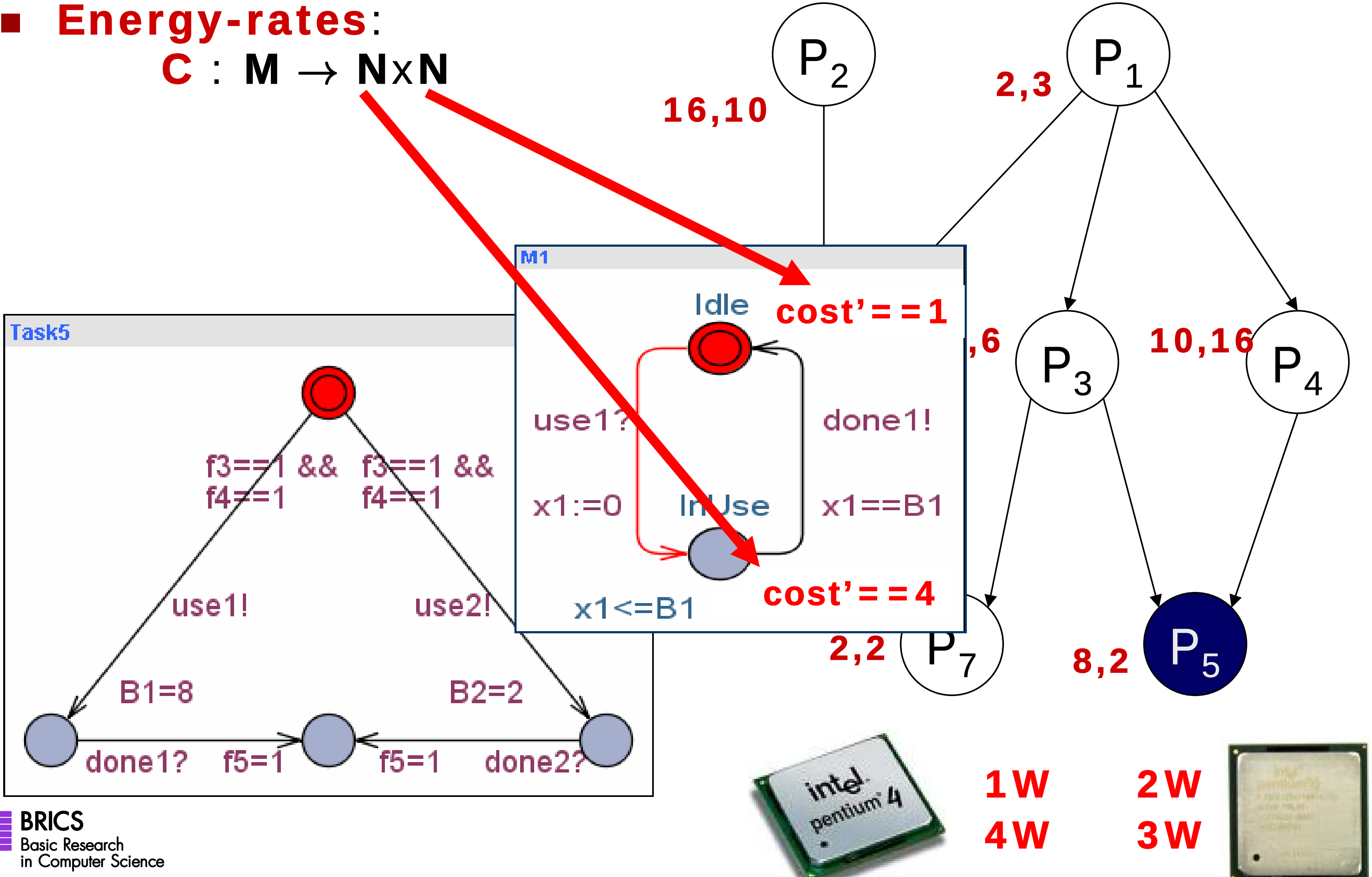
name	#tasks	#chains	# machines	optimal	TA
001	437	125	4	1178	1182
000	452	43	20	537	537
018	730	175	10	700	704
074	1007	66	12	891	894
021	1145	88	20	605	612
228	1187	293	8	1570	1574
071	1193	124	20	629	634
271	1348	127	12	1163	1164
237	1566	152	12	1340	1342
231	1664	101	16	t.o.	1137
235	1782	218	16	t.o.	1150
233	1980	207	19	1118	1121
294	2014	141	17	1257	1261
295	2168	965	18	1318	1322
292	2333	318	3	8009	8009
298	2399	303	10	2471	2473

Abdeddaïm, Kerbaa, Maler

Optimal Task Graph Scheduling

Power-Optimality

- **Energy-rates**:
  C : M → NxN



Priced Timed Automata

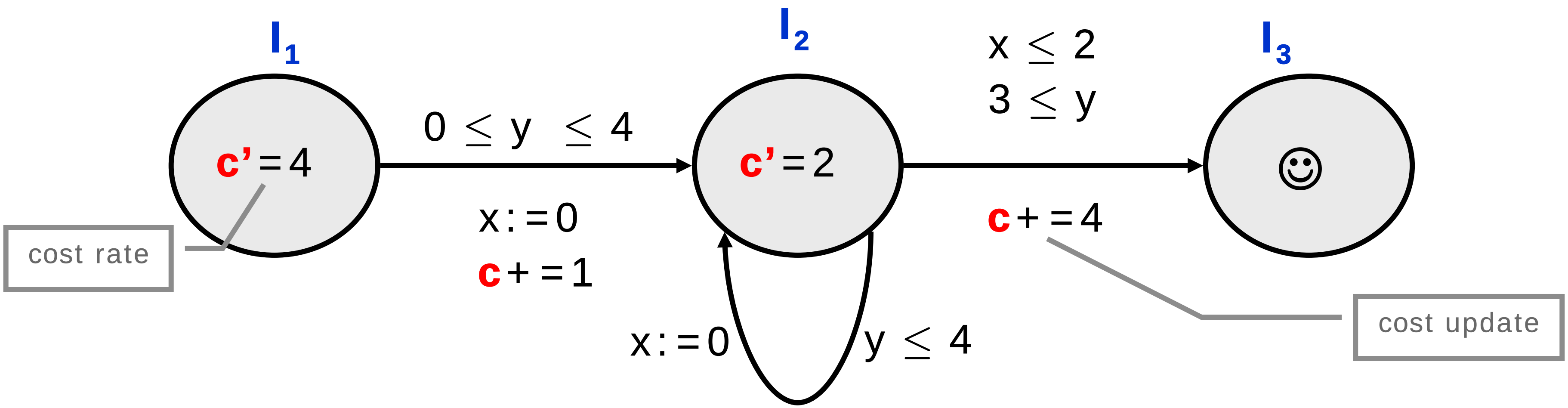
Optimal Scheduling

Priced Timed Automata

Timed Automata + **COST** variable

Behrmann, Fehnker, et all (HSCC'01)

Alur, Torre, Pappas (HSCC'01)



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Priced Timed Automata

Timed Automata + **COST** variable

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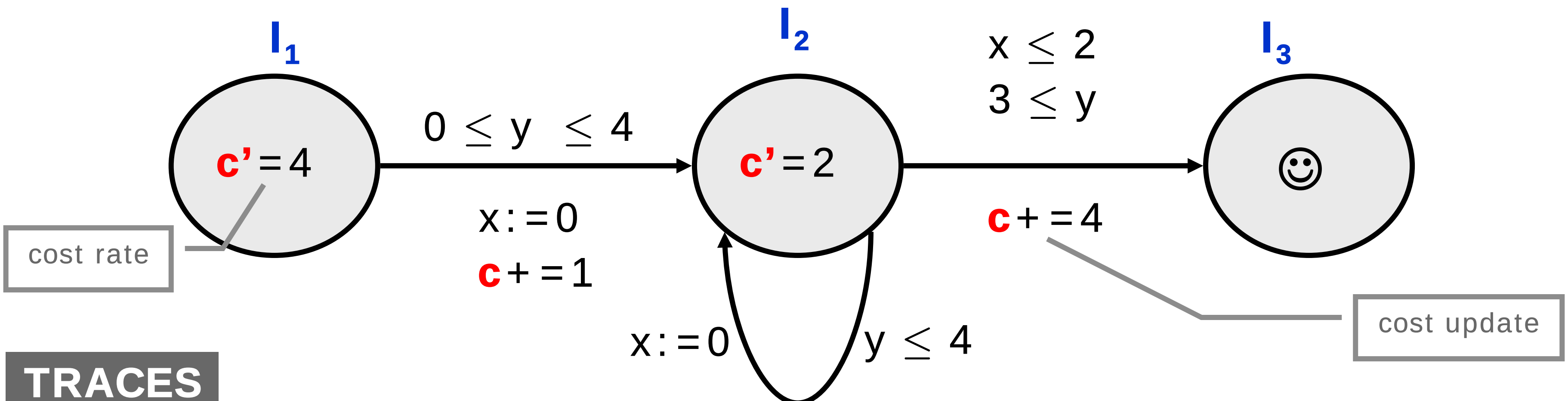

TRACES

$$(l_1, x=y=0) \overset{\varepsilon(3)}{\underset{12}{\dashrightarrow}} (l_1, x=y=3) \xrightarrow[1]{} (l_2, x=0, y=3) \xrightarrow[4]{} (l_3, \_, \_)$$

$\sum c = 17$

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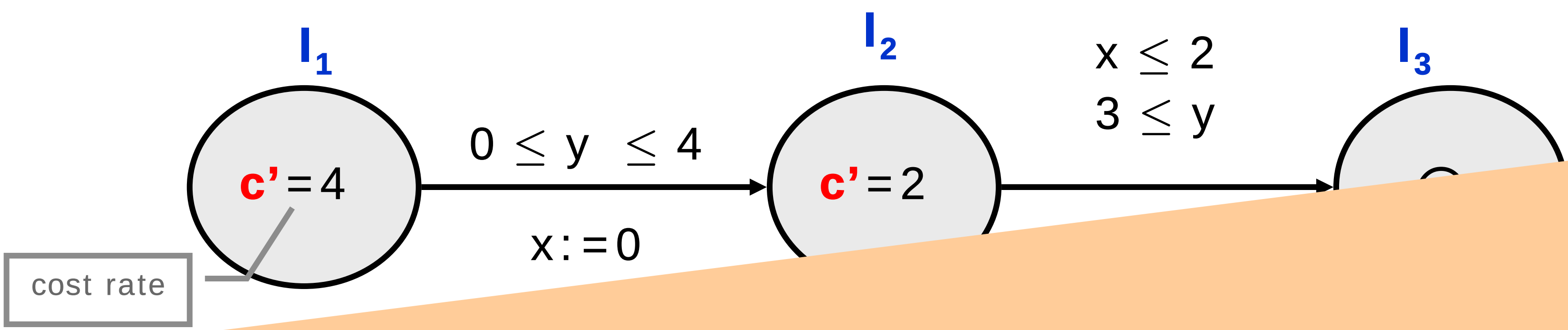
in Computer Science

Priced Timed Automata

Timed Automata + **COST** variable

Behrmann, Fehnker, et all (HSCC'01)

Alur, Torre, Pappas (HSCC'01)



TRA

Problem :

Find the minimum cost of reaching location l_3

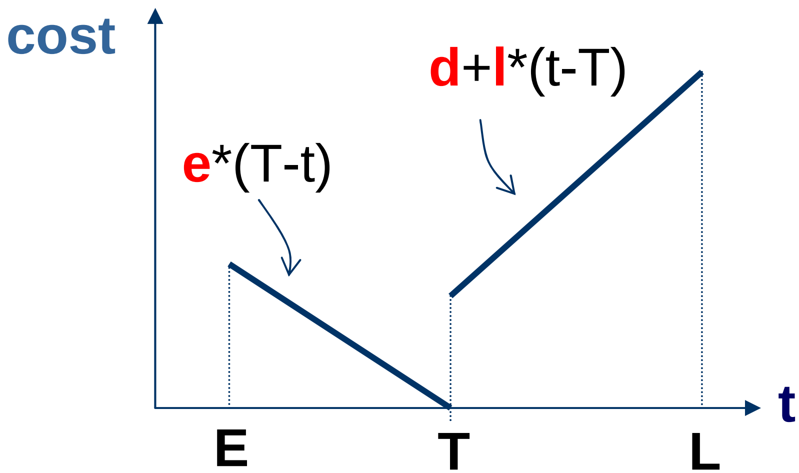
Efficient Implementation:

CAV'01 and TACAS'04

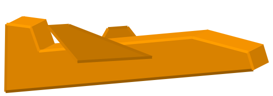
$(l_3,\_,\_)$ $\sum c=16$

$(l_1,x=y=0) \xrightarrow[1]{} (l_2,x=0,y=0) \overset{\varepsilon(3)}{\underset{6}{\dashrightarrow}} (l_2,x=3,y=3) \xrightarrow[0]{} (l_2,x=0,y=3) \xrightarrow[4]{} (l_3,\_,\_)$ $\sum c=11$

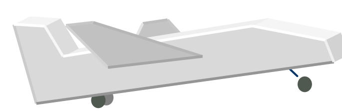
Aircraft Landing Problem

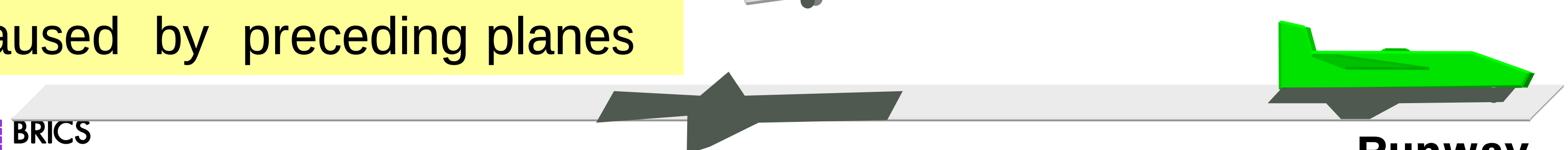


E earliest landing time
T target time
L latest time
e cost rate for being early
l cost rate for being late
d fixed cost for being late



Planes have to keep separation distance to avoid turbulences caused by preceding planes





Runway

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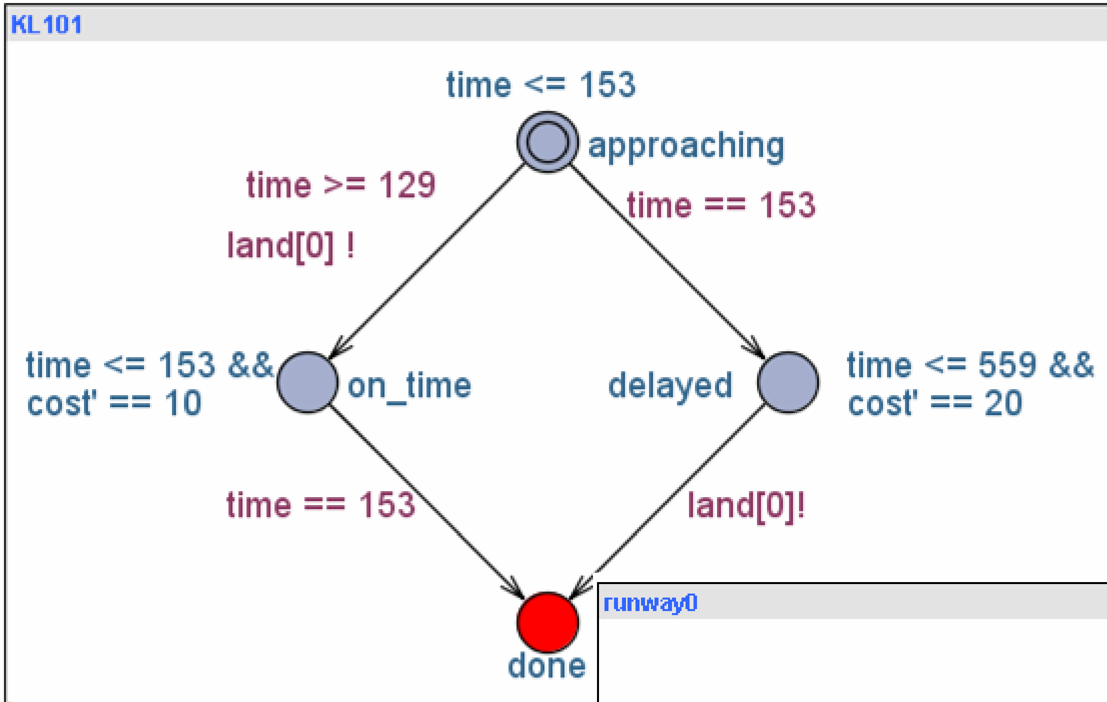
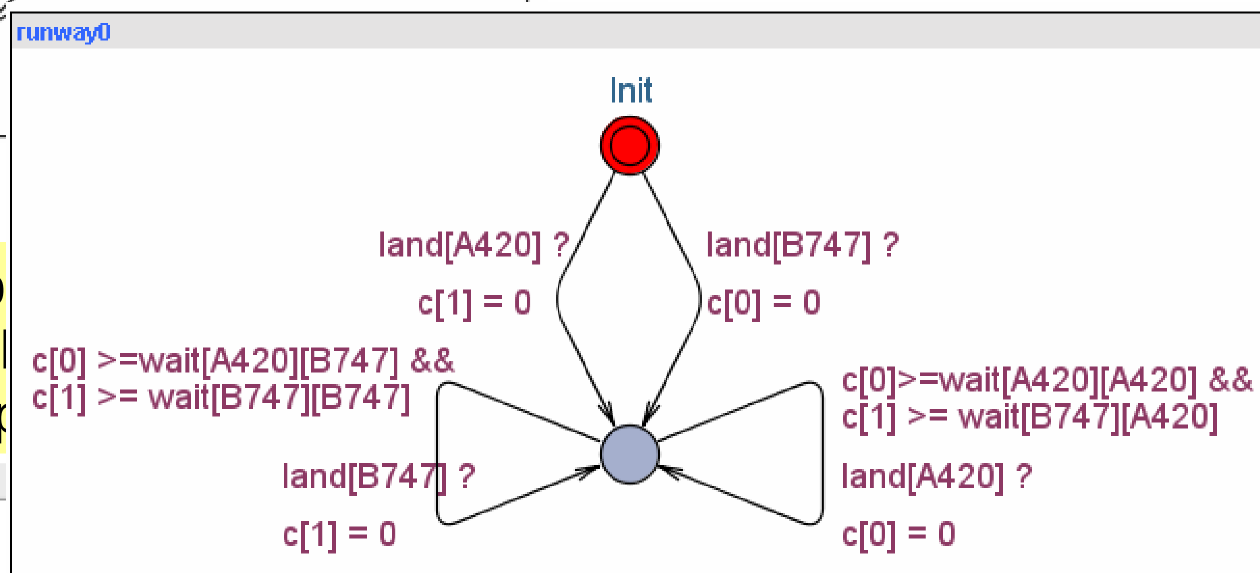
Modeling ALP with PTA



129: Earliest landing time
153: Target landing time
559: Latest landing time
10: Cost rate for early
20: Cost rate for late

Runway handles 2 types of planes

Planes have to keep sep
distance to avoid turbul
caused by preceding p



Symbolic ”A*”

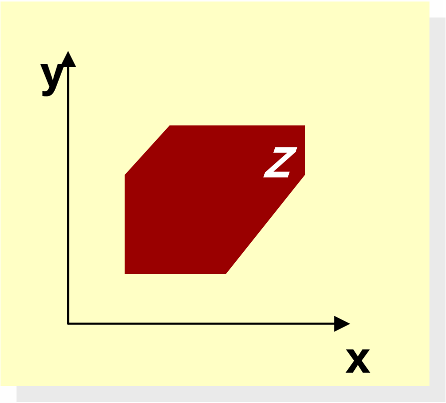
Zones

Definition
A *zone* Z over a set of clocks C is a finite conjunction of simple constraints of the forms:

$$x \geq l \qquad x \leq u \qquad x - y \geq l' \qquad x - y \leq u'$$

where $x, y \in C$, $l, u \in \mathbb{N}$ and $l', u' \in \mathbb{Z}$.

For $u \in \mathbb{R}^C$ and Z a zone we write $u \models Z$ if u satisfies all constraints of Z.



Operations

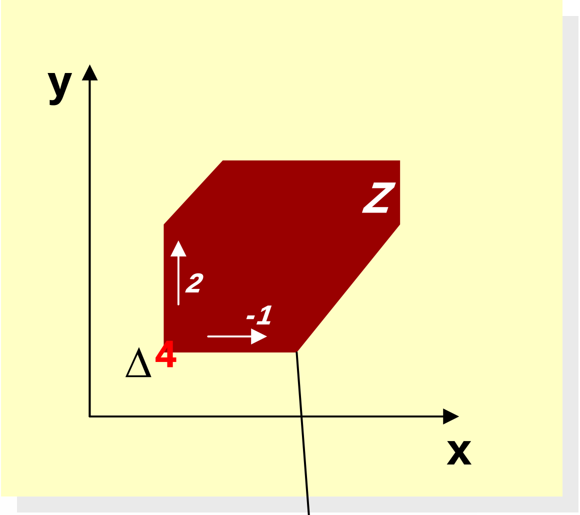
Reset: $\{x\}Z = \{u[0/x] \mid u \models Z\}$

Delay: $Z^{\uparrow} = \{u + d \mid u \models Z\}$

Offset: $\Delta_Z \models Z$ such that $\forall u \models Z. \forall x \in C. \Delta_Z(x) \leq u(x)$.

Priced Zone

CAV'01



Definition

A priced zone P is a tuple (Z, c, r), where:

- Z is a zone
- $c \in \mathbb{N}$ describes the cost of Δ_Z
- $r : C \to \mathbb{Z}$ gives a *rate* for any clock $x \in C$.

We write $u \models P$ whenever $u \models Z$. For $u \models P$ we define Cost(u, P) as follows:

$$\text{Cost}(u, P) = c + \sum_{x \in C} r(x) \cdot (u(x) - \Delta_Z(x))$$

$$Cost(x, y) = 2y - x + 2$$

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Branch & Bound Algorithm

Cost := ∞

Passed := $\emptyset$

Waiting := $\{(l_0, Z_0)\}$

while Waiting $\neq \emptyset$ **do**

  select (l, Z) from Waiting

  if $l = l_g$ and minCost(Z) < Cost **then**

    Cost := minCost(Z)

  if minCost(Z) + Rem$_{(l,Z)} \geq$ Cost **then** break

  if for all (l, Z') in Passed: $Z' \not\leq Z$ **then**

    add (l, Z) to Passed

    add all (l', Z') with $(l, Z) \rightarrow (l', Z')$ to Waiting

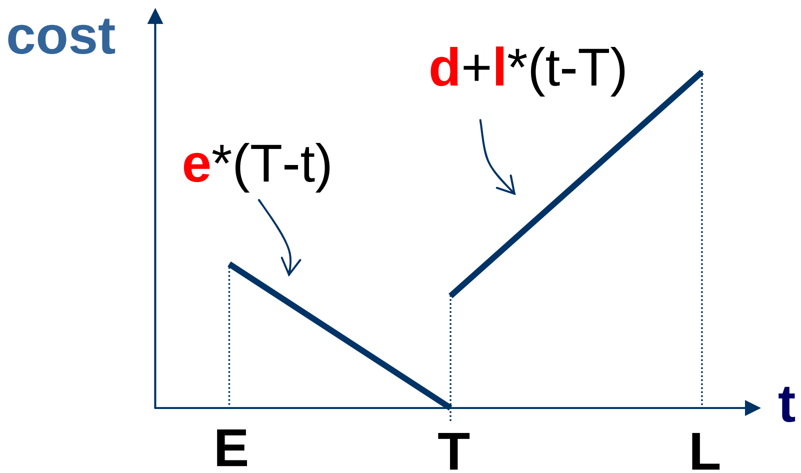
return Cost

Experimental Results

Experiments *MC Order*

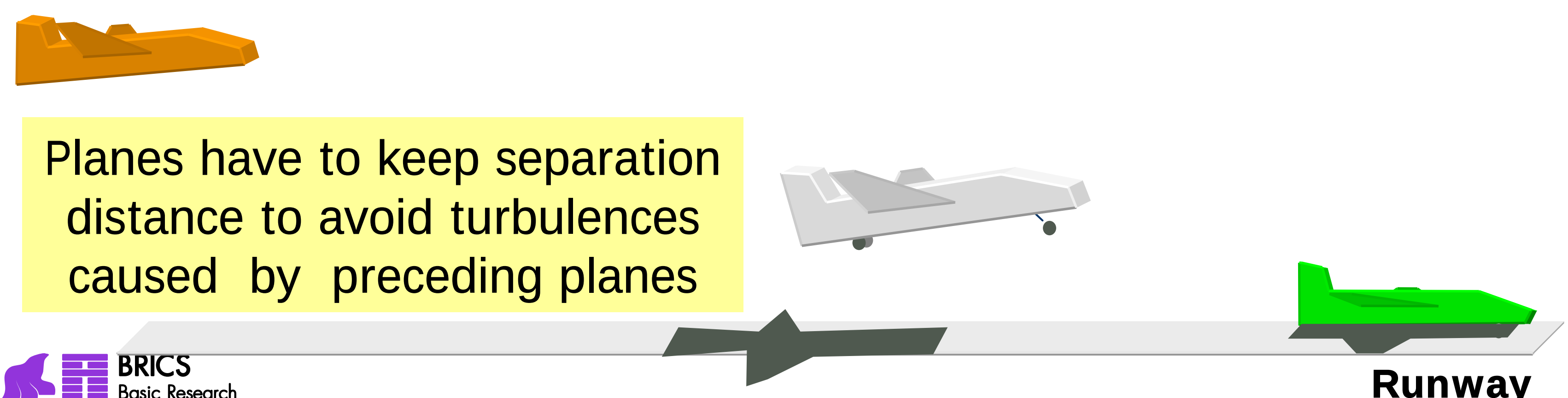
COST-rates				SCHEDULE	COST	TIME	#Expl	#Pop'd
G_5	C_{10}	B_{20}	D_{25}					
Min Time				CG> G< BD> C< CG>		60	1762 1538	2638
1	1	1	1	CG> G< BG> G< GD>	55	65	252	378
9	2	3	10	GD> G< CG> G< BG>	195	65	149	233
1	2	3	4	CG> G< BD> C< CG>	140	60	232	350
1	2	3	10	CD> C< CB> C< CG>	170	65	263	408
1	20	30	40	BD> B< CB> C< CG>	975 1085	85 time<85	-	-
0	0	0	0	-	0	-	406	447

Example: Aircraft Landing

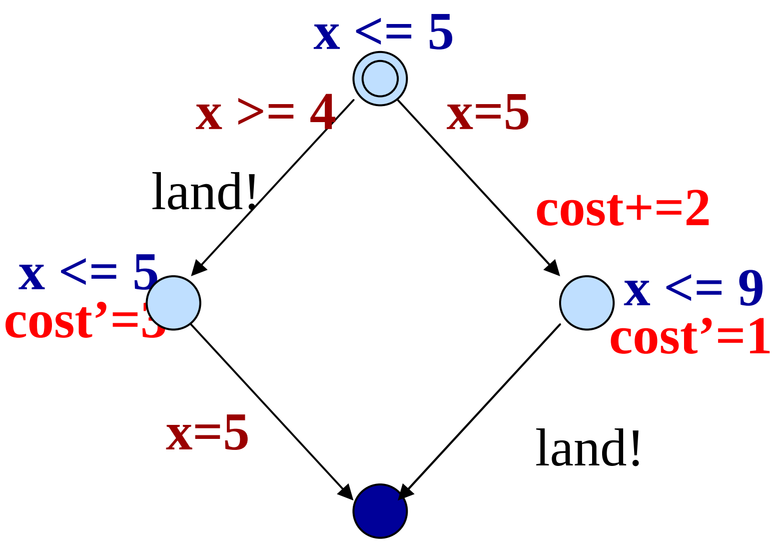


E earliest landing time
T target time
L latest time
e cost rate for being early
l cost rate for being late
d fixed cost for being late

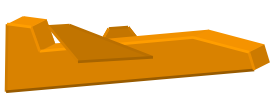
Planes have to keep separation distance to avoid turbulences caused by preceding planes



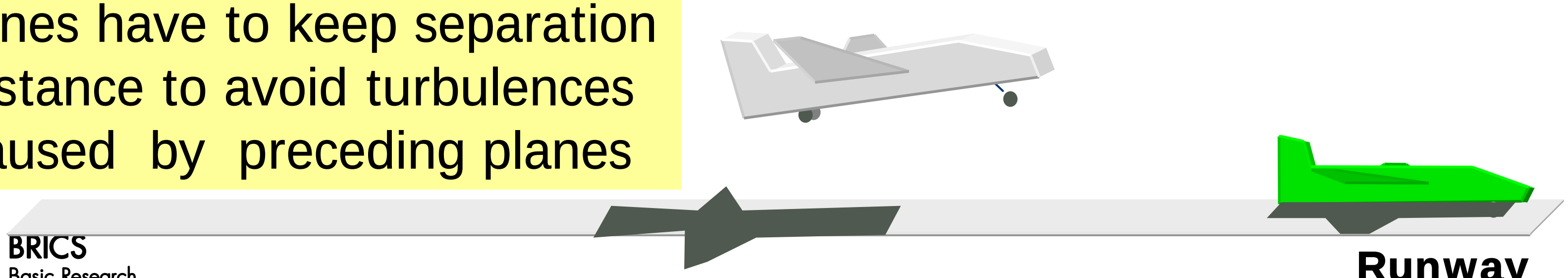
Example: Aircraft Landing



4 earliest landing time
5 target time
9 latest time
3 cost rate for being early
1 cost rate for being late
2 fixed cost for being late



Planes have to keep separation distance to avoid turbulences caused by preceding planes



Aircraft Landing

CAV'01

Source of examples:
Baesley et al'2000

	problem instance	1	2	3	4	5	6	7
	number of planes	10	15	20	20	20	30	44
	number of types	2	2	2	2	2	4	2
1	optimal value	700	1480	820	2520	3100	24442	1550
	explored states	481	2149	920	5693	15069	122	662
	cputime (secs)	4.19	25.30	11.05	87.67	220.22	0.60	4.27
2	optimal value	90	210	60	640	650	554	0
	explored states	1218	1797	669	28821	47993	9035	92
	cputime (secs)	17.87	39.92	11.02	755.84	1085.08	123.72	1.06
3	optimal value	0	0	0	130	170	0	N/A
	explored states	24	46	84	207715	189602	62	
	cputime (secs)	0.36	0.70	1.71	14786.19	12461.47	0.68	
4	optimal value	N/A	N/A	N/A	0	0	N/A	N/A
	explored states				65	64		
	cputime (secs)				1.97	1.53		

Branch & Bound Algorithm

Zone based Linear Programming Problems

Cost := ∞

Passed := $\emptyset$

Waiting := $\{(l_0, Z_0)\}$

while Waiting $\neq \emptyset$ **do**

  select (l, Z) from Waiting

  if $l = l_g$ and minCost(Z) < Cost **then**

    Cost := minCost(Z)

  if minCost(Z) + Rem$_{(l,Z)}$ $\geq$ Cost **then** break

  if for all (l, Z') in Passed: $Z' \not\subseteq Z$ **then**

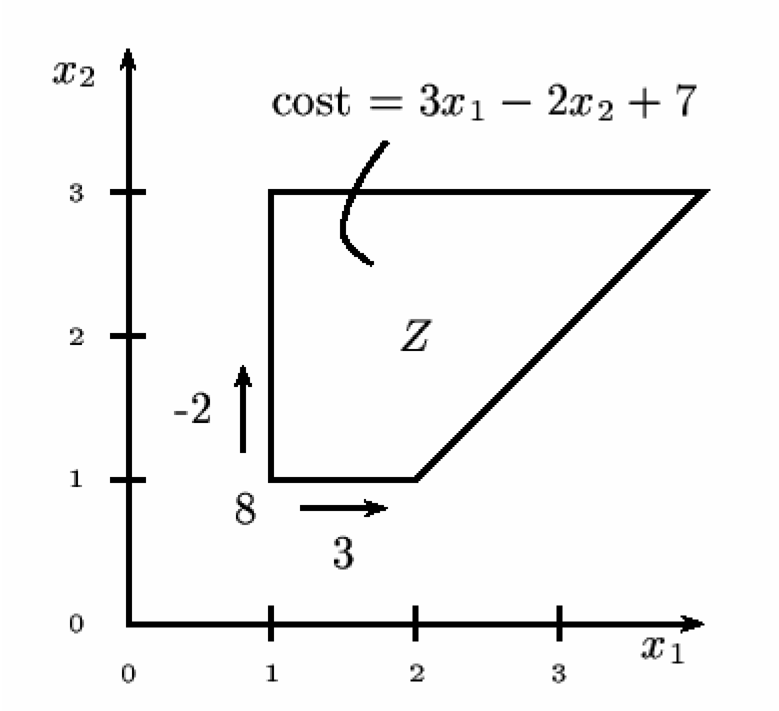
    add (l, Z) to Passed

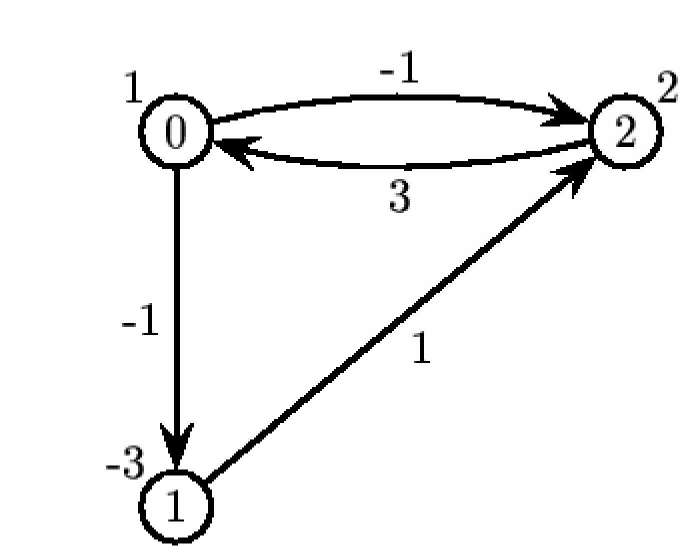
    add all (l', Z') with $(l, Z) \rightarrow (l', Z')$ to Waiting

return Cost

Zone LP → Min Cost Flow

Exploiting duality





minimize $\mathbf{3x_1-2x_2+7}$
when $x_1 - x_2 \leq 1$
$1 \leq x_2 \leq 3$
$x_2 \geq 1$

minimize $\mathbf{3y_{2,0}-y_{0,2}+y_{1,2} - y_{0,1}}$
when $y_{2,0}-y_{0,1}-y_{0,2}=1$
$y_{0,2}+y_{1,2}=2$
$y_{0,1}-y_{1,2}=-3$

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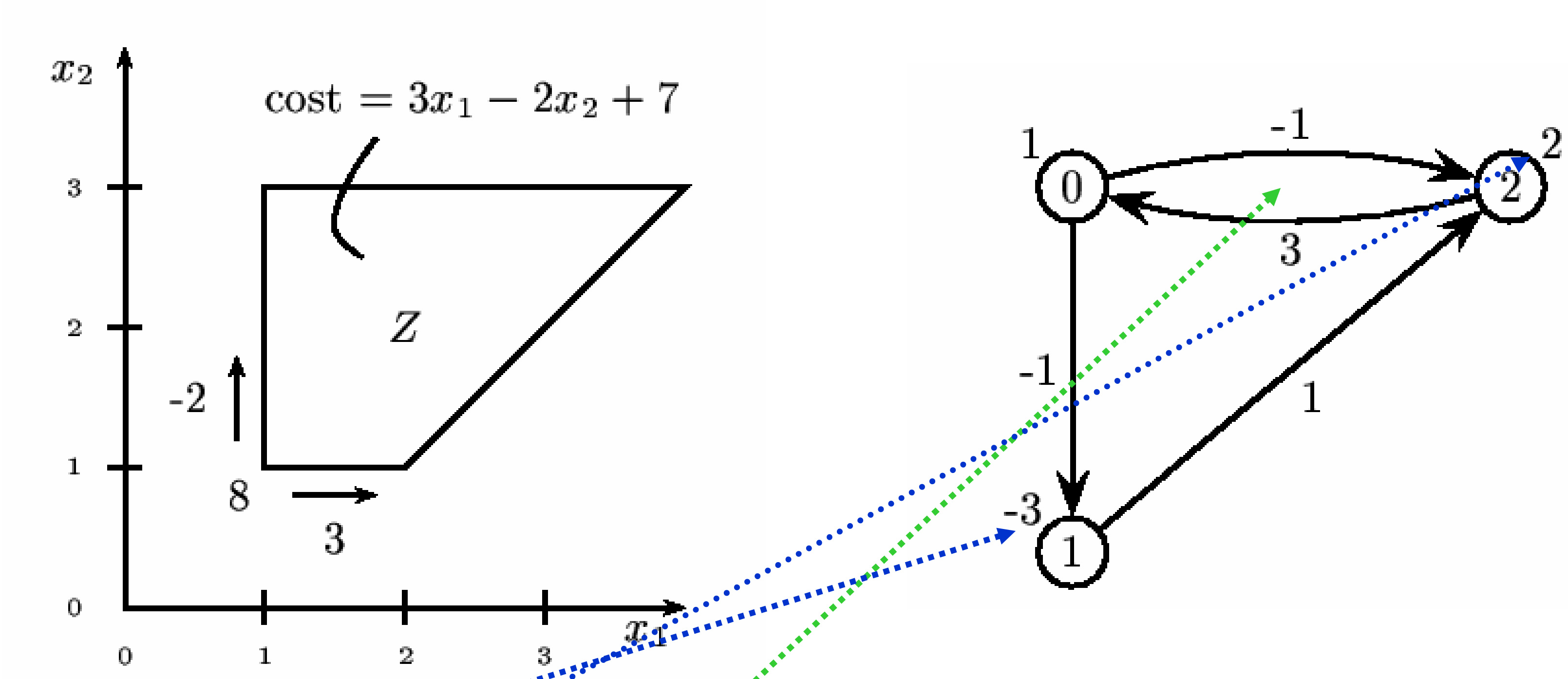
Zone LP → Min Cost Flow

Exploiting duality



minimize $3x_1 - 2x_2 + 7$

when $x_1 - x_2 \leq 1$

$1 \leq x_2 \leq 3$

$x_2 \geq 1$

minimize $3y_{2,0} - y_{0,2} + y_{1,2} - y_{0,1}$

when $y_{2,0} - y_{0,1} - y_{0,2} = 1$

$y_{0,2} + y_{1,2} = 2$

$y_{0,1} - y_{1,2} = -3$

Aircraft Landing

Using MCF/Netsimplex

Rasmussen, Larsen, Subramani
TACAS04

RW	Planes	10	15	20	20	20	30	44
	Types	2	2	2	2	2	4	2
1	simplex	0.844s	5.210s	2.135s	17.888s	44.878s	0.451s	0.670s
	netsimplex	0.156s	0.657s	0.369s	2.363s	5.503s	0.127s	0.322s
factor		**5.41**	**7.93**	**5.79**	**7.57**	**8.16**	**3.55**	**2.08**
2	simplex	2.577s	7.436s	2.175s	94.357s	120.004s	2.322s	0.264s
	netsimplex	0.332s	1.036s	0.436s	13.376s	18.033s	0.600s	0.179s
factor		**8.00**	**7.18**	**4.99**	**7.054**	**6.65**	**3.87**	**1.474**
3	simplex	0.120s	0.181s	0.357s	740.100s	516.678s	0.166s	N/A
	netsimplex	0.064s	0.104s	0.129s	170.176s	124.805s	0.079s	N/A
factor		**1.87**	**1.74**	**2.77**	**4.34**	**4.14**	**2.10**	
4	simplex	N/A	N/A	N/A	1.603s	0.318s	N/A	N/A
	netsimplex	N/A	N/A	N/A	0.378s	0.093s	N/A	N/A
factor					**4.24**	**3.42**		

A. Loebel (2000). MCF Version 1.2 - A network simplex implementation. (http://www.zib.de)

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Optimal Infinite Scheduling

with Ed Brinksma
Patricia Bouyer
Arne Skou

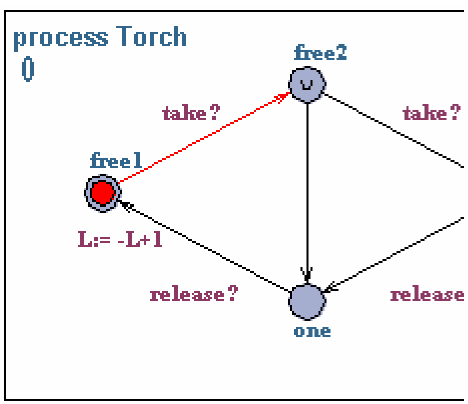
EXAMPLE: Optimal WORK plan for cars with different subscription rates for city driving !

5

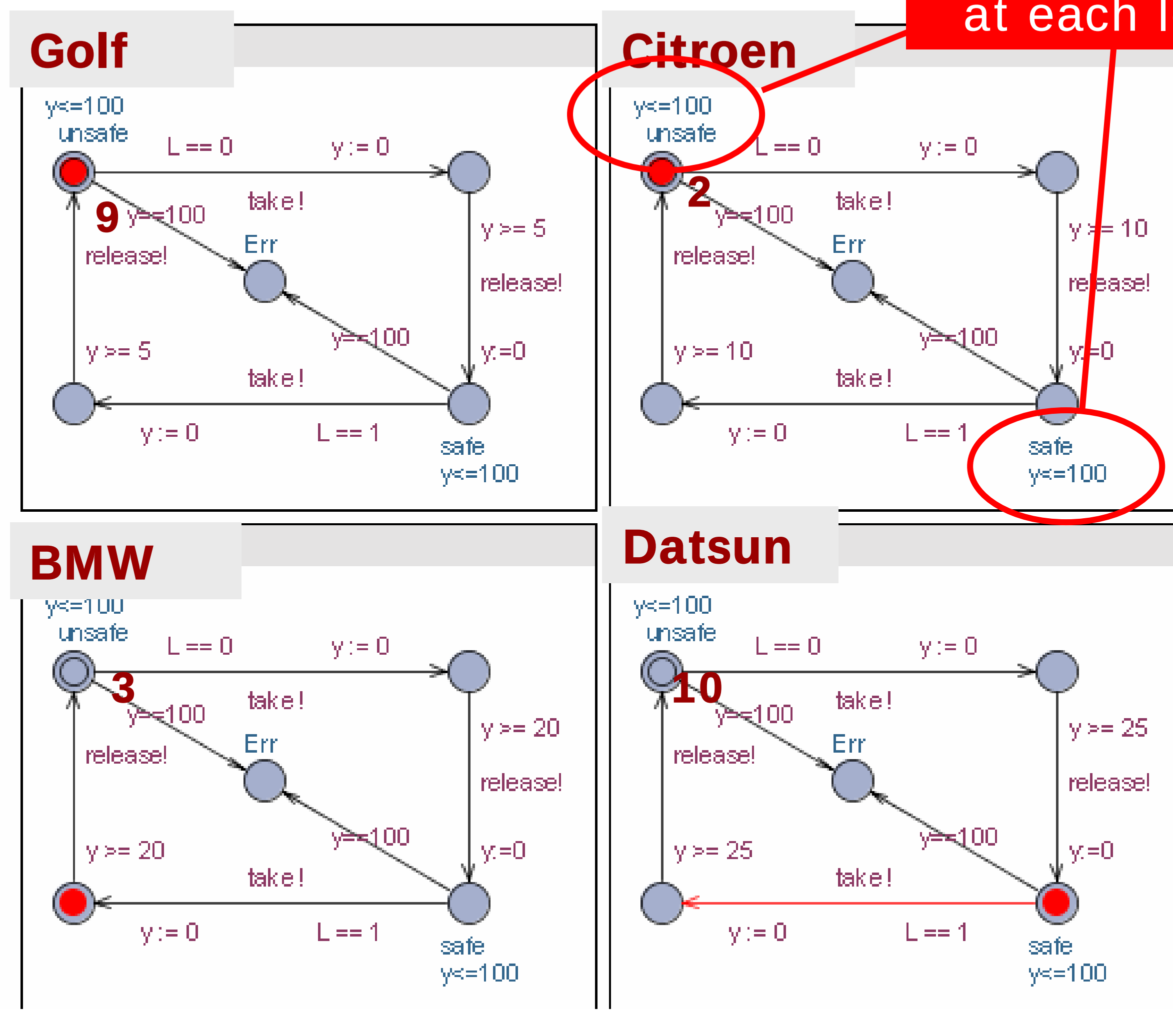
10

20

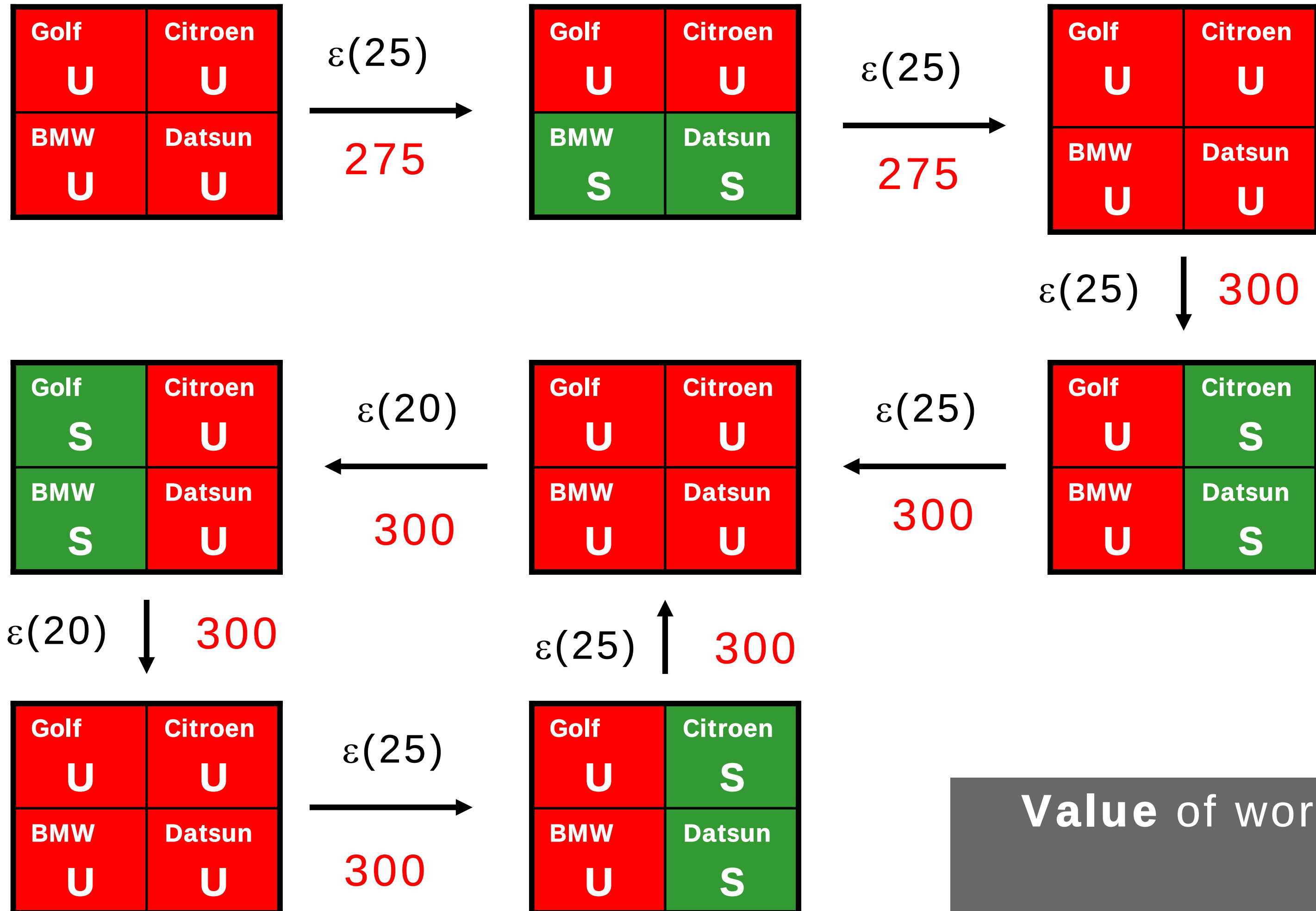
25



maximal 100 min. at each location



Workplan I



Value of workplan:

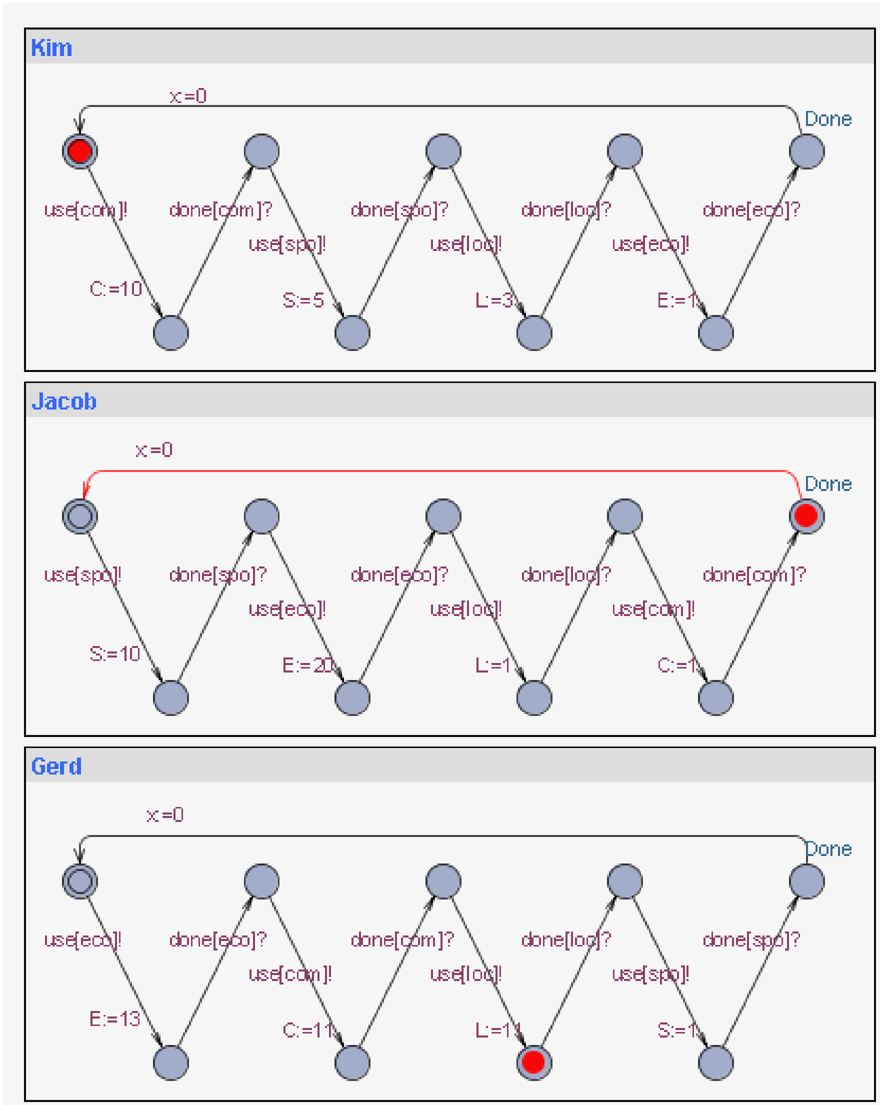
(4 x **300**) / 90 = **13.33**

Workplan II

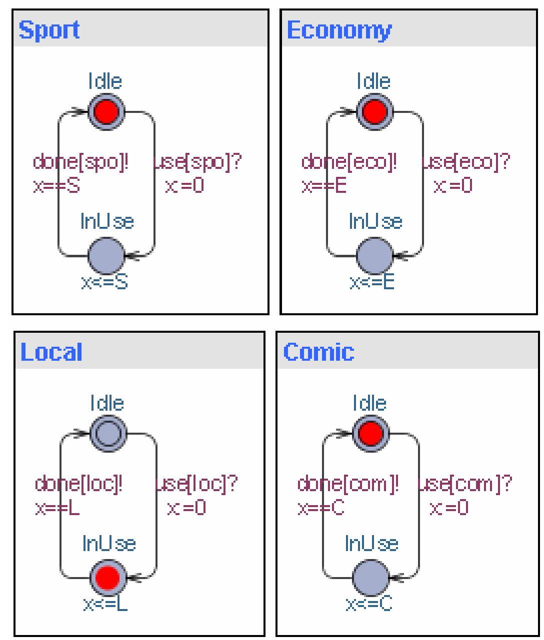
Value of workplan:

560 / 100 = **5.6**

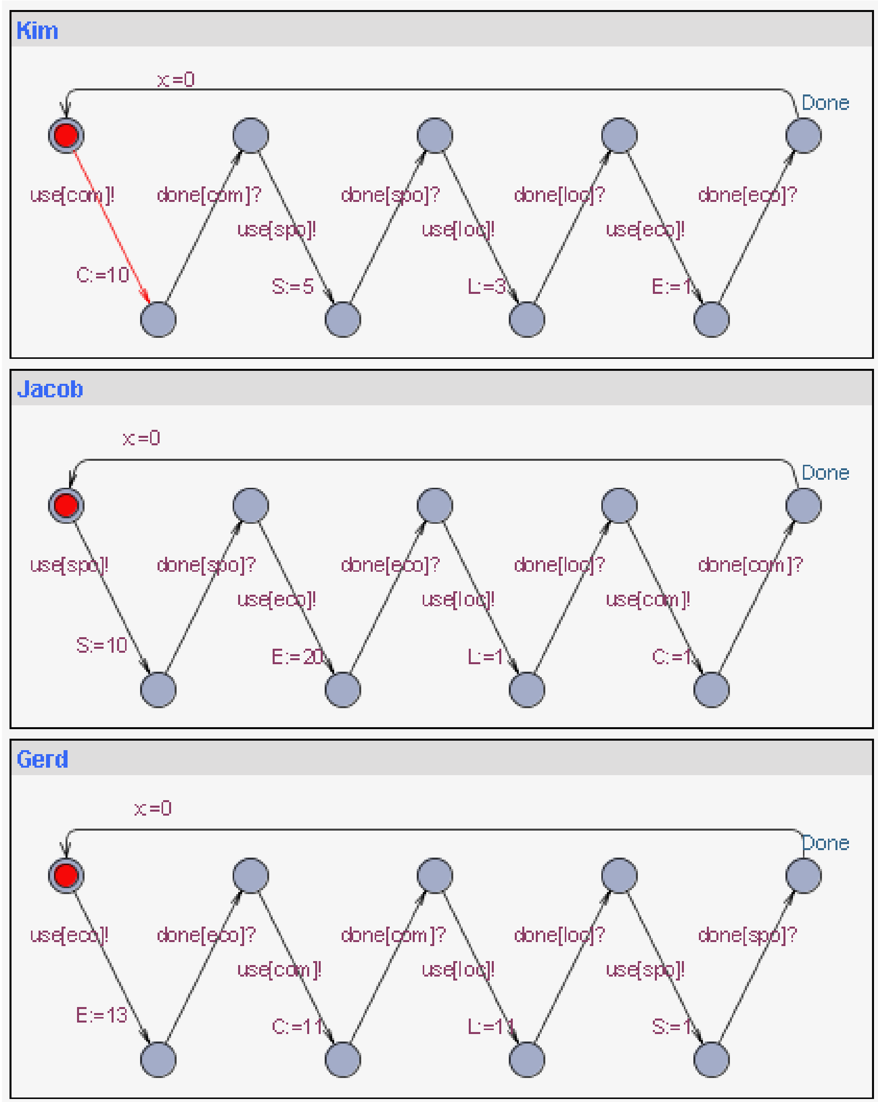
Infinite Scheduling



E[] (Kim.x $\leq$ 100 and Jacob.x $\leq$ 90 and Gerd.x $\leq$ 100)

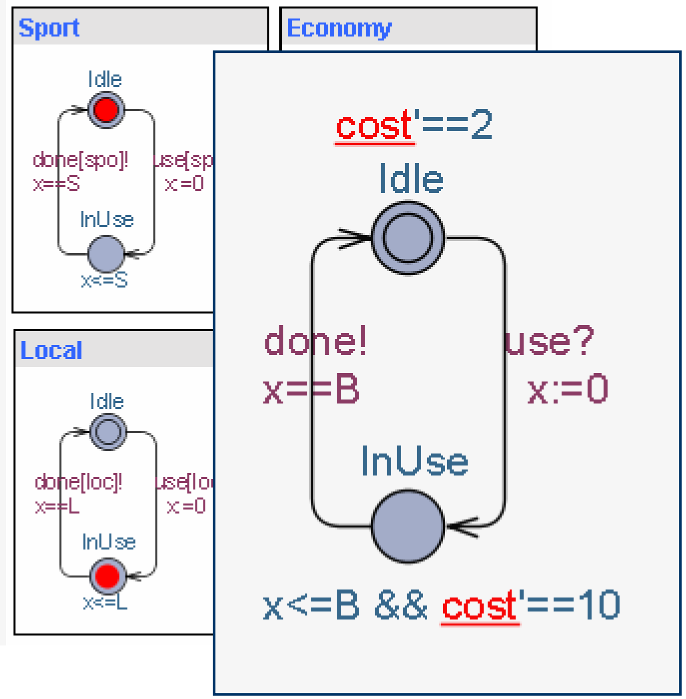


Infinite Optimal Scheduling



E[] (Kim.x ≤ 100 and
Jacob.x ≤ 90 and
Gerd.x ≤ 100)

+ most minimal limit of cost / time



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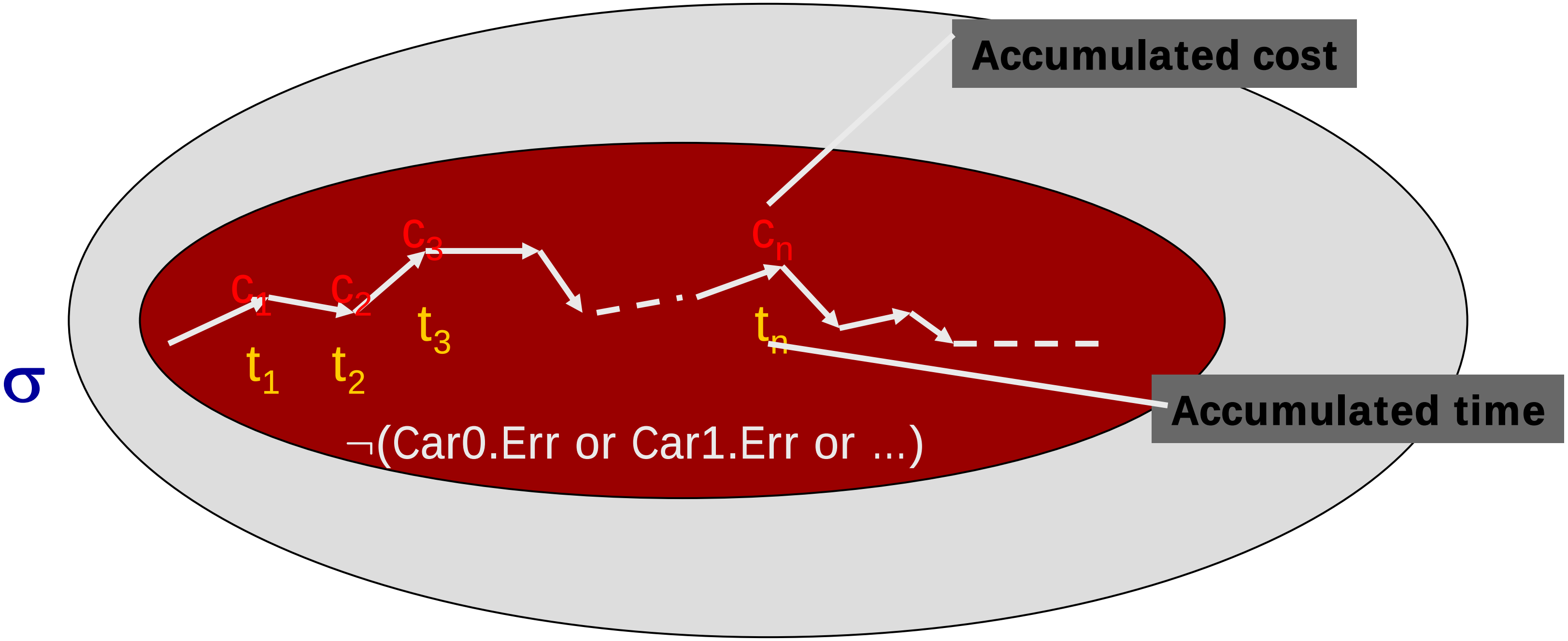
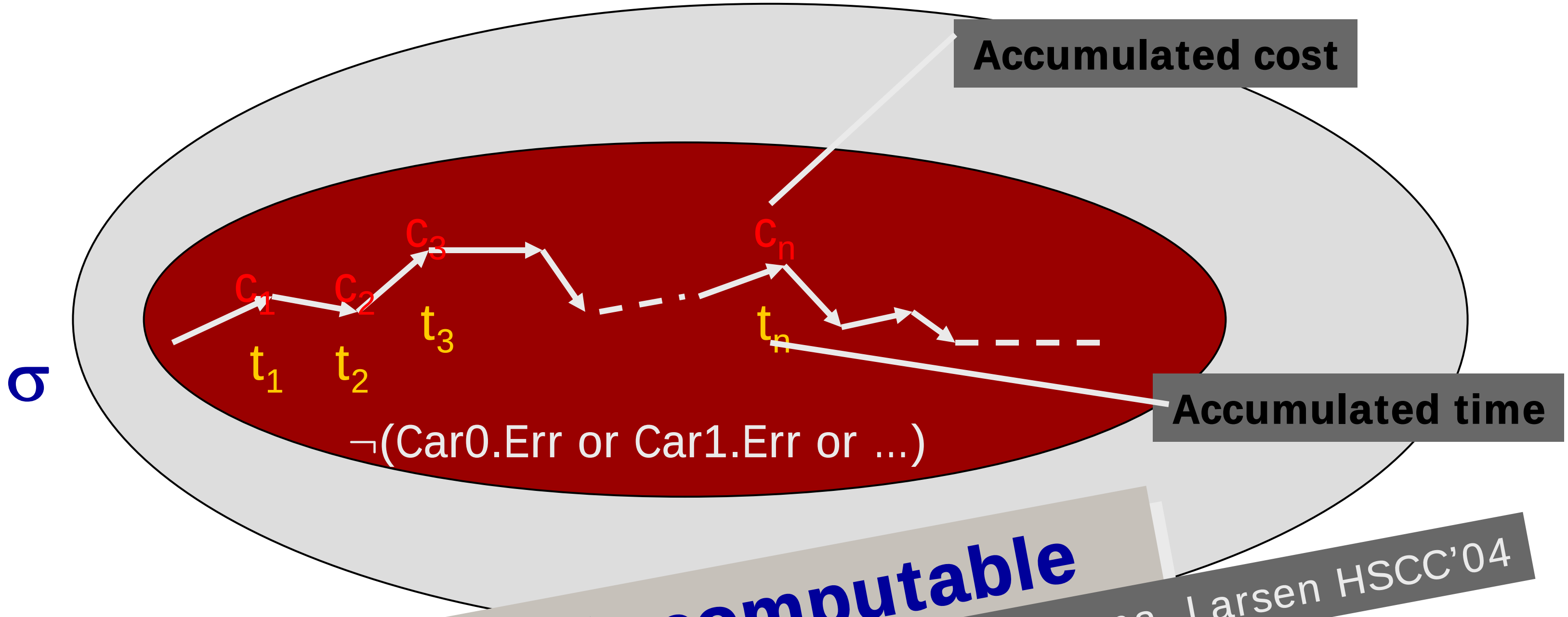
Cost Optimal Scheduling = *Optimal Infinite Path*



Value of path σ: $val(\sigma) = \lim_{n\to\infty} c_n/t_n$

Optimal Schedule σ^*: $val(\sigma^*) = \inf_{\sigma} val(\sigma)$

Cost Optimal Scheduling = *Optimal Infinite Path*



THEOREM: σ^* is computable

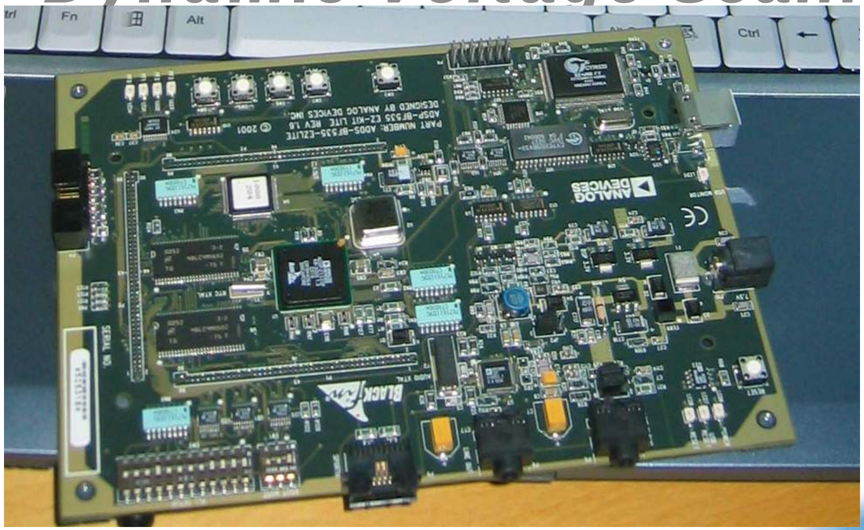
Bouyer, Brinksma, Larsen HSCC'04

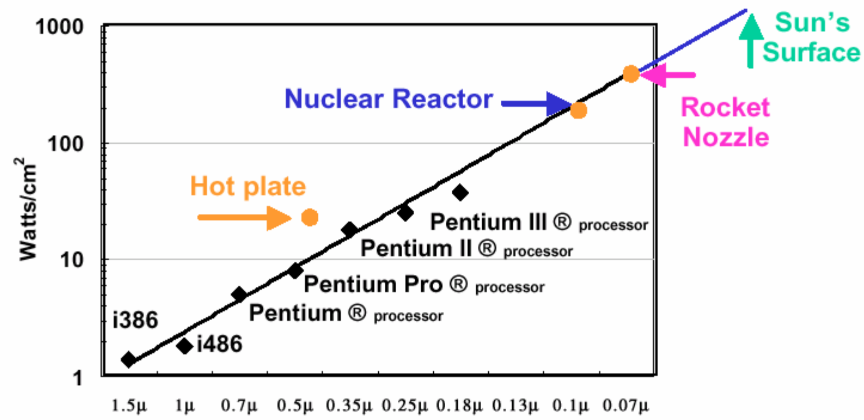
path σ: val(σ) = $\lim_{n\to\infty} c_n/t_n$

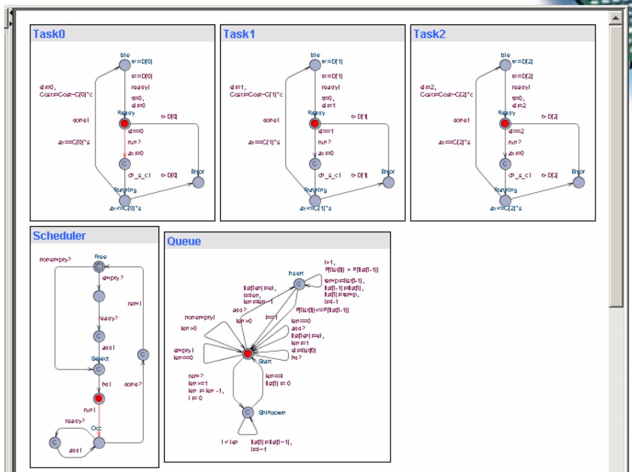
Optimal Schedule σ^*: val(σ^*) = $\inf_\sigma$ val(σ)

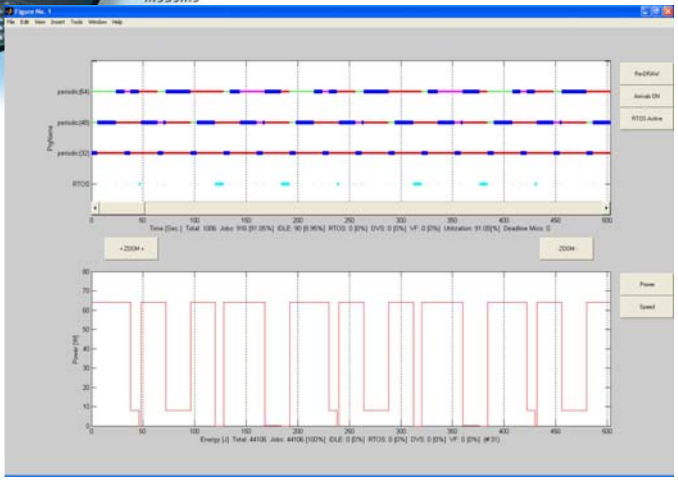
Application

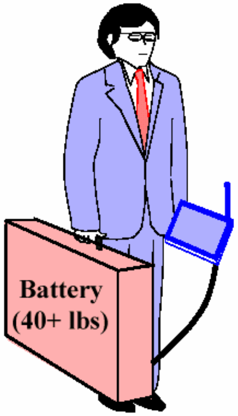
Dynamic Voltage Scaling



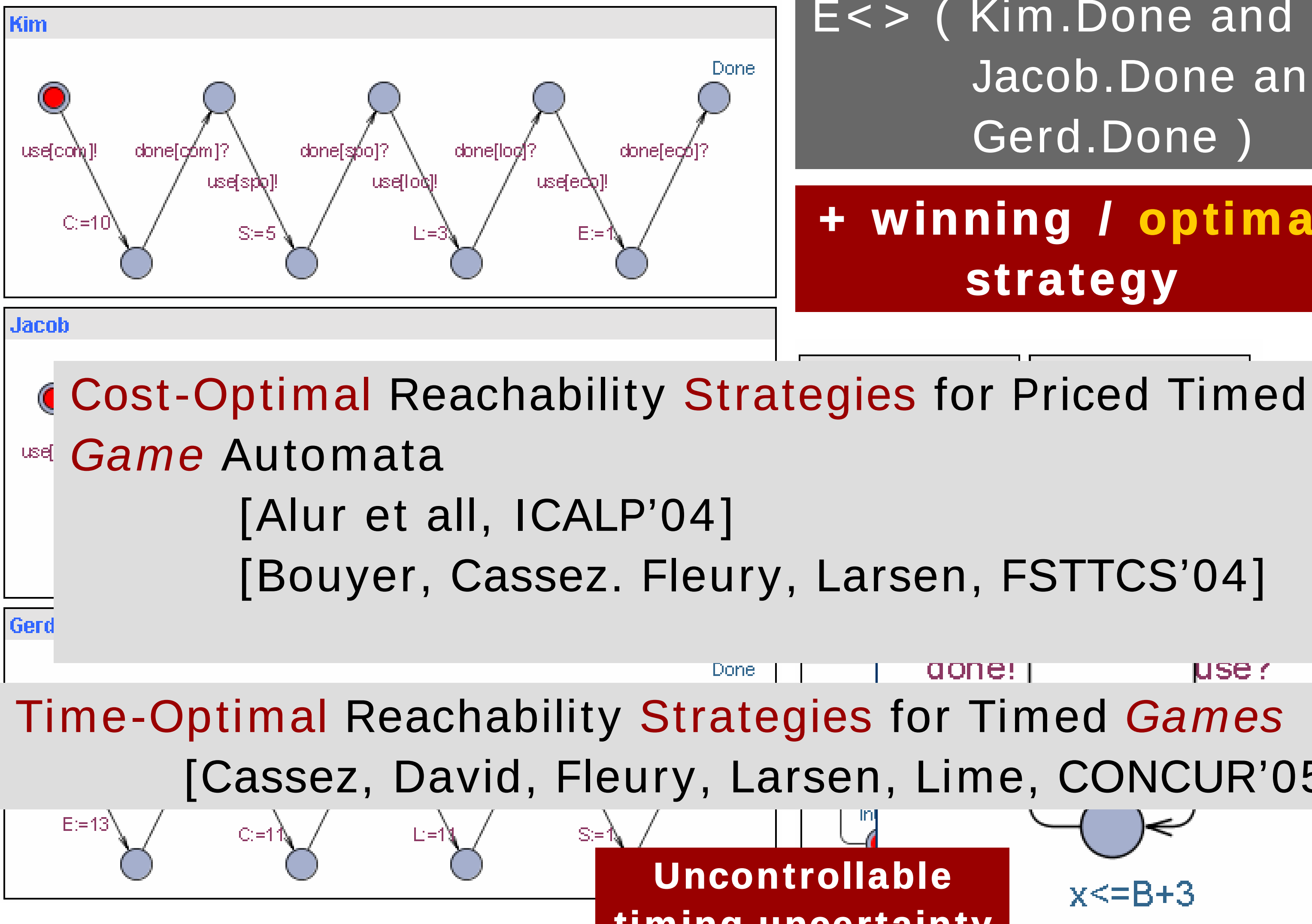








Dynamic Scheduling



E<> (Kim.Done and
Jacob.Done and
Gerd.Done)

+ winning / optimal strategy

Cost-Optimal Reachability Strategies for Priced Timed *Game* Automata
[Alur et all, ICALP'04]
[Bouyer, Cassez. Fleury, Larsen, FSTTCS'04]

Time-Optimal Reachability Strategies for Timed *Games*
[Cassez, David, Fleury, Larsen, Lime, CONCUR'05]

Uncontrollable timing uncertainty