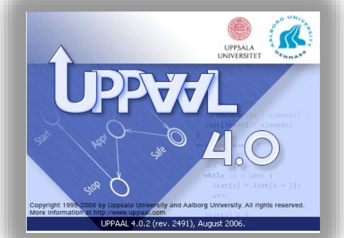
From Timed Automata to Stochastic Hybrid Games

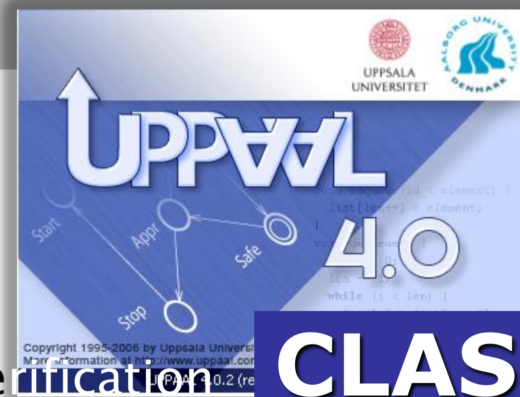
Model Checking, Performance Analysis, Optimization, Synthesis, and Machine Learning



Kim G. Larsen
Aalborg University, DENMARK

Topics

- Timed Automata
  - Decidability (regions)
  - Symbolic Verification (zones)
- Priced Timed Automata
  - Decidability (priced regions)
  - Symbolic Verification (priced zones)
- Stochastic Timed Automata
  - Stochastic Semantics
  - Statistical Model Checking
  - Stochastic Hybrid Automata
- Timed Games & Interfaces
  - Strategies, Symbolic Synthesis
  - Refinement
- Stochastic Priced Timed Games
  - Strategies
  - Symbolic Synthesis (zones)
  - Stochastic Strategies
  - Reinforcement Learning



Verification **CLASSIC** 1995

Optimization **CORA** 2001

Synthesis **TIGA** 2005

Component **ECDAR** 2010

Testing **TRON** 2004

Performance Analysis **SMC** 2011

Optimal Synthesis **STRATEGO** 2014

Priced Timed Automata
Optimal Scheduling

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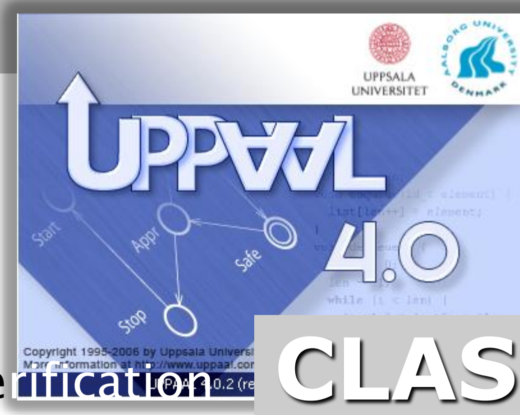
Overview

- Timed Automata
  - Scheduling
- **Priced** Timed Automata
  - Optimal Reachability
  - Optimal Infinite Scheduling
  - Multi Objectives
- **Energy** Automata



Verification — CLASSIC

Optimization — CORA

Synthesis — TIGA

Component — ECDAR

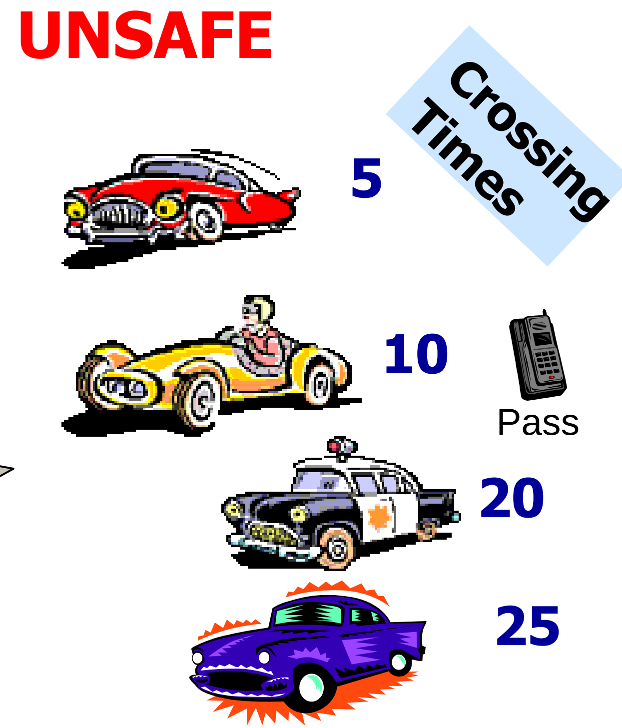
Testing — TRON

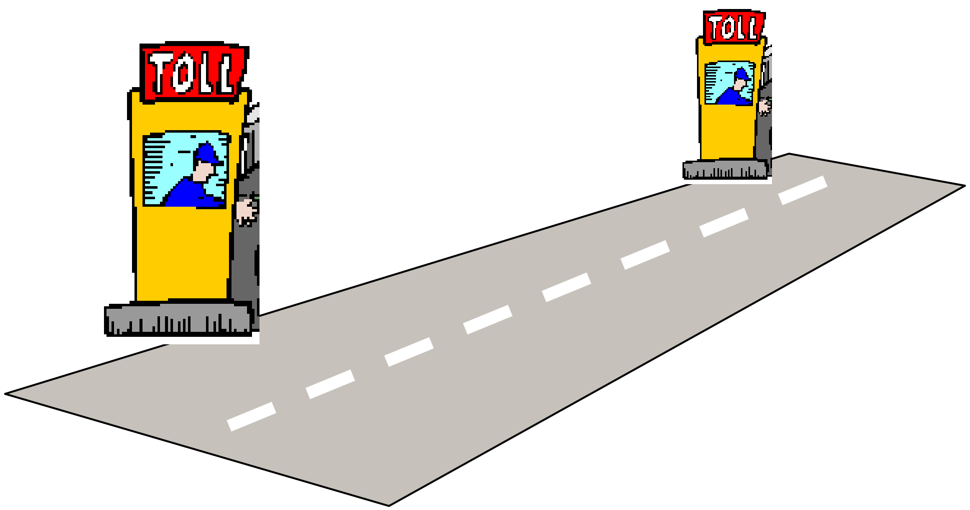
Performance Analysis — SMC

Optimal Synthesis — STRATEGO

Real Time Scheduling

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



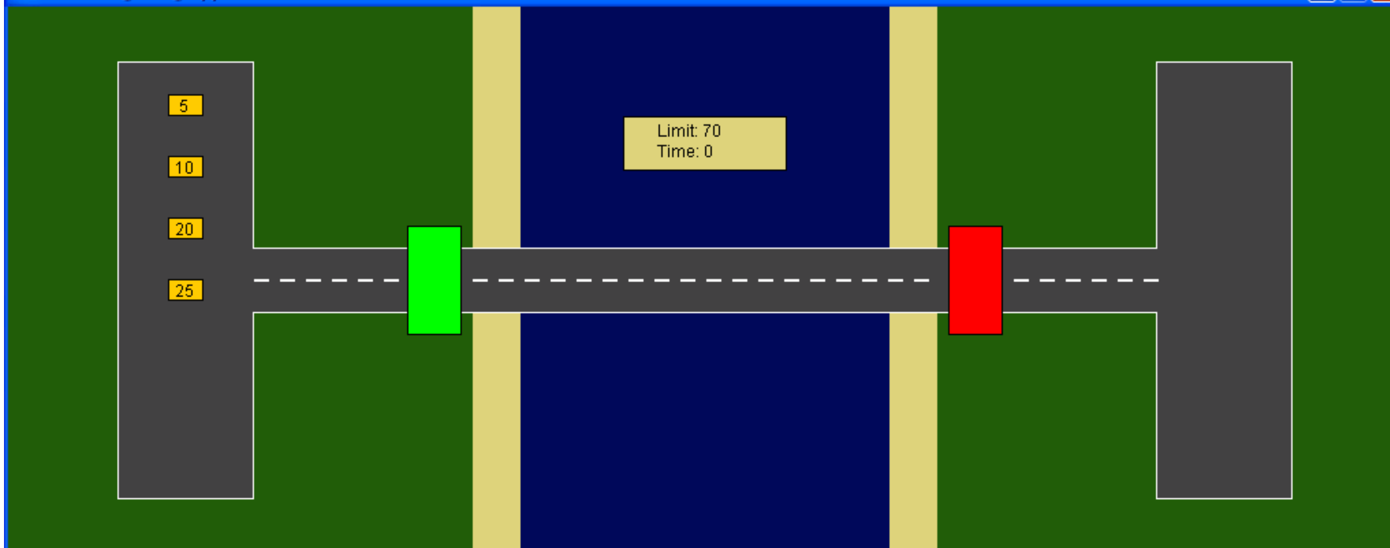


SAFE

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

Let us play!

Scheduling using Uppaal



Configure | Interact | Find some solution | Find best solution

Solving scheduling problems using Uppaal

A number of cars are to pass a bridge. There is a toll for passing the bridge -- and a device (known as the 'BroBizz' or 'EasyPass') must be used in order to pass the bridge.

There is only one BroBizz available to the cars -- but luckily the toll booth system can be *cheated* if two cars drive close to each other. Only cars from the side at which BroBizz is located can pass the bridge. The toll booth at the side at which the BroBizz is located is colored green.

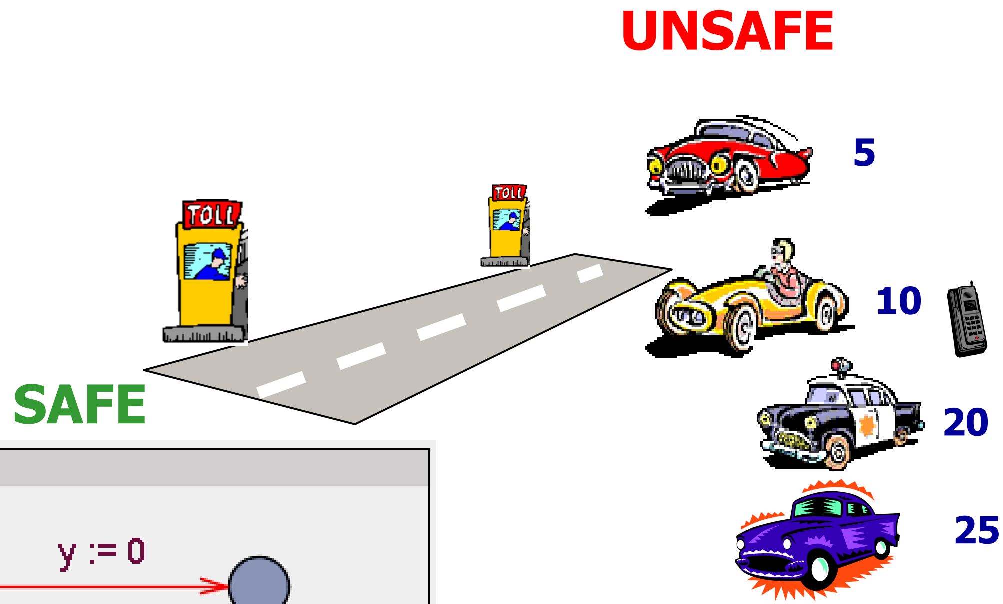
All cars must pass the bridge within a given time limit (shown at the center of the screen). Each car spends a given number of minutes passing the bridge. This *schedulability* problem can be solved using the Uppaal tool.

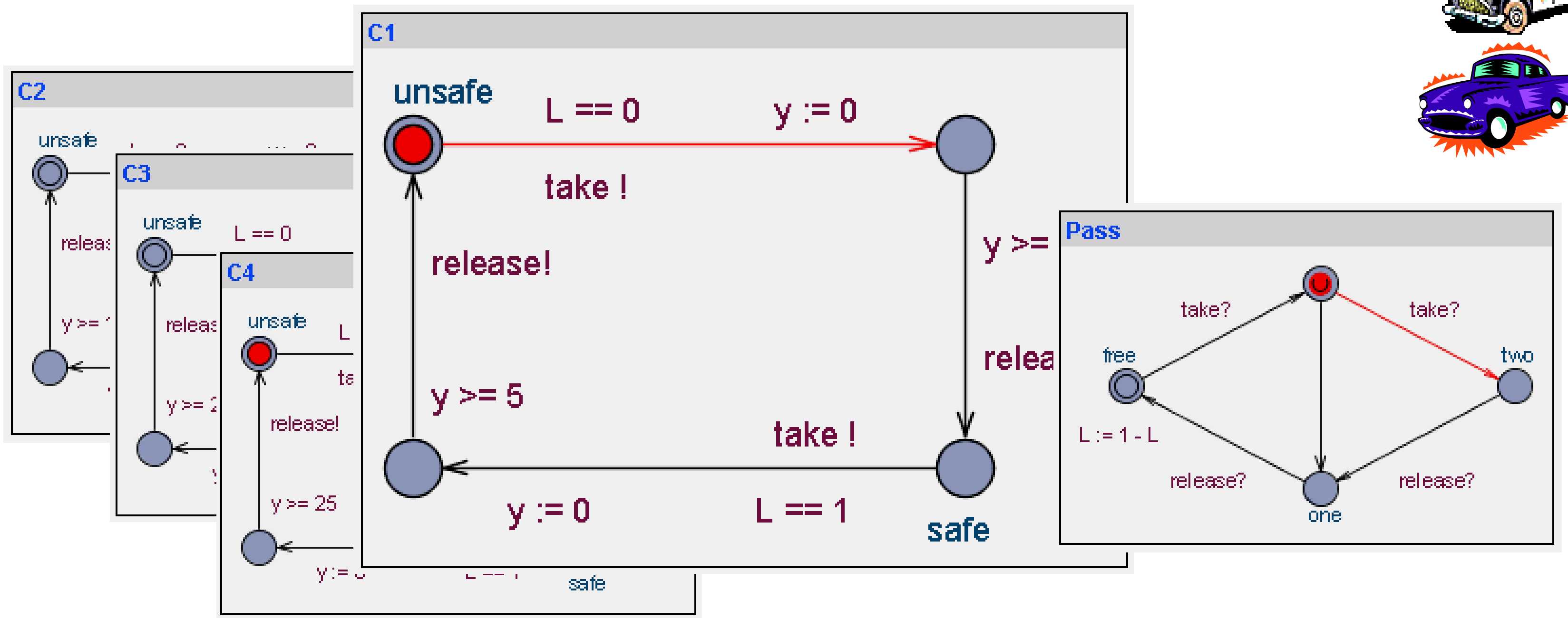
Using the buttons above you can:

- **Configure:**
  Setup the number of cars, their speed, and the time limit
- **Interact:**
  Try to solve the problem manually
- **Find some solution:**
  Use Uppaal to solve the problem and display the solution
- **Find best solution:**
  Use Uppaal to find the best solution to the problem

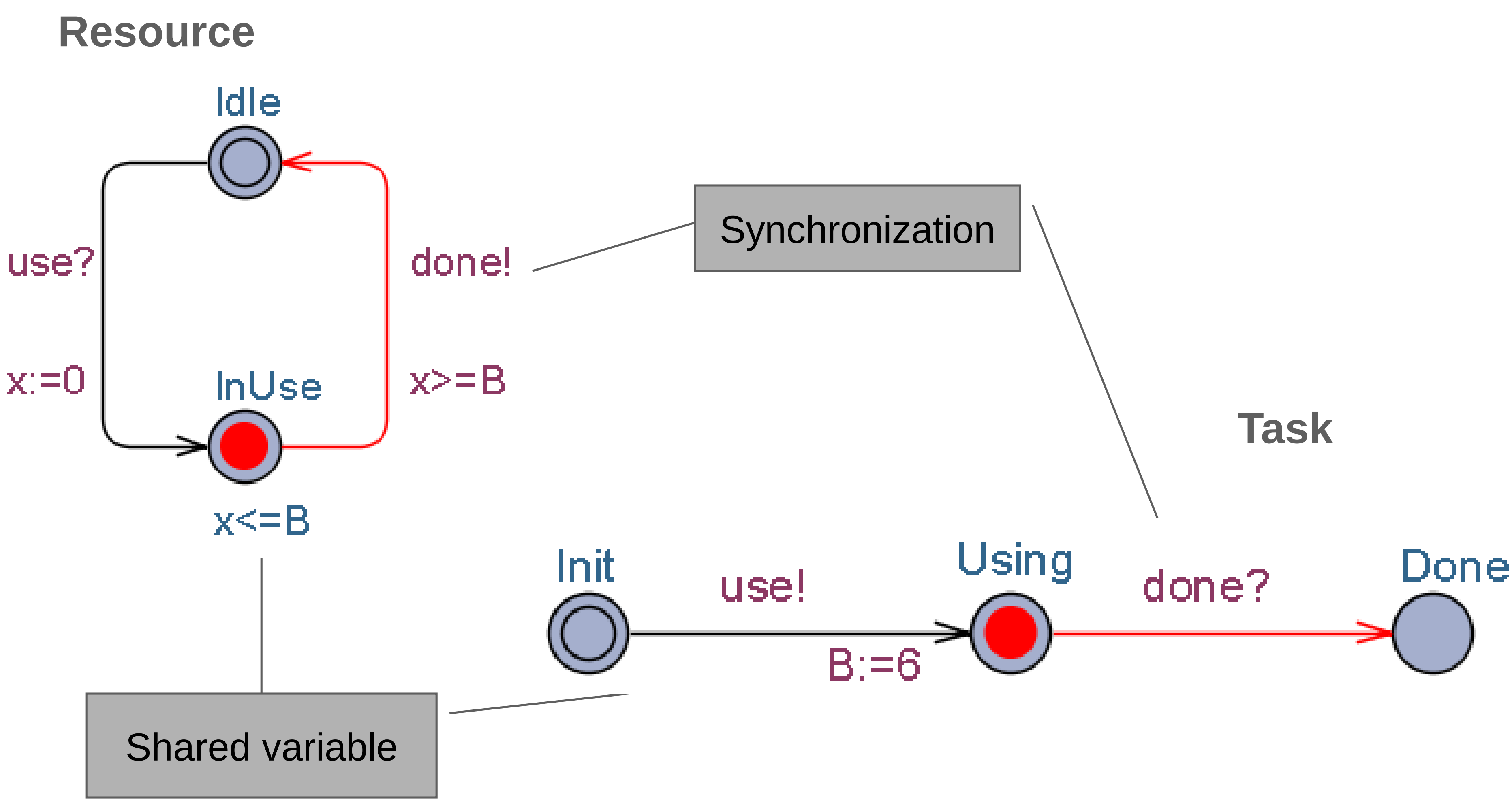
Real Time Scheduling

Solve Scheduling Problem using UPPAAL

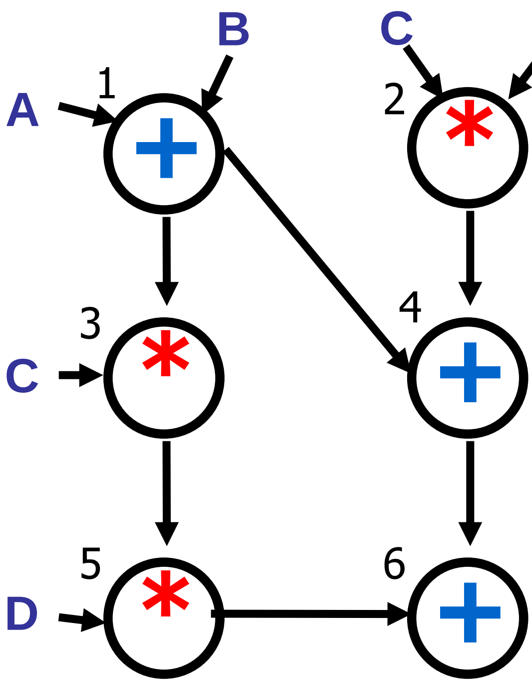




Resources & Tasks



Task Graph Scheduling – Example



Compute :

(D * (C * (A + B)) + ((A + B) + (C * D))

4

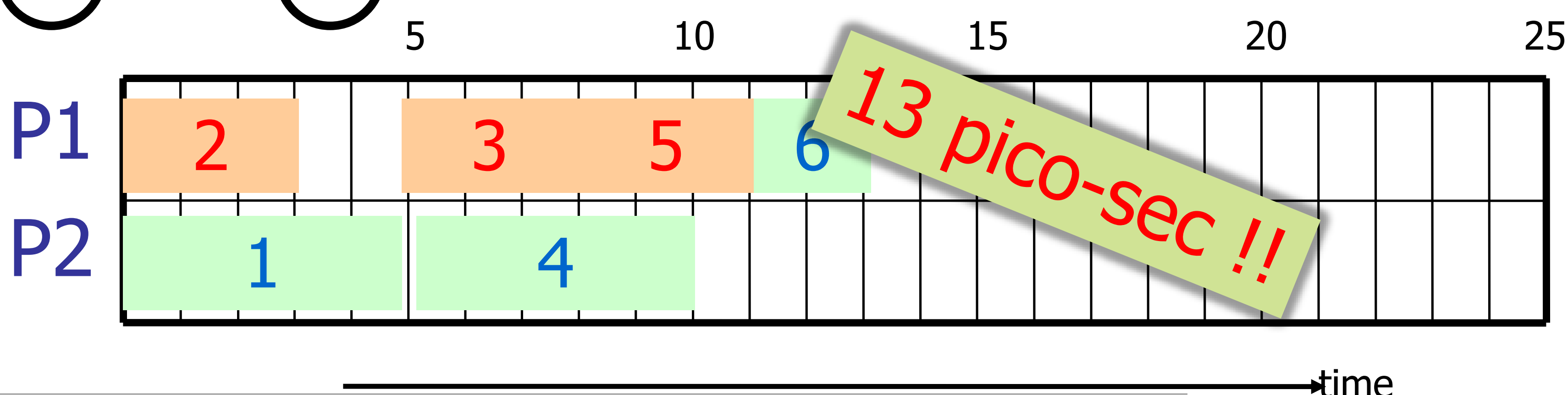
using 2 processors

P1 (fast)

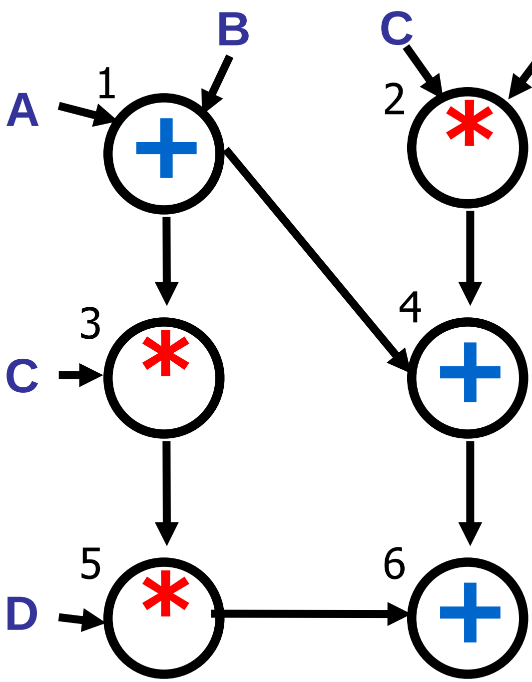
+	2ps
*	3ps

P2 (slow)

+	5ps
*	7ps



Task Graph Scheduling – Example



Compute :

(D * (C * (A + B)) + ((A + B) + (C * D))

using 2 processors

P1 (fast)

+	2ps
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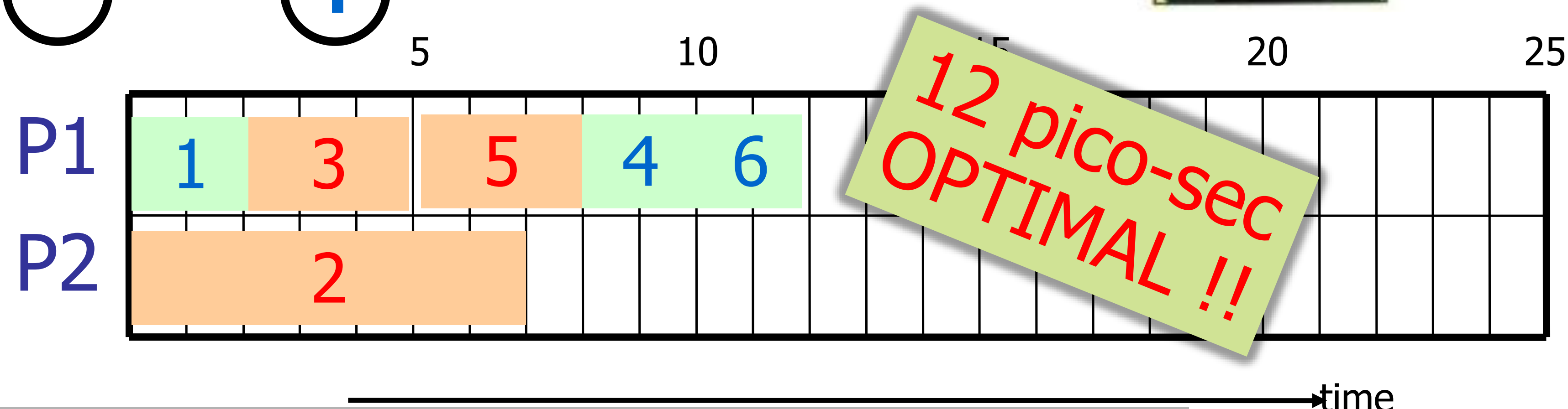
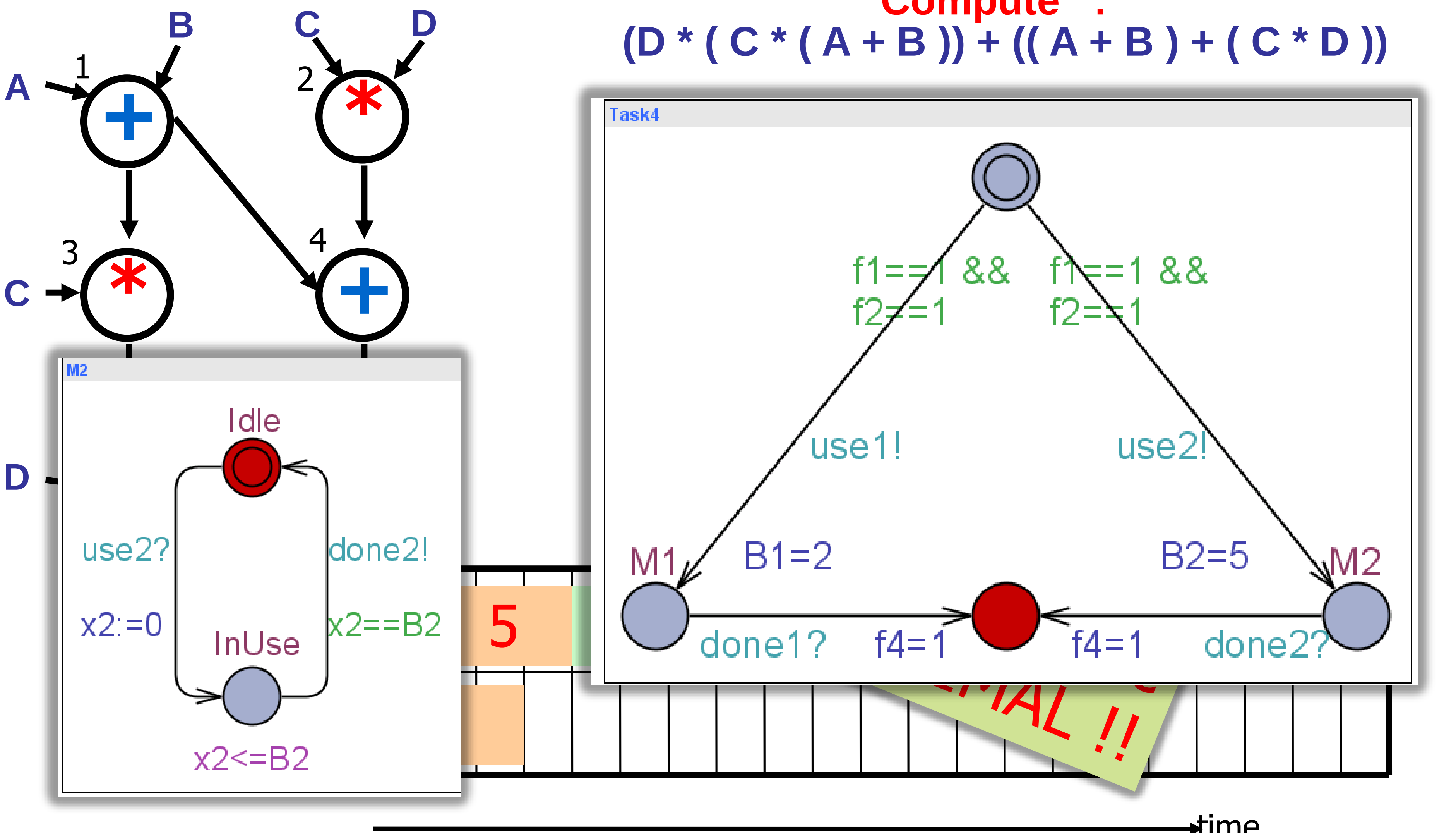


Task Graph Scheduling – Example

Compute :
(D * (C * (A + B)) + ((A + B) + (C * D))

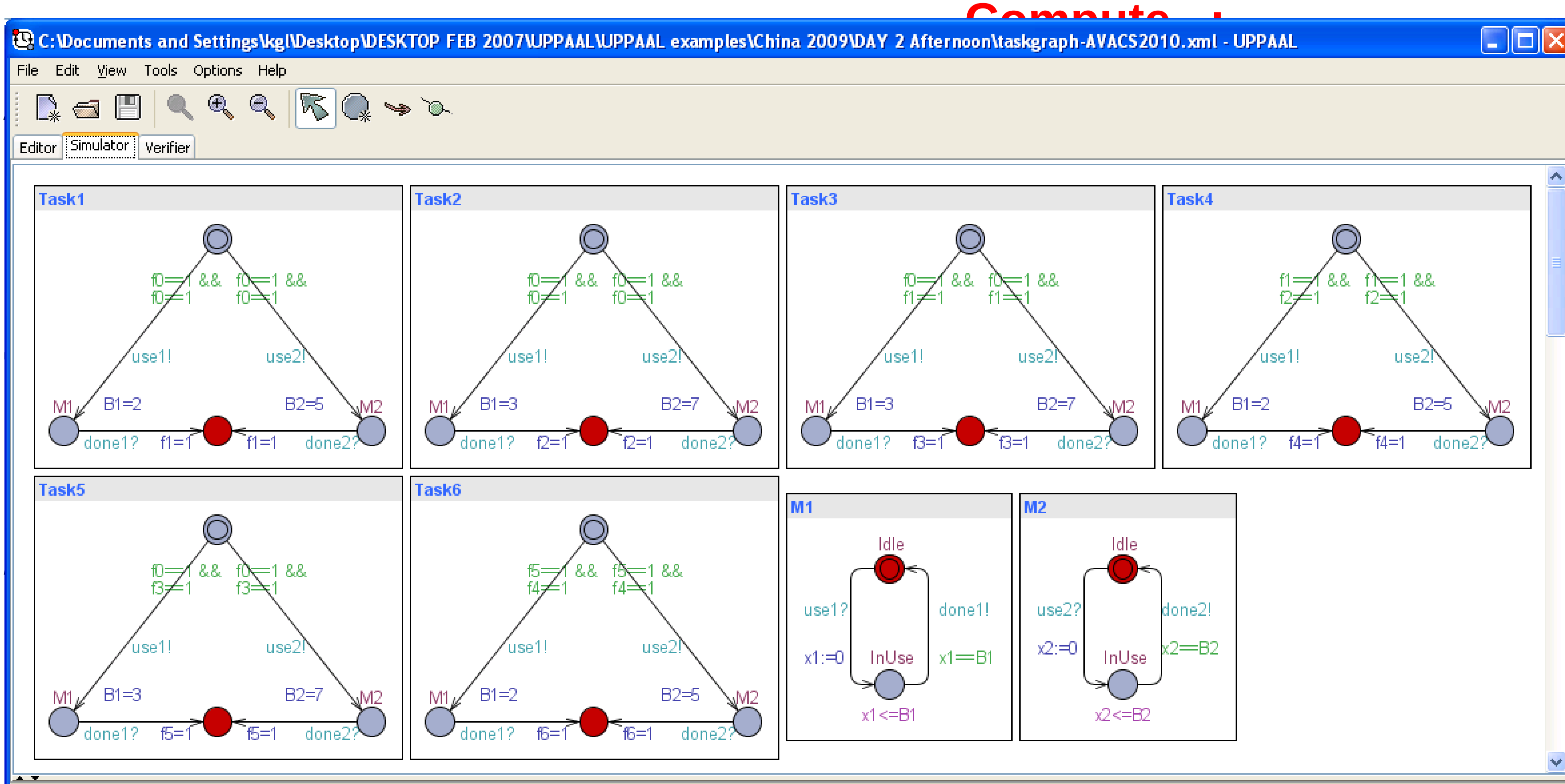


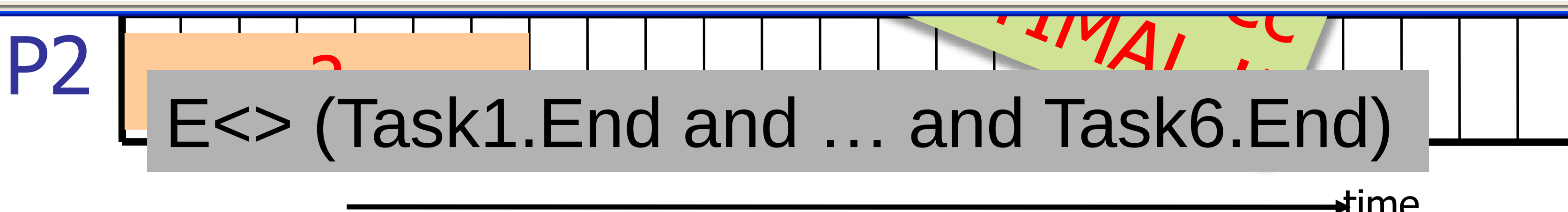
Task Graph Scheduling – Example

A

C

D





E<> (Task1.End and … and Task6.End)

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

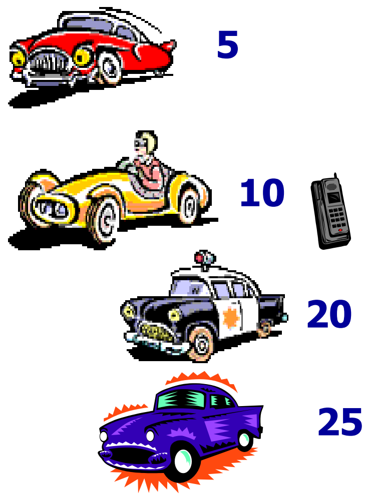
AMETIST
advanced methods for timed systems

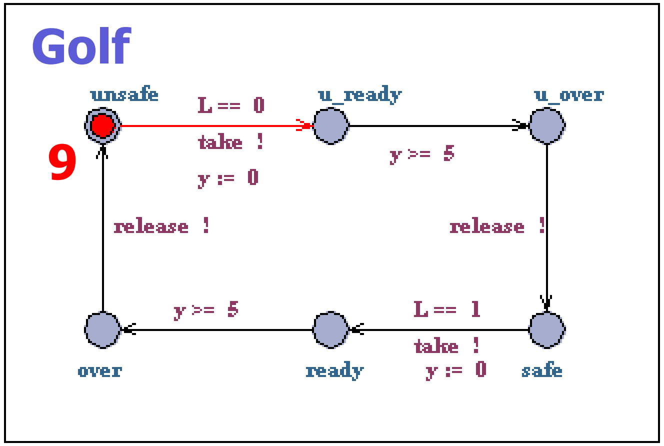
Symbolic A*
Branch-&-Bound
60 sec

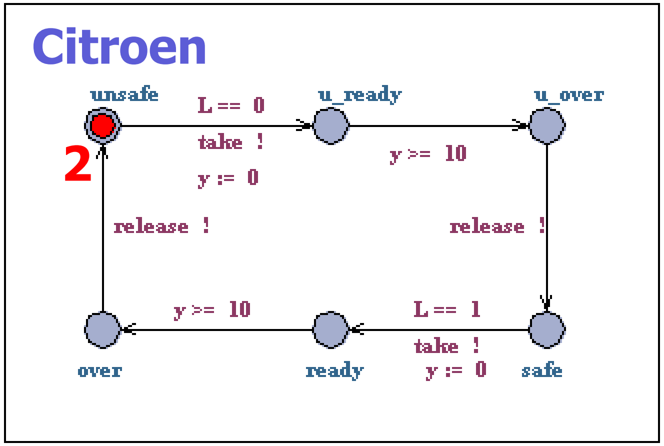
Abdeddaïm, Kerbaa, Maler

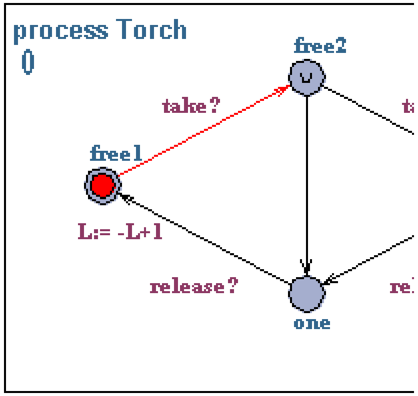
Priced Timed Automata

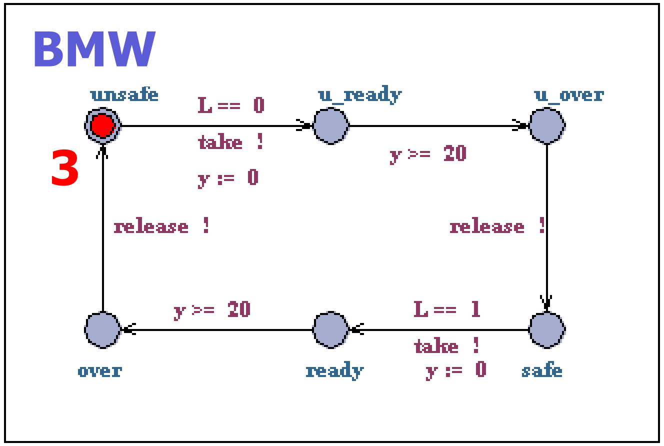
EXAMPLE: Optimal rescue plan for cars with different subscription rates for city driving !

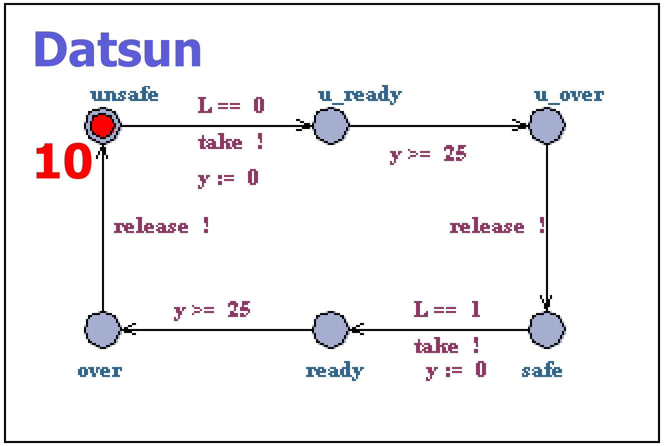










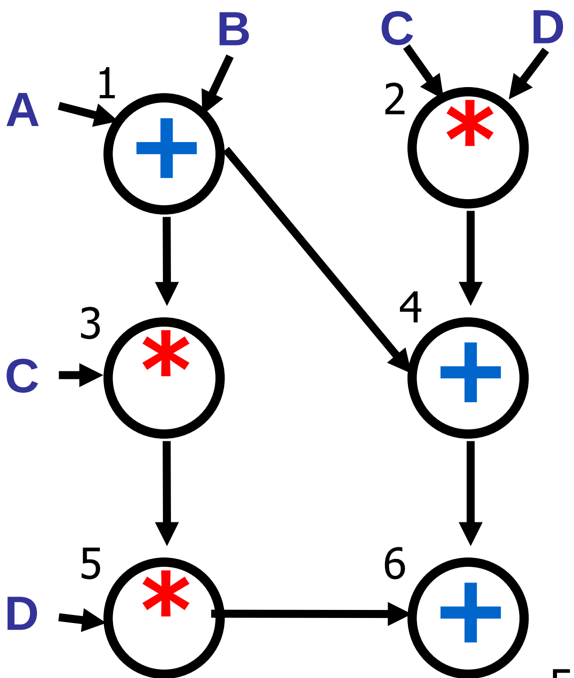


OPTIMAL PLAN HAS ACCUMULATED COST=195 and TOTAL TIME=65!

Experiments

COST-rates				SCHEDULE	COST	TIME	#Expl	#Pop'd
G	C	B	D					
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

Task Graph Scheduling – Revisited



Compute :

(D * (C * (A + B)) + ((A + B) + (C * D))

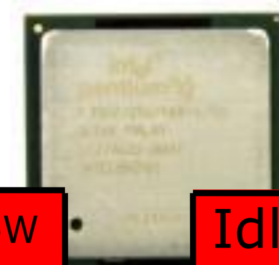
using 2 processors

P1 (fast)

+	2ps
*	3ps

Idle	10W
In use	90W

P2 (slow)



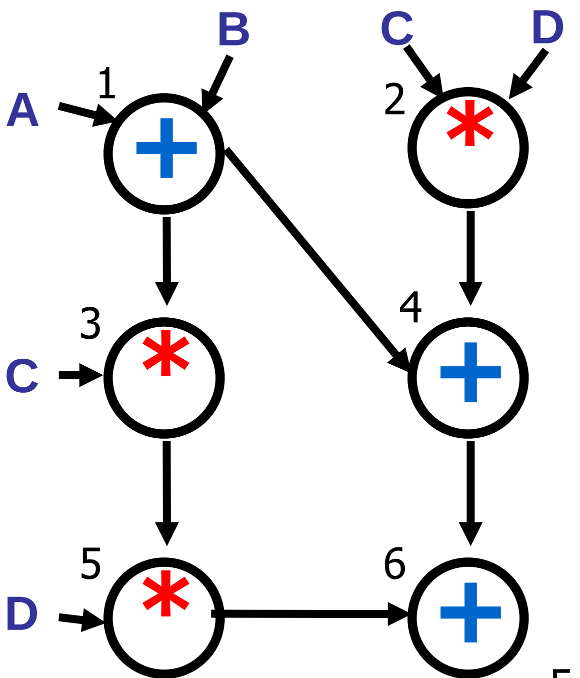
+	5ps
*	7ps

Idle	20W
In use	30W

ENERGY:

Energy:
1.39 nano-joule !!

Task Graph Scheduling – Revisited



Compute :

(D * (C * (A + B)) + ((A + B) + (C * D))

using 2 processors

P1 (fast)

+	2ps
*	3ps

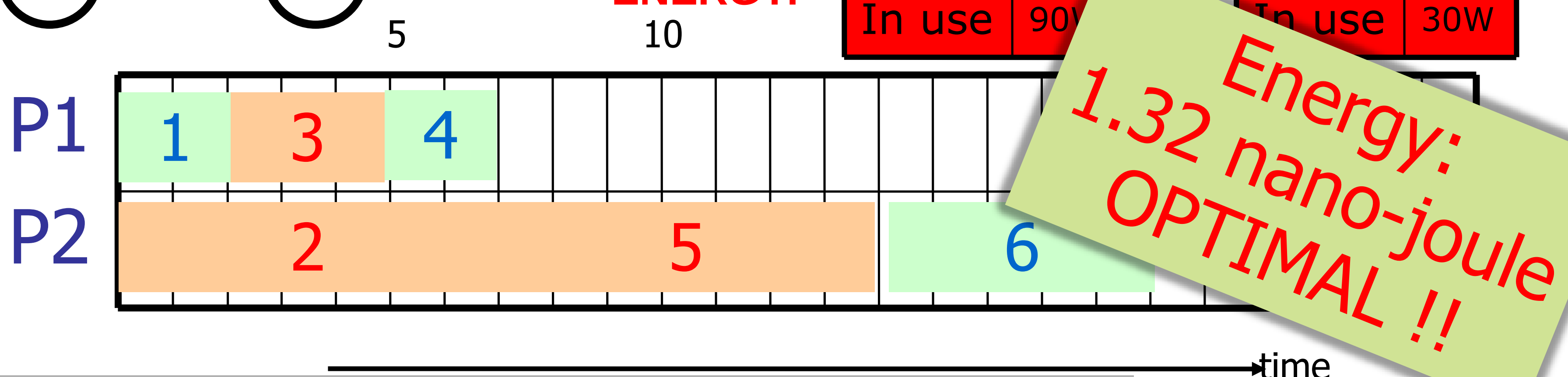
Idle	10W
In use	90W

P2 (slow)

+	5ps
*	7ps

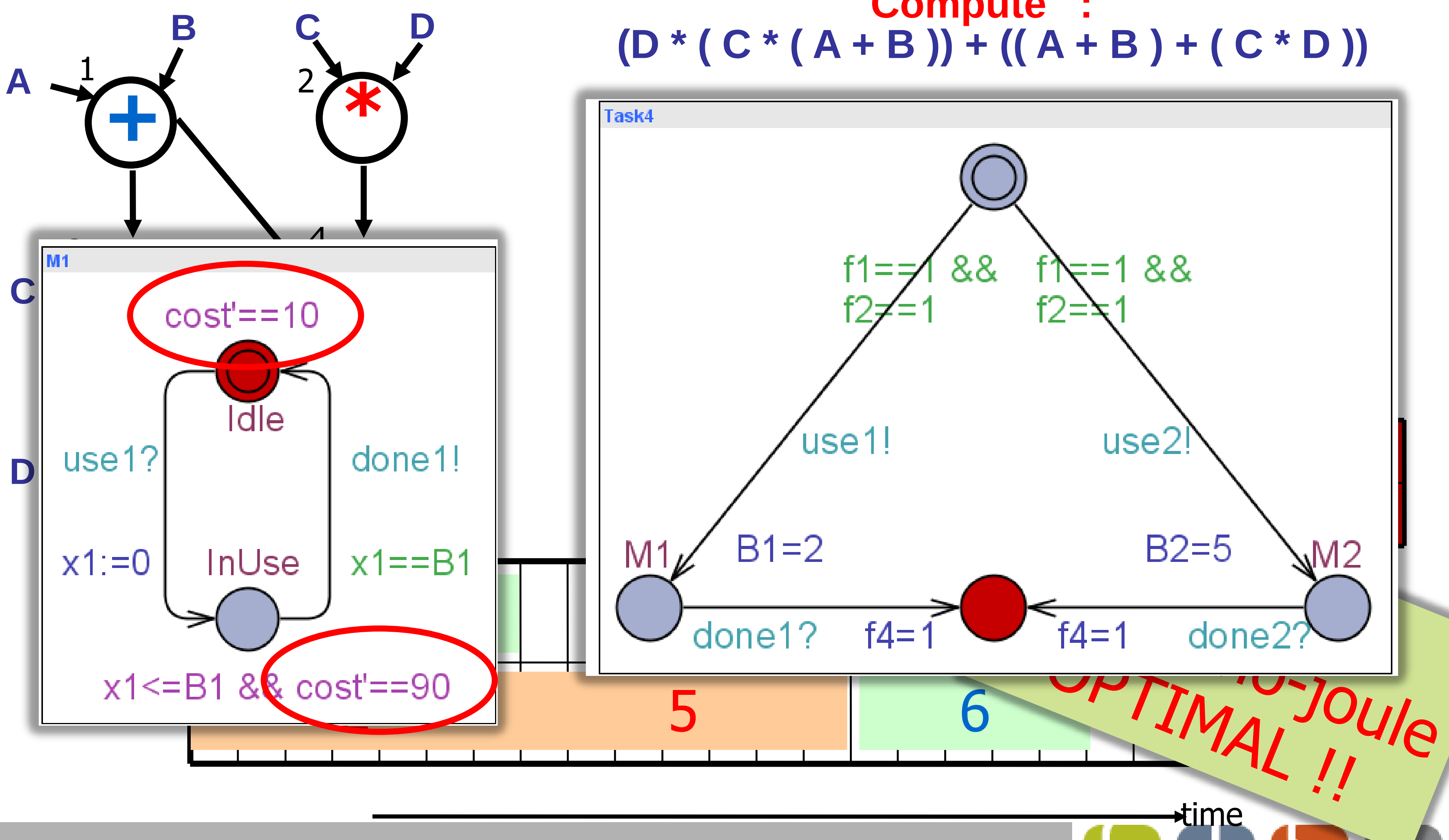
Idle	20W
In use	30W

ENERGY:



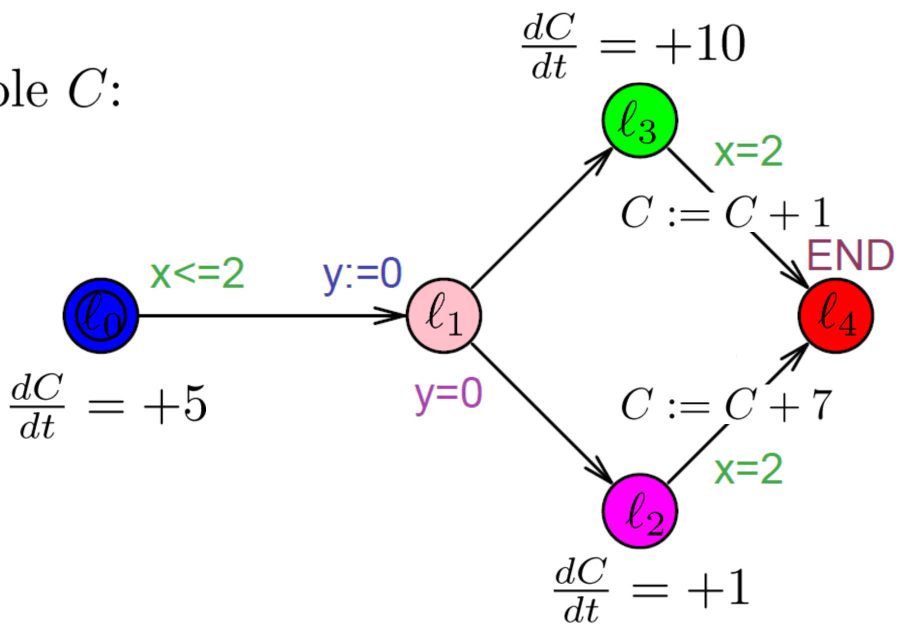
Task Graph Scheduling – Revisited

Compute :
(D * (C * (A + B)) + ((A + B) + (C * D))



A simple example

Observer variable C:



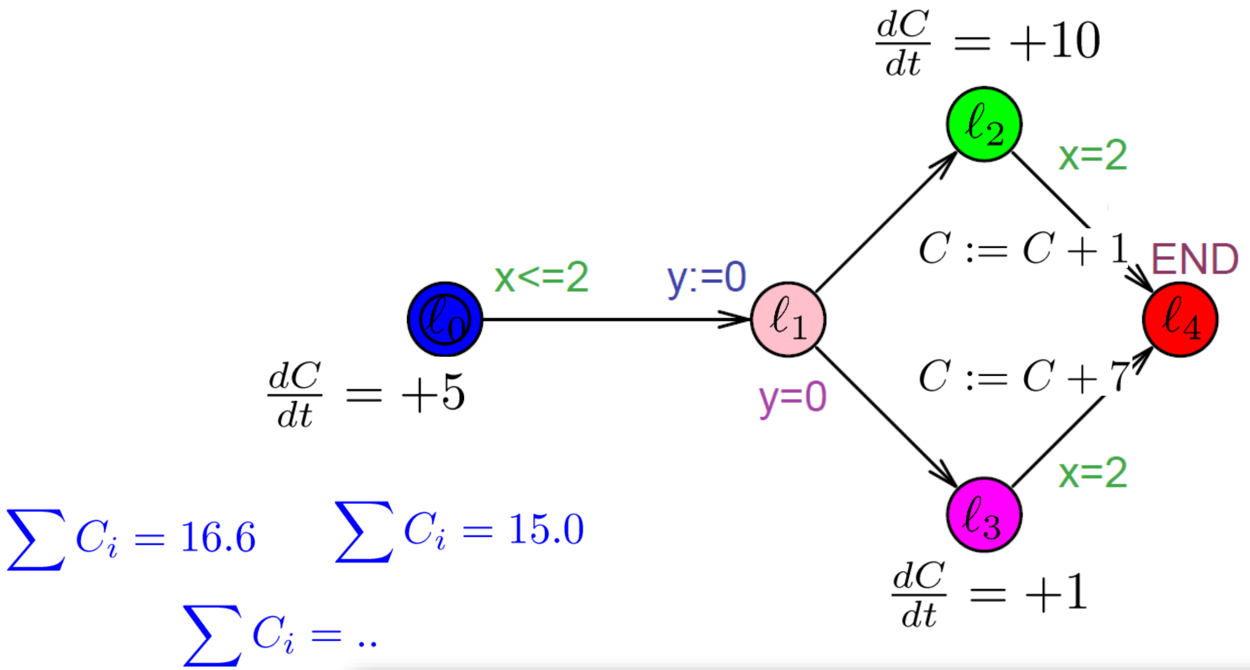
$$(\ell_0, [0,0]) \xrightarrow{1.9}_{9.5} (\ell_0, [1.9, 1.9]) \rightarrow_0 (\ell_1, [1.9, 0]) \rightarrow_0 (\ell_2, [1.9, 0]) \xrightarrow{0.1}_{0.1} (\ell_2, [2, 0.1]) \rightarrow_7 (\ell_4, [2, 0.1])$$

$$\sum C_i = 16.6$$

$$(\ell_0, [0,0]) \xrightarrow{1.2}_{6.0} (\ell_0, [1.2, 1.2]) \rightarrow_0 (\ell_1, [1.2, 0]) \rightarrow_0 (\ell_3, [1.2, 0]) \xrightarrow{0.8}_{8.0} (\ell_3, [2, 0.8]) \rightarrow_1 (\ell_4, [2, 0.8])$$

$$\sum C_i = 15.0$$

A simple example

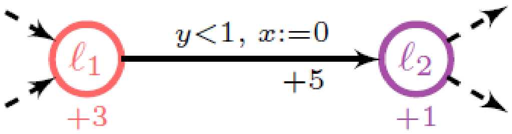


Q: What is cheapest cost for reaching ℓ_4 ?

$$\inf_{0 \le t \le 2} \min\{5t + 10(2-t) + 1, 5t + (2-t) + 4\} = 9$$

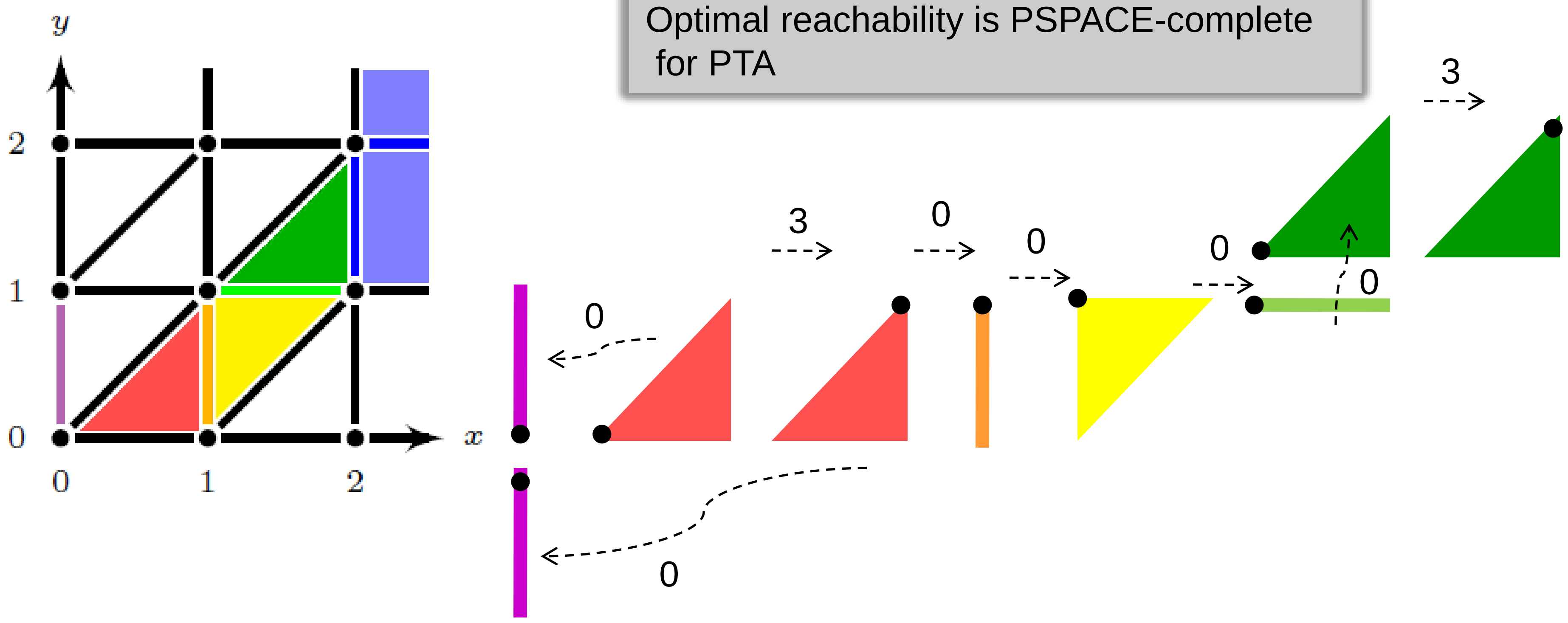
➜ **strategy:** leave immediately ℓ_0, go to ℓ_3, and wait there 2 t.u.

Corner Point Regions

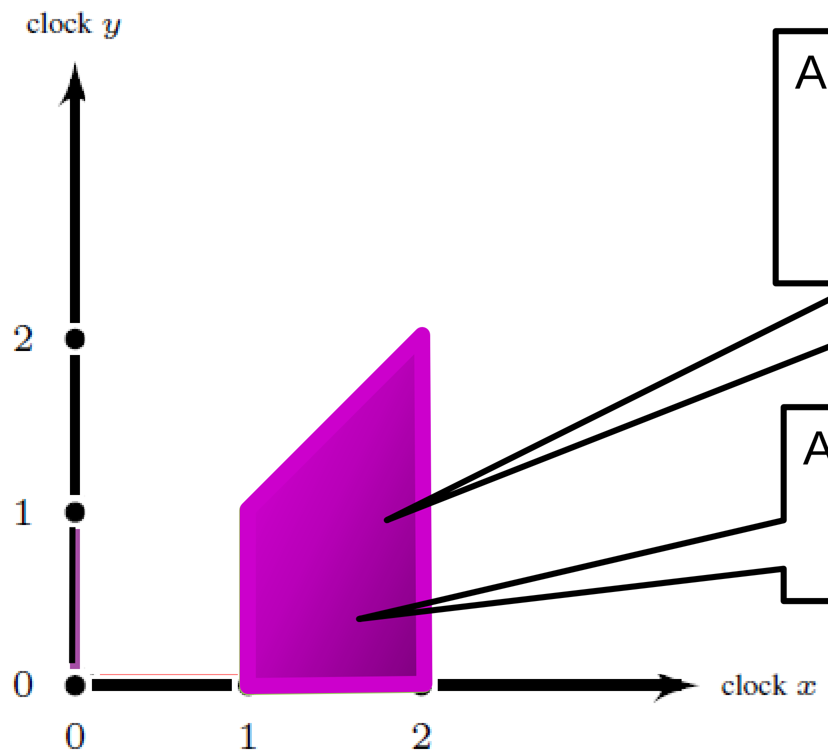


THM [Behrmann, Fehnker ..01] [Alur,Torre,Pappas 01]
Optimal reachability is decidable for PTA

THM [Bouyer, Brojaue, Briuere, Raskin 07]
Optimal reachability is PSPACE-complete
for PTA



Priced Zones [CAV01]



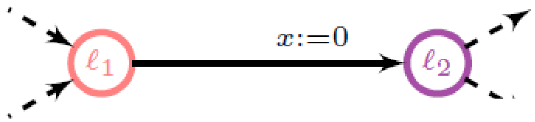
A zone **Z**:

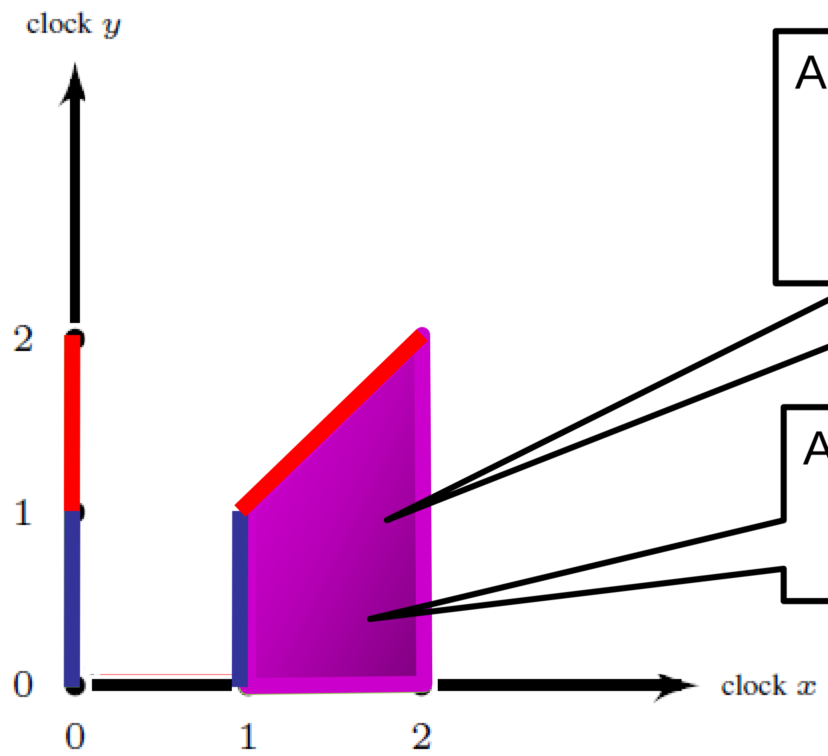
$1 \leq x \leq 2 \quad \wedge$
$0 \leq y \leq 2 \quad \wedge$
$x - y \geq 0$

A cost function **C**

$C(x,y) =$
$2 \cdot x - 1 \cdot y + 3$

Priced Zones – Reset [CAV01]





Z[x=0]:
$x=0 \wedge$
$0 \leq y \leq 2$

C = $1{\cdot}y + 3$

C= $-1{\cdot}y + 5$

A zone **Z**:
$1 \leq x \leq 2 \wedge$
$0 \leq y \leq 2 \wedge$
$x - y \geq 0$

A cost function **C**
$C(x,y) =$
$2{\cdot}x - 1{\cdot}y + 3$

Symbolic 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$_{(l,Z)} \geq$ Co

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

    add (l, Z) to Passed

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

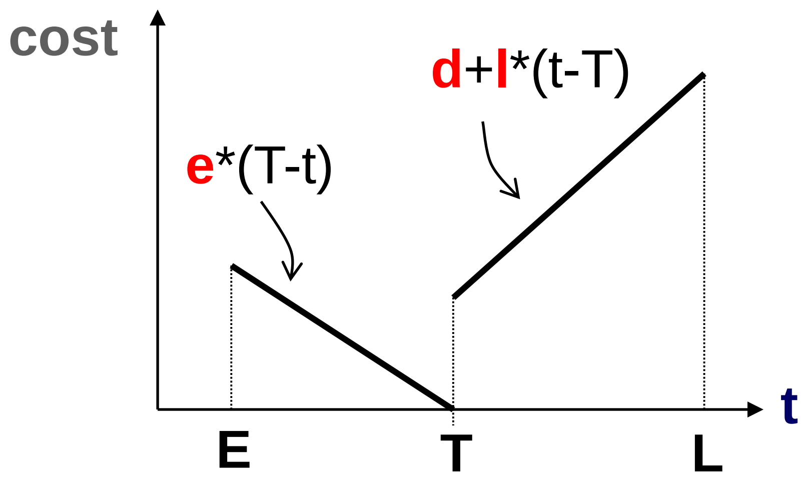
return Cost

$Z' \leq Z$

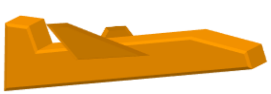
Z′ **is bigger & cheaper than *Z***

$\leq$ is a well-quasi ordering which guarantees termination!

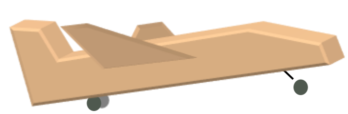
Example: Aircraft Landing



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

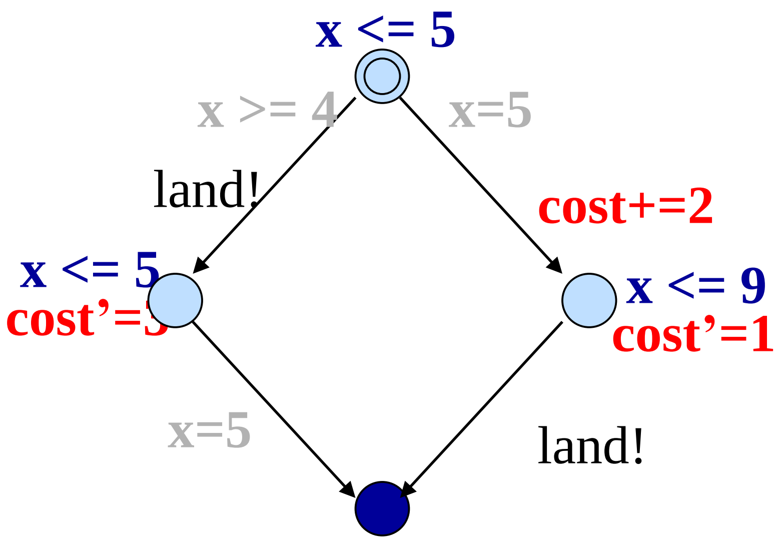


Planes have to keep separation distance to avoid turbulences caused by preceding planes

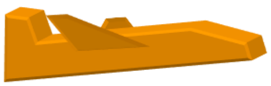


Runway

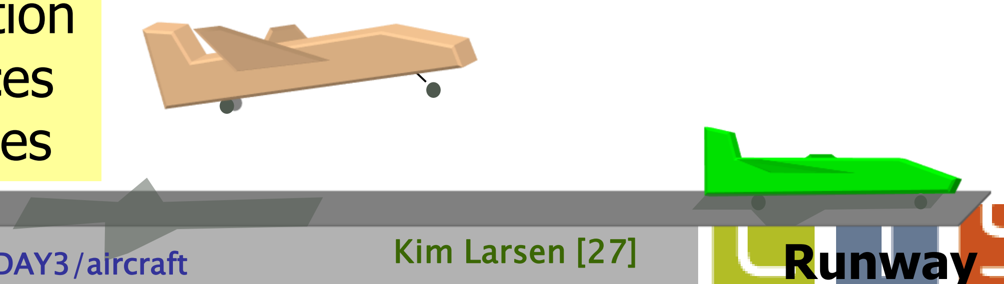
Example: Aircraft Landing



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

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		

Symbolic 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

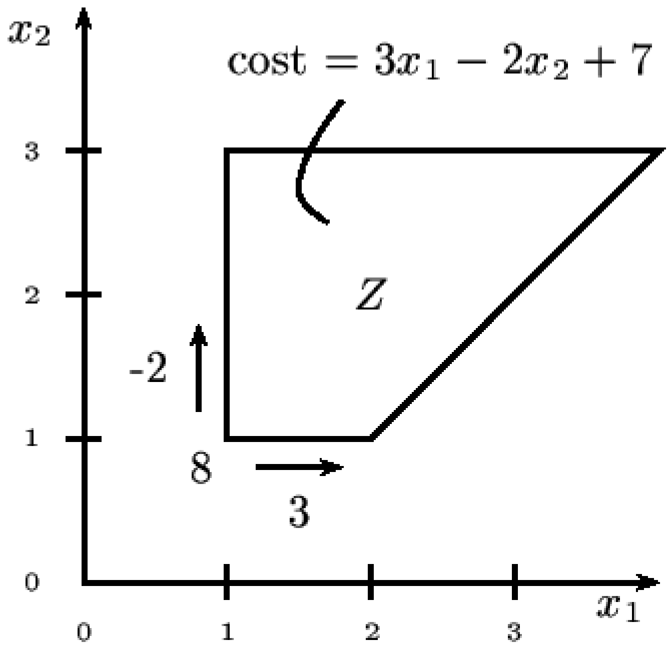
        add all (l', Z') with $(l, Z) \rightarrow (l', Z')$ to Waiting

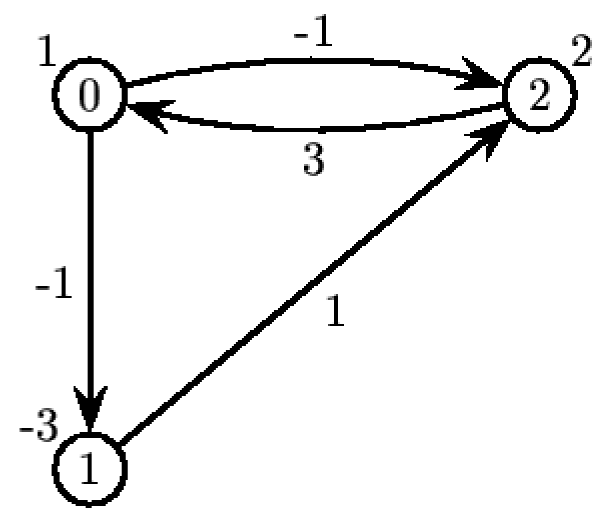
return Cost

Zone based
Linear Programming Problems
→(dualize)
Min Cost Flow

Zone LP → Min Cost Flow

Exploiting duality



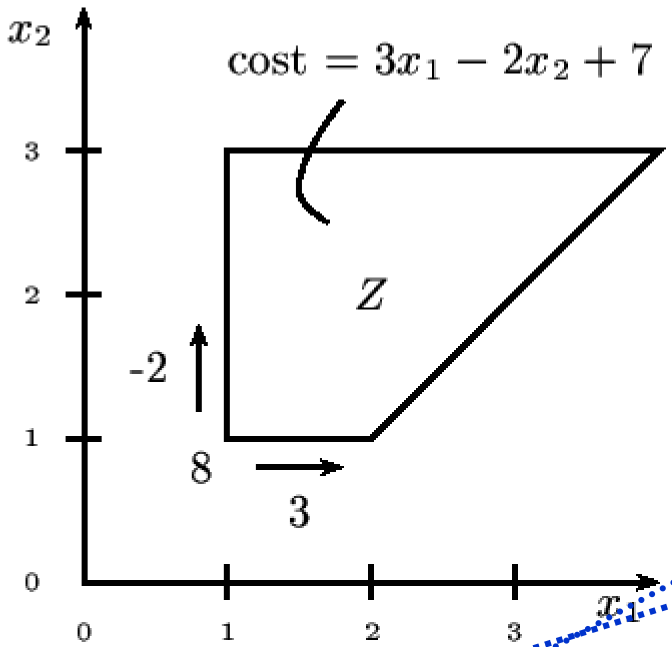


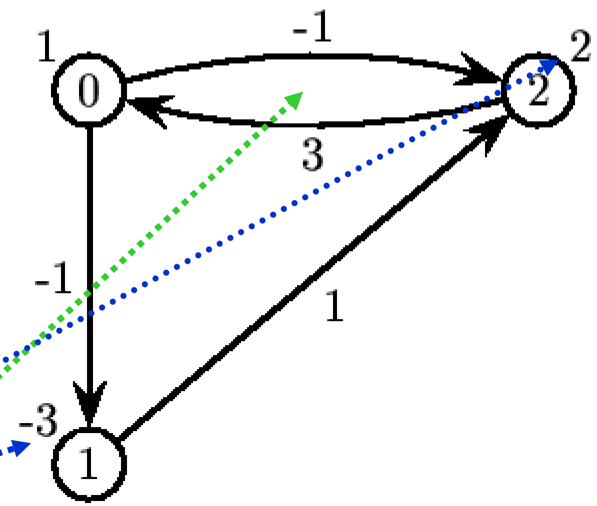
minimize $\mathbf{3x_1 - 2x_2 + 7}$
when $x_1 - x_2 \leq 1$
$1 \leq x_2 \leq 3$
$x_2 \geq 1$

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

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 (revisited)

[TACAS04]

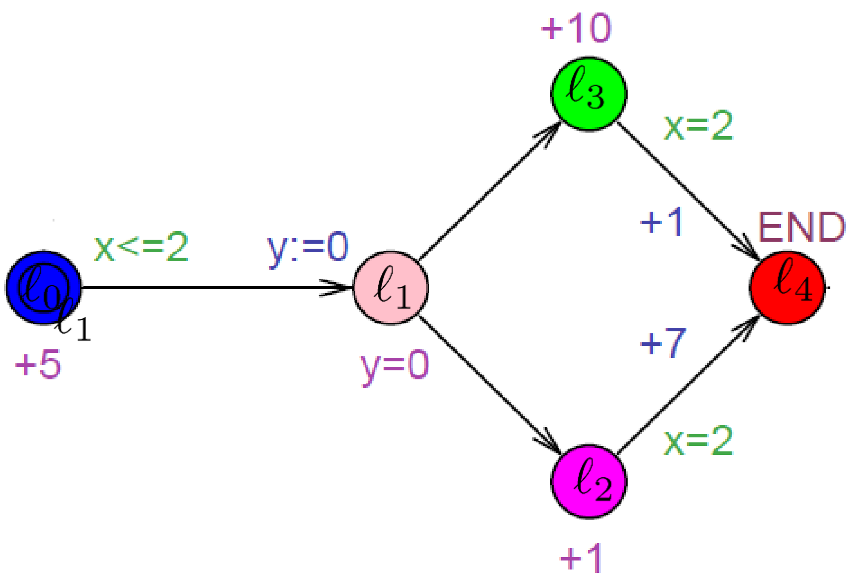
Using MCF/Netsimplex

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)

NOT IMPLEMENTED w ZONES

Optimal Schedule



$$(\ell_0,[0,0]) \xrightarrow{1.2}_{6.0} (\ell_0,[1.2,1.2]) \rightarrow_0 (\ell_1,[1.2,0]) \rightarrow_0$$

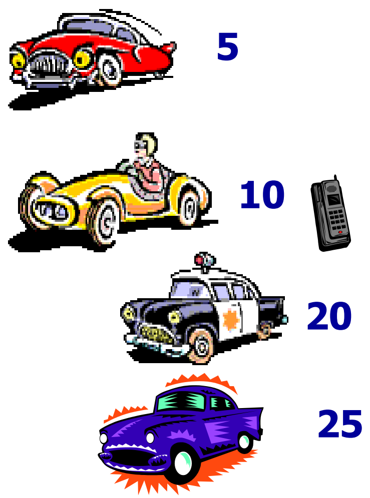
$$(\ell_3,[1.2,0]) \xrightarrow{0.8}_{8.0} (\ell_3,[2,0.8]) \rightarrow_1 (\ell_4,[2,0.8])$$

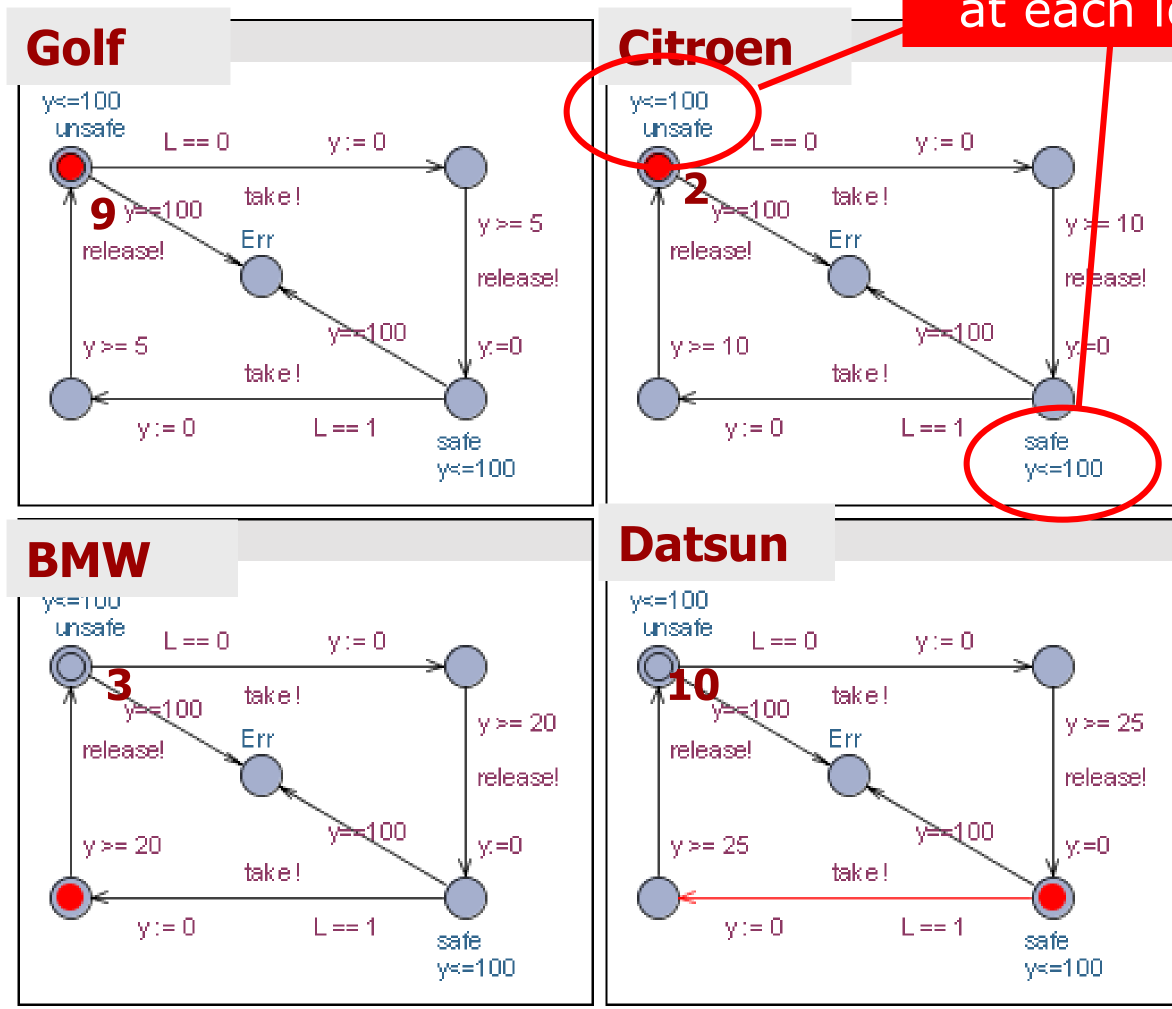
$$\rightarrow_{2.0} (\ell_0,[0,0])$$

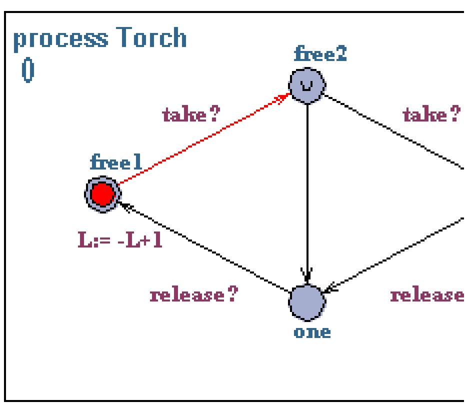
$$\boxed{\sum_i C_i / \sum_i t_i = 17/2 = 8.5}$$

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

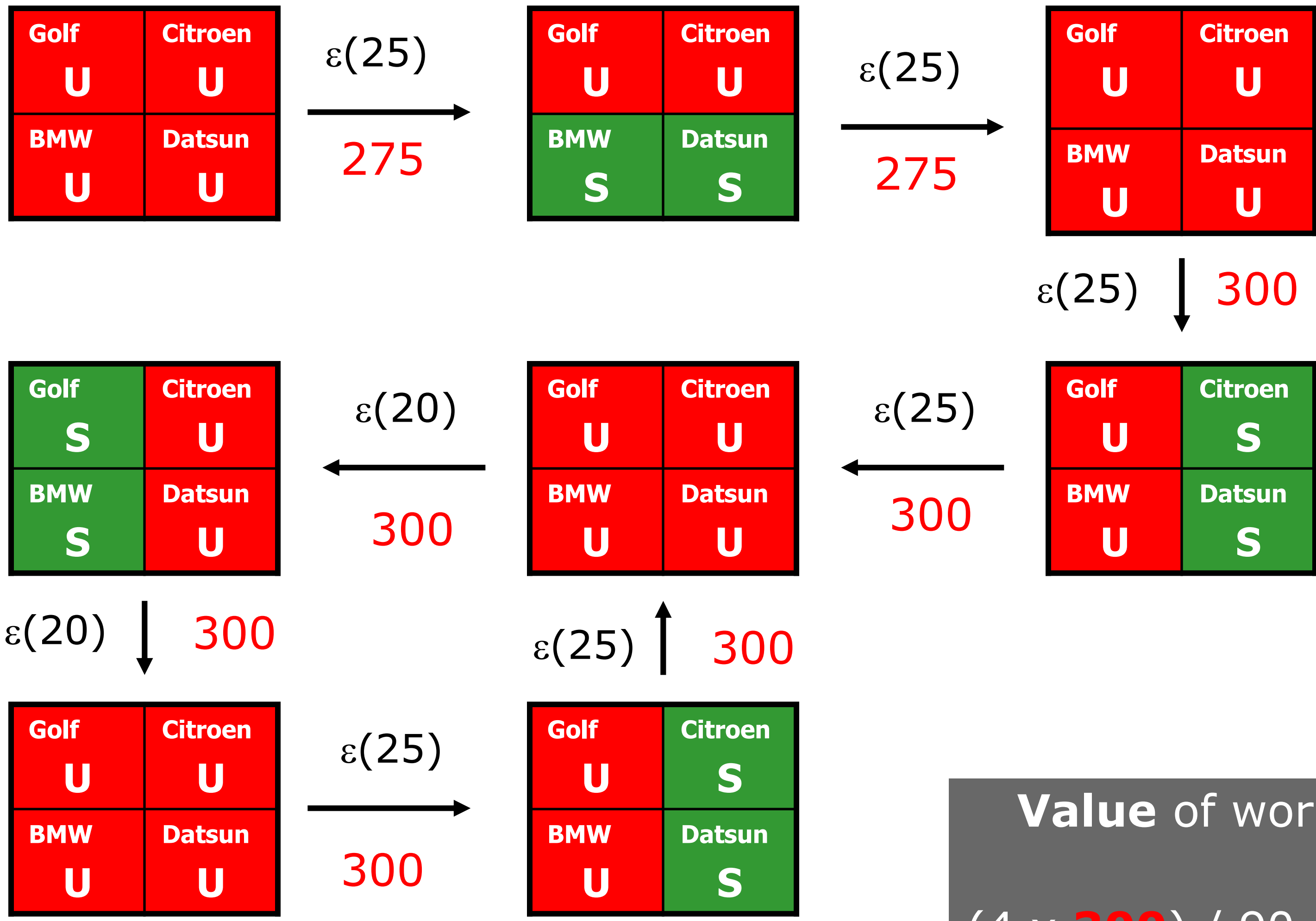
maximal 100 min. at each location







Workplan I

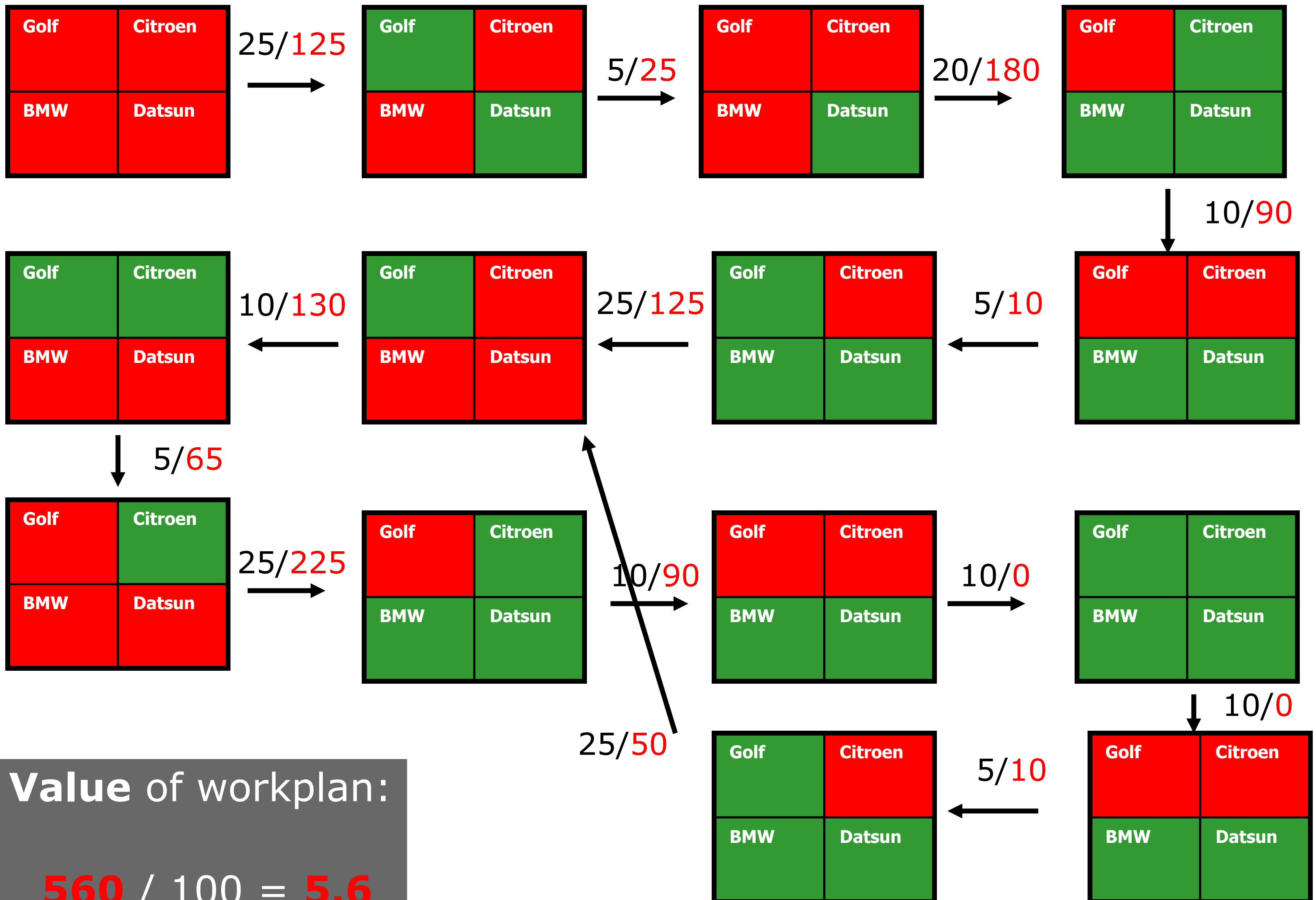


Value of workplan:

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

UCb

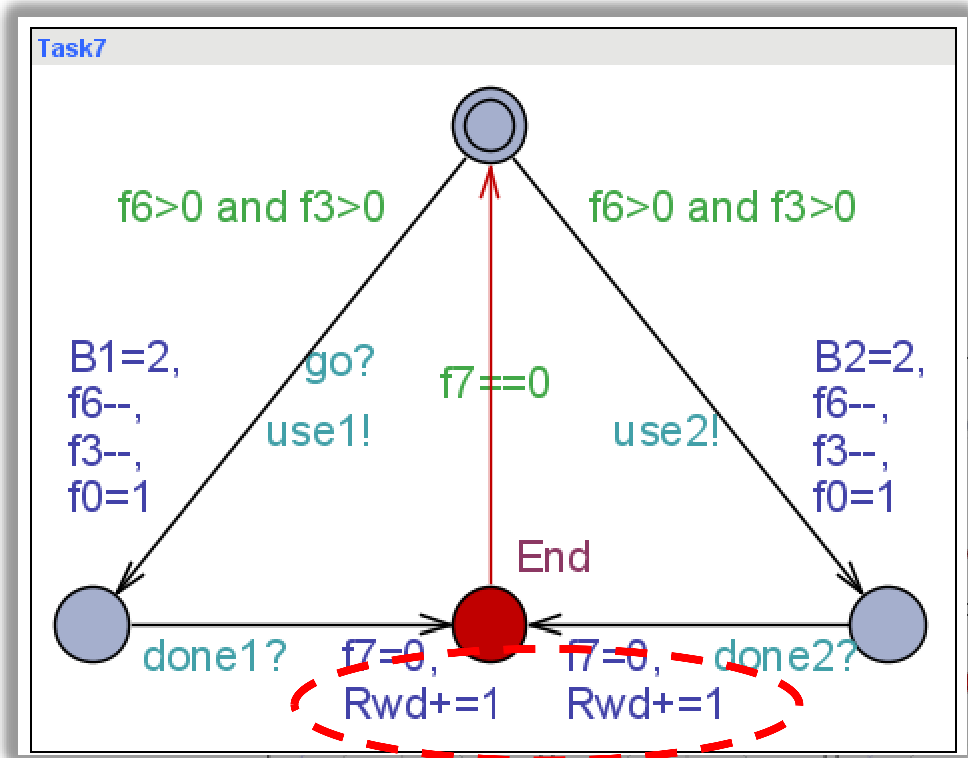
Workplan II

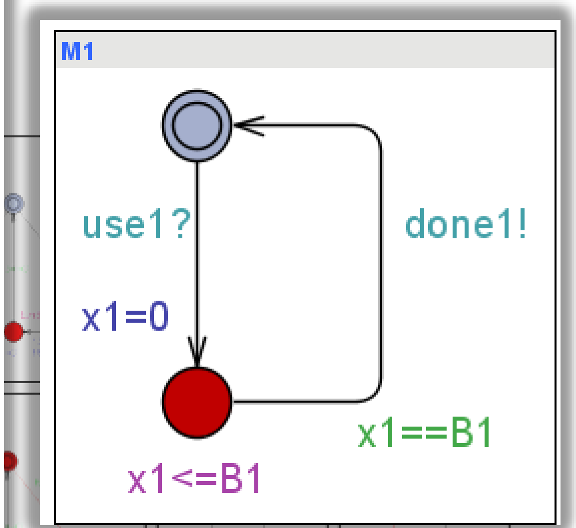


Value of workplan:

560 / 100 = **5.6**

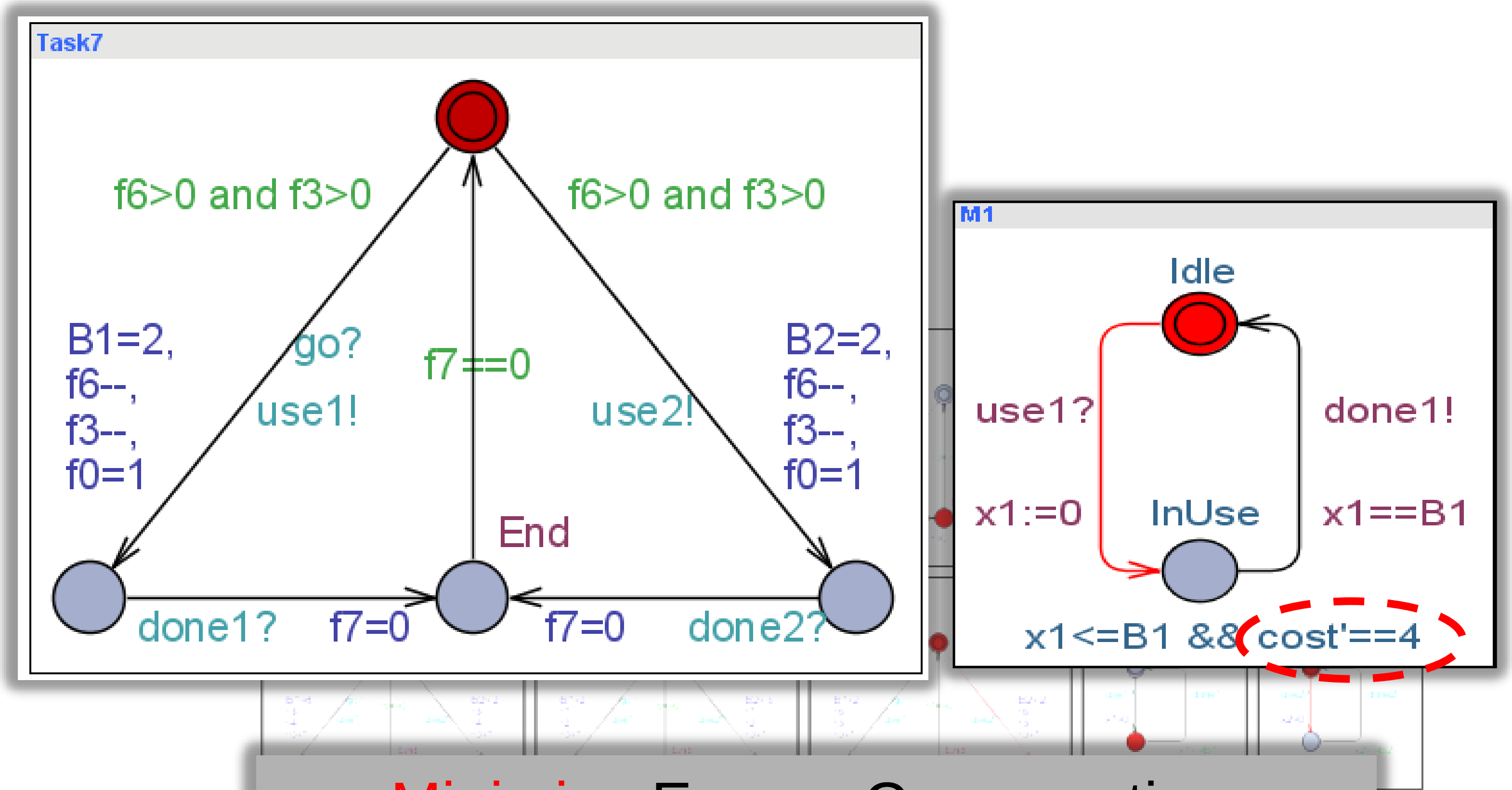
Optimal Infinite Scheduling





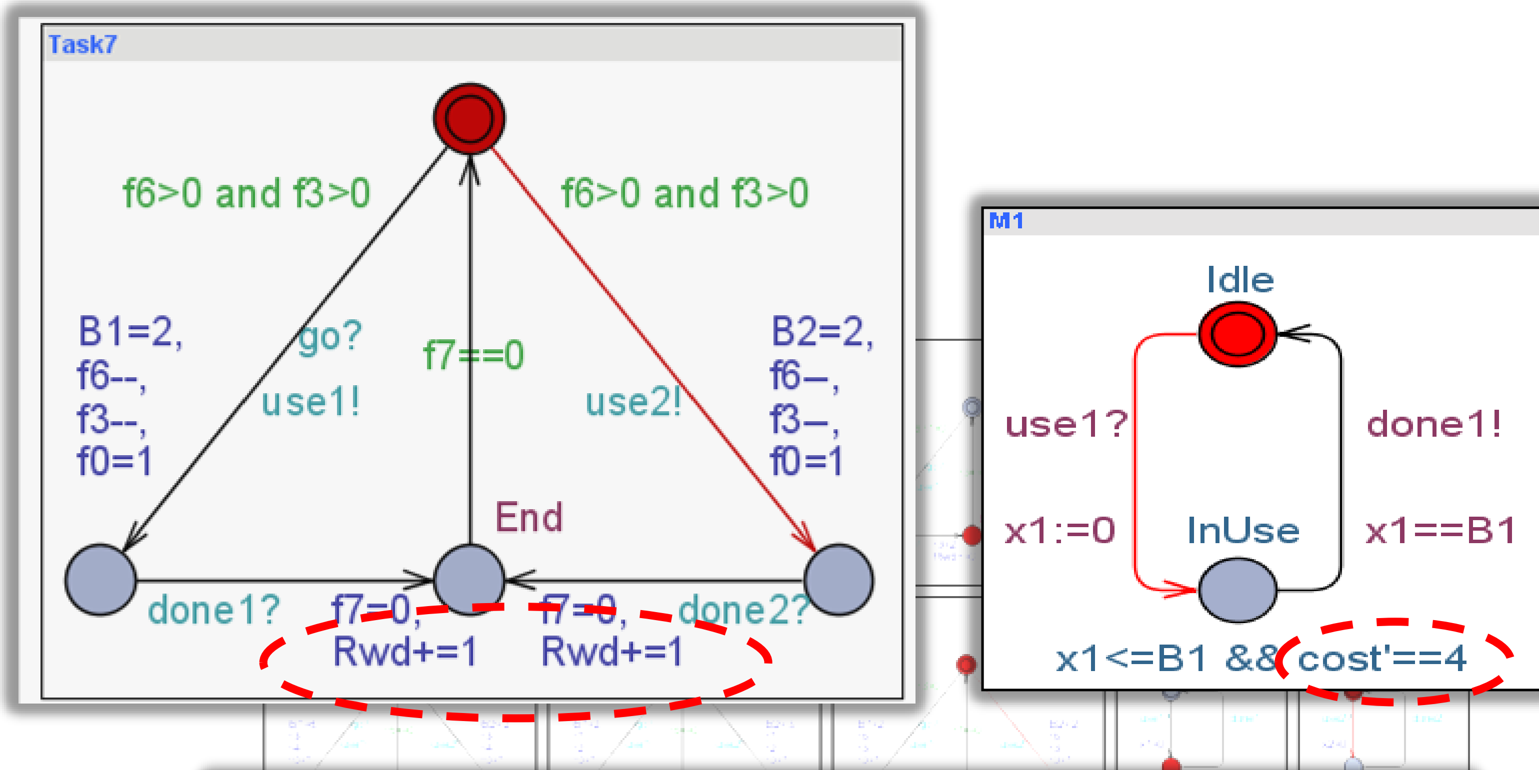
Maximize throughput:
i.e. maximize Reward / Time in the long run!

Optimal Infinite Scheduling



Minimize Energy Consumption:
i.e. minimize Cost / Time in the long run

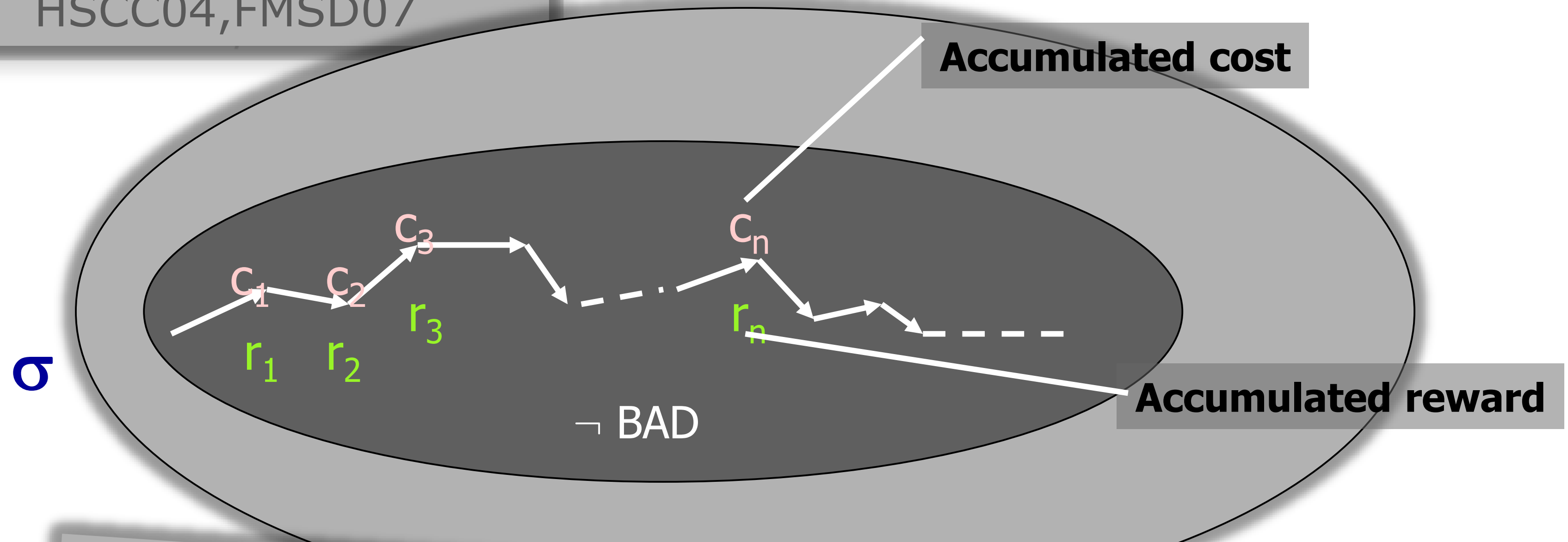
Optimal Infinite Scheduling



Maximize throughput:
i.e. maximize Reward / Cost in the long run

Mean Pay-Off Optimality

Bouyer, Brinksma, Larsen: HSCC04,FMSD07



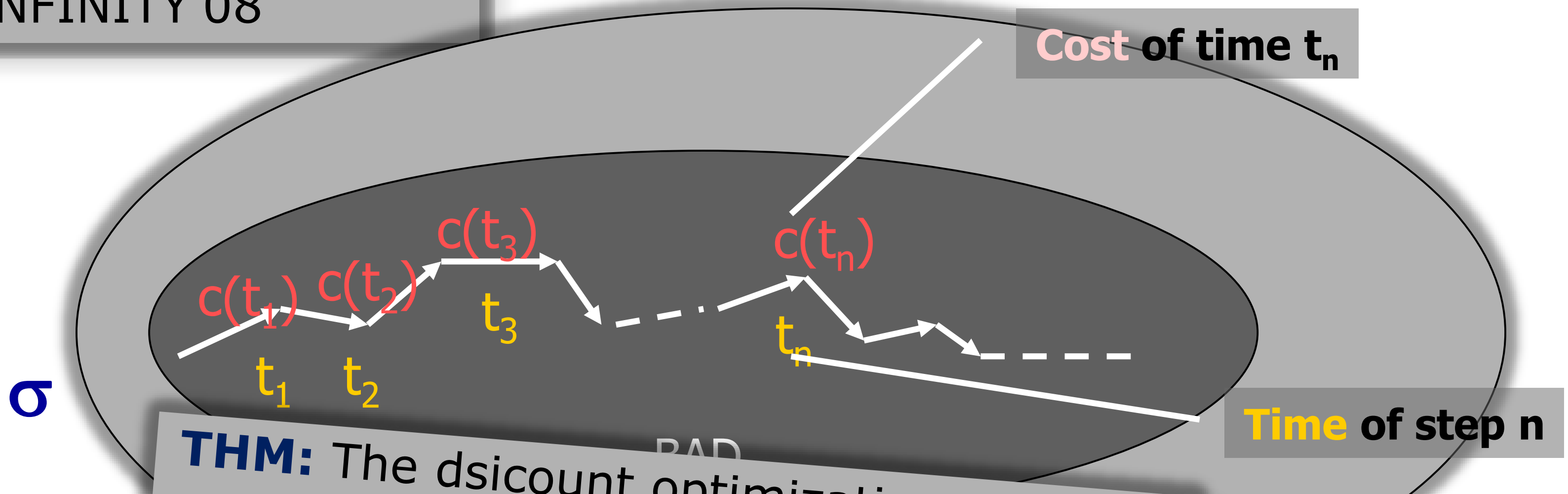
THM: The mean-pay off optimization problem is decidable (and PSPACE-complete) for PTA.
Corner Point Abstract Sound & Complete

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

Discount Optimality

$\lambda < 1$: discounting factor

Larsen, Fahrenberg:
INFINITY'08



THM: The dsicount optimization problem is decidable for PTA.
Corner Point Abstract Sound & Complete

Value of path σ: val(σ) = $\int_{t=0}^{t=\infty} c(t)\lambda^t dt$

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

Soundness of Corner Point Abstraction

Lemma
Let Z be a (bounded, closed) zone and let f be a(well-defined) function over Z defined by:

$$f : (t_1, \ldots, t_n) \mapsto \frac{a_1 t_1 + \cdots + a_n t_n + a}{c_1 t_1 + \cdots + c_n t_n + d}$$

then $\inf_Z f$ is obtained at a corner-point of Z (with integer coefficients).

Lemma
Let Z be a (bounded, closed) zone and let f be a function over Z defined by:

$$f : (t_1, \ldots, t_n) \mapsto a_1 \lambda^{t_1} + \cdots a_n \lambda^{t_n} + a$$

then $\inf_Z f$ is obtained at a corner-point of Z (with integer coefficients).

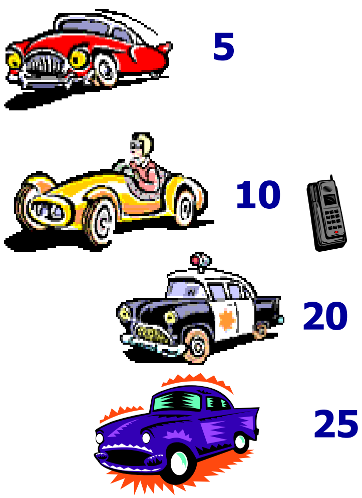
Optimal Conditional Reachability

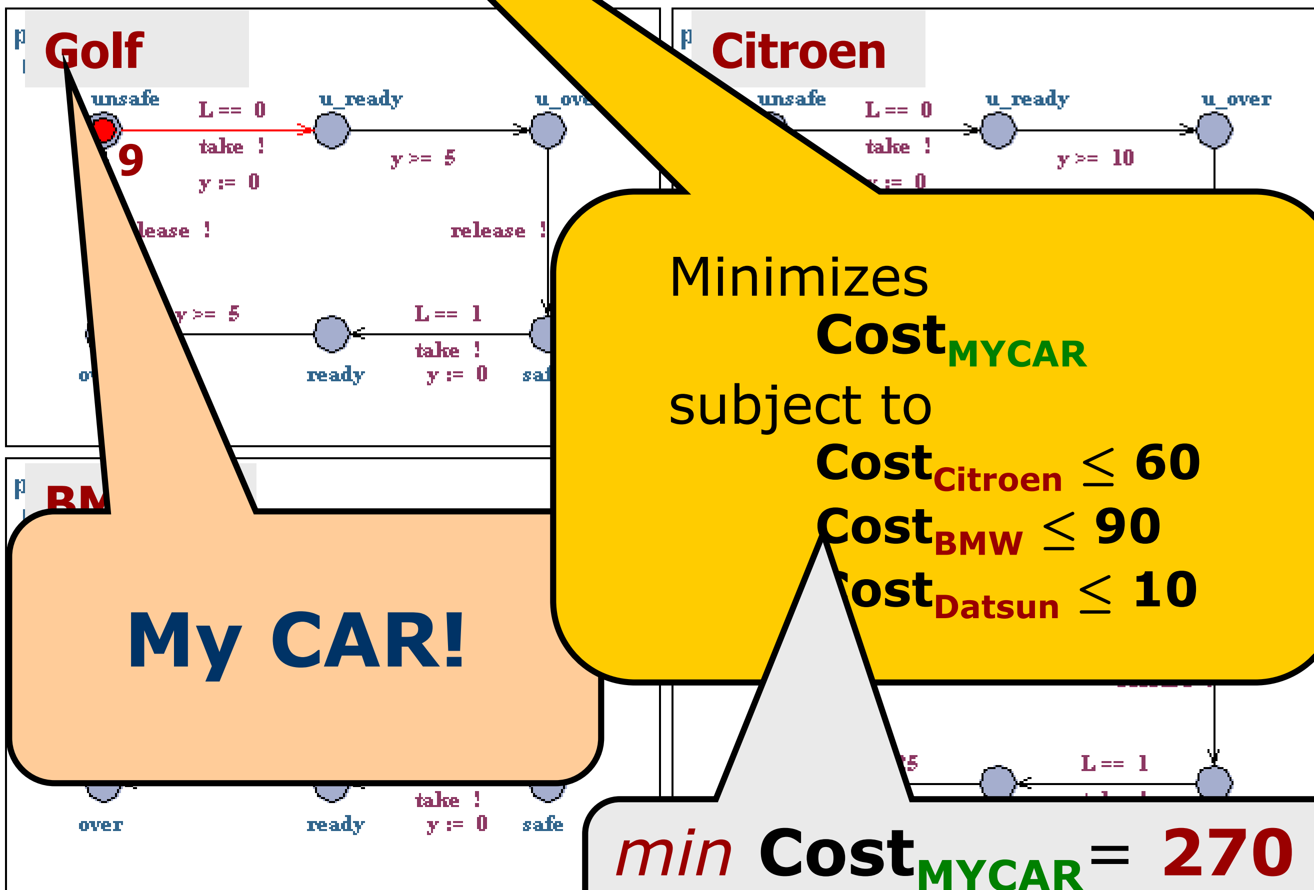
with Jacob I. Rasmussen

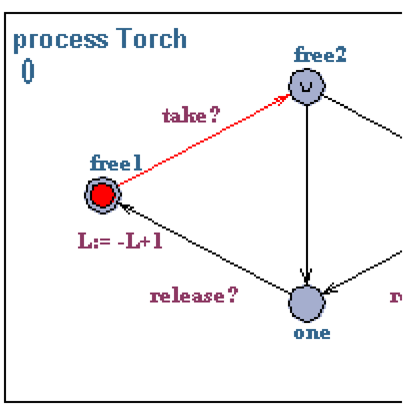
EXAMPLE: Optimal rescue plan for cars with different subscription rates for city driving !

CONDITIONAL

UNSAFE





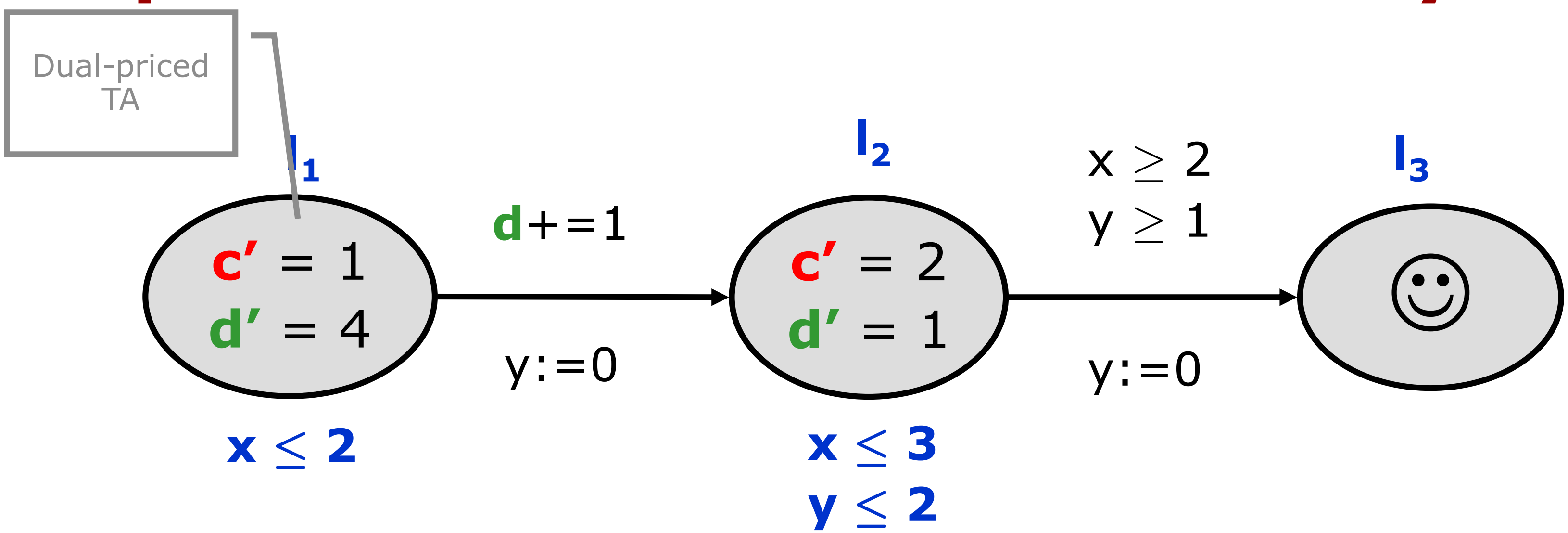


My CAR!

Minimizes
$\text{Cost}_{\text{MYCAR}}$
subject to
$\text{Cost}_{\text{Citroen}} \leq 60$
$\text{Cost}_{\text{BMW}} \leq 90$
$\text{Cost}_{\text{Datsun}} \leq 10$

min $\text{Cost}_{\text{MYCAR}} = 270$
time = 70

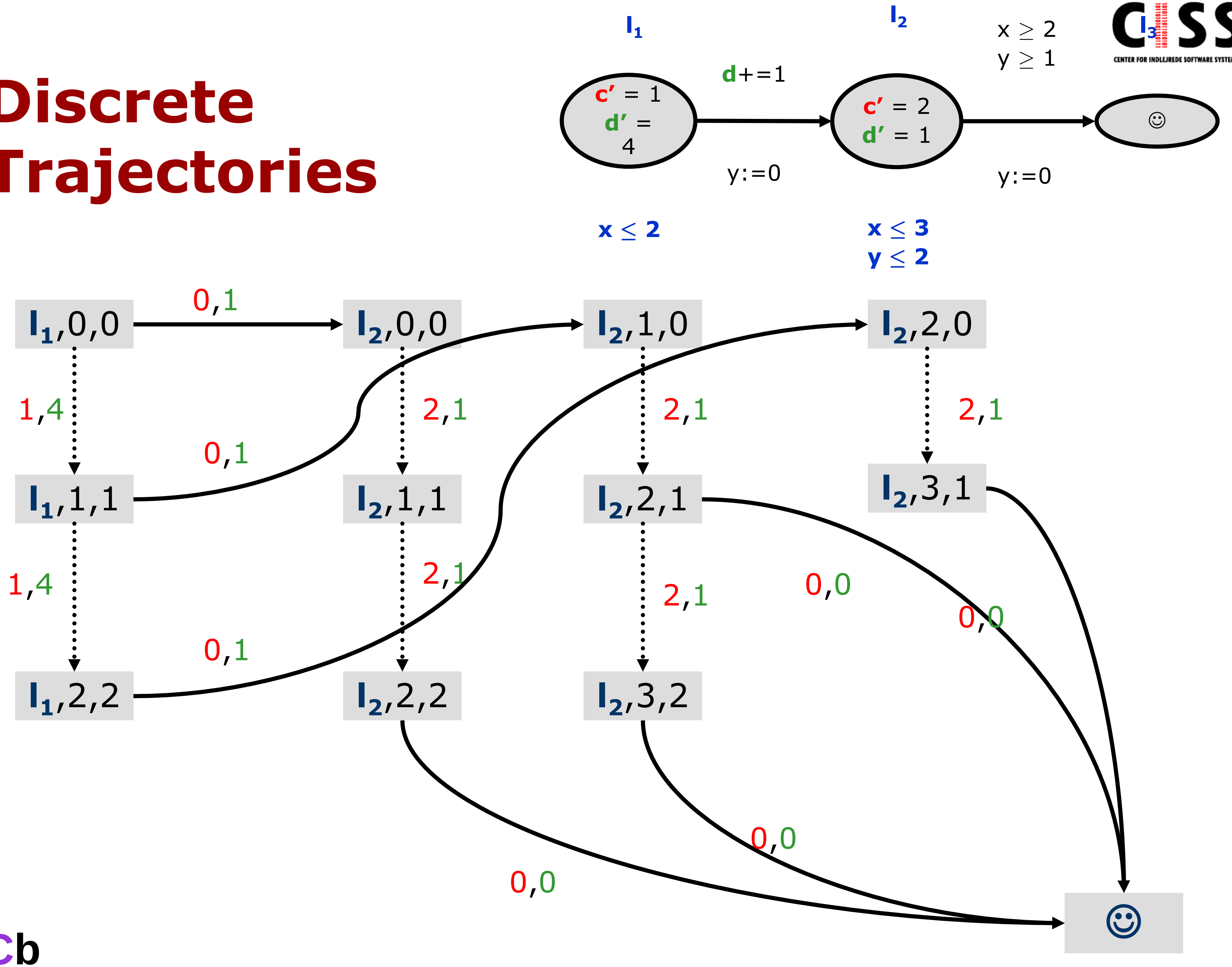
Optimal *Conditional* Reachability



PROBLEM:
Reach l_3 in a way which
minimizes c
subject to $d \leq 4$

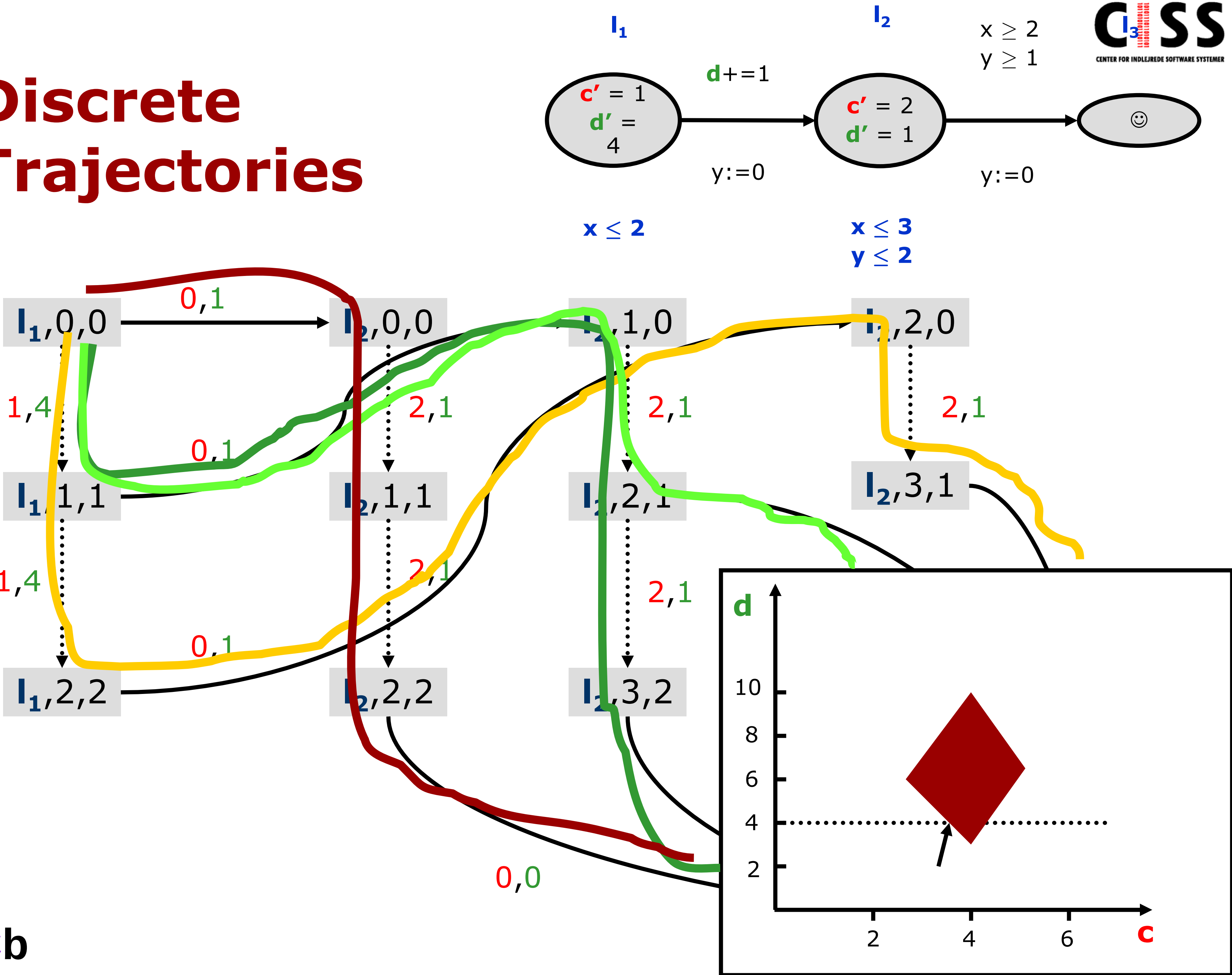
SOLUTION:
$c = 11/3 \rightarrow$
wait 1/3 in l_1; goto l_2;
wait 5/3 in l_2; goto l_3

Discrete Trajectories



UCb

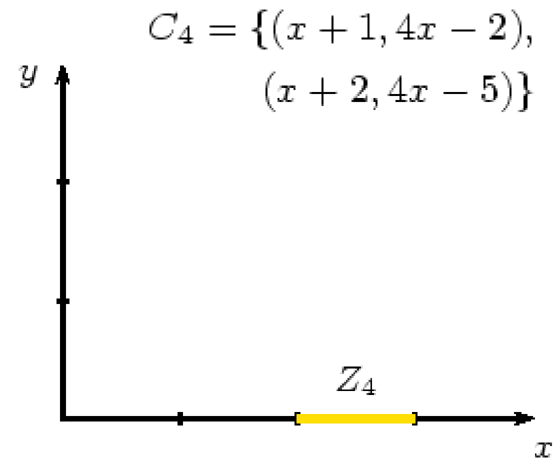
Discrete Trajectories



Dual Priced Zones

Definition

A dual-priced zone is a pair (Z, C), where Z is a zone and C is a set of pairs of affine cost functions $\{(e_1, d_1), \ldots, (e_n, d_n)\}$.



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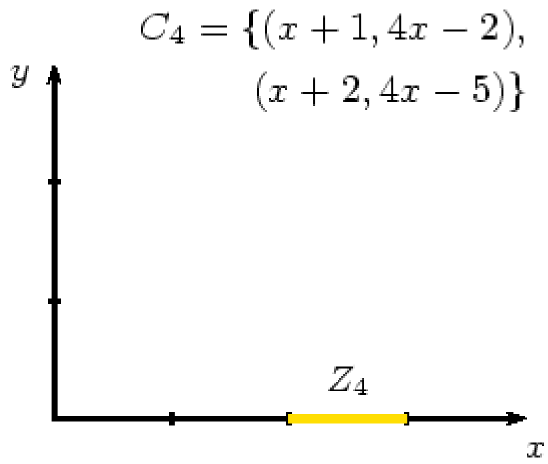
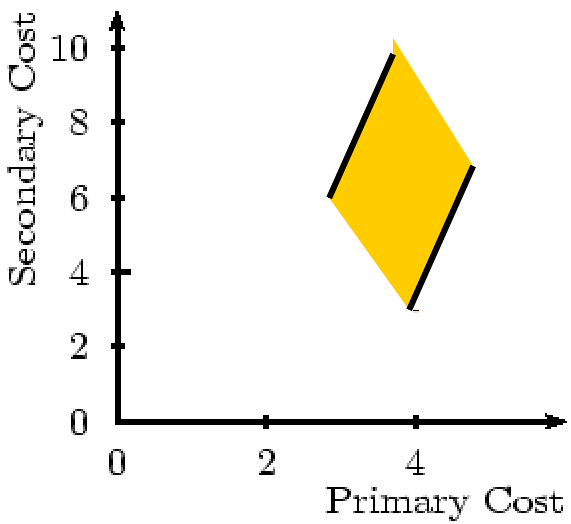


Definition

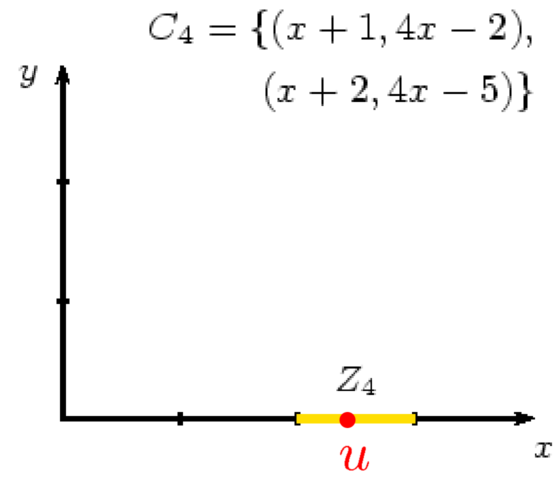
The dual-priced zone (Z, C) associates with a clock-valuation $u \in Z$ all cost pairs (c_1, c_2) such that:

$$(c_1, c_2) \in \lambda(C(u))$$

where $C(u) = \{(e_1(u), d_1(u)), \ldots, (e_n(u), d_n(u))\}$ and $\lambda()$ is convex-hull closure.



Dual Priced Zones



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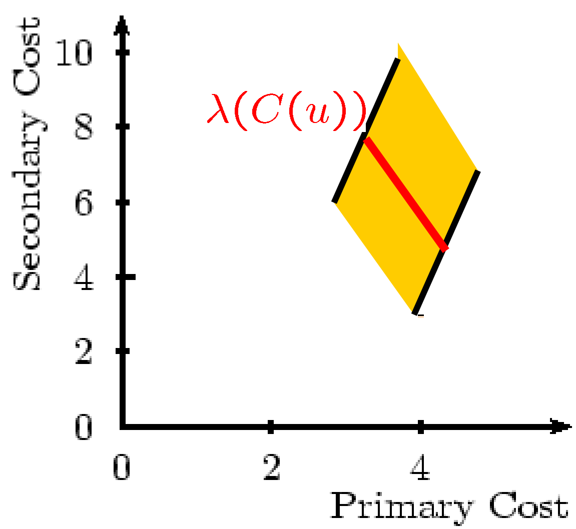

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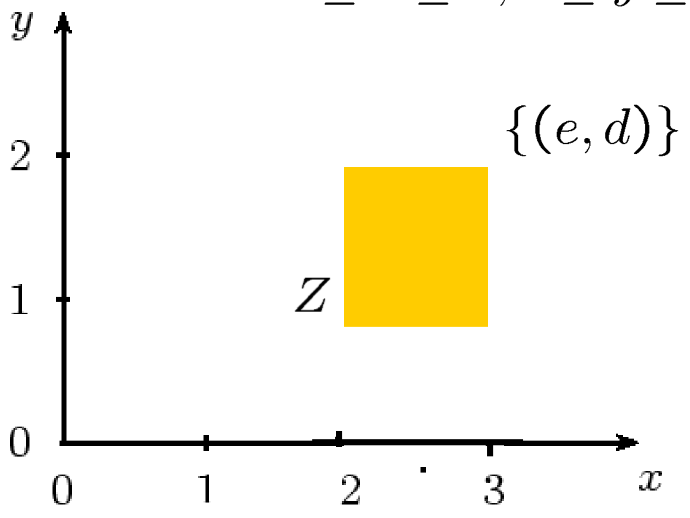
Reset

$$e = x + y$$
$$d = 4x - 3y + 1$$
$$Z : 2 \leq x \leq 3, 1 \leq y \leq 2$$



UCb

Reset

$$e = x + y$$

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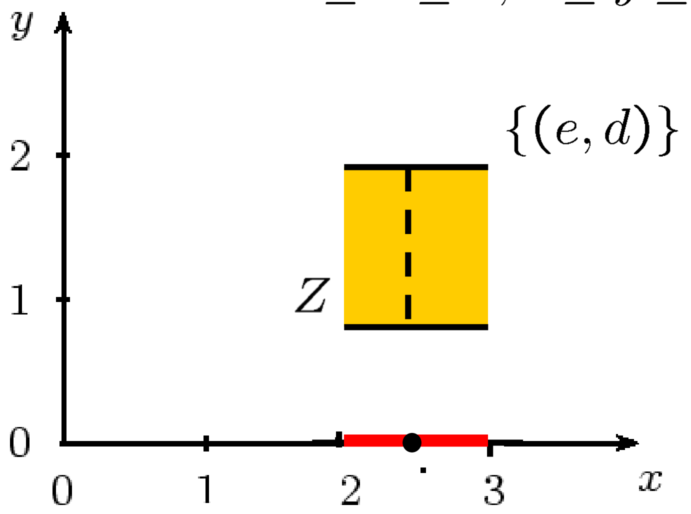

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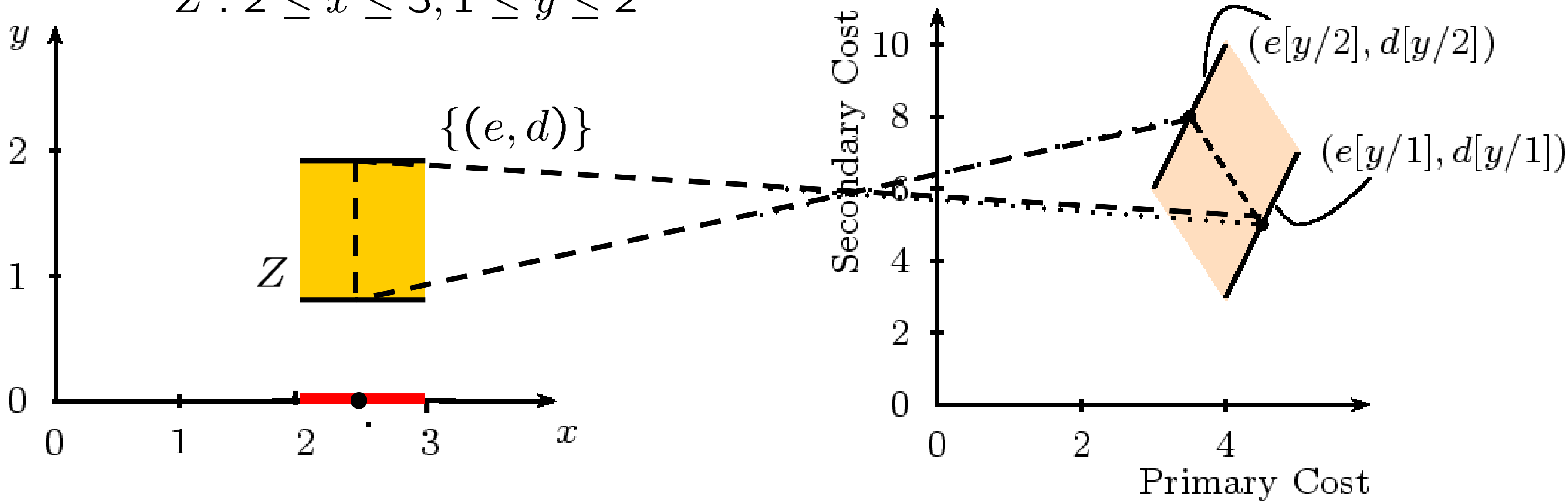

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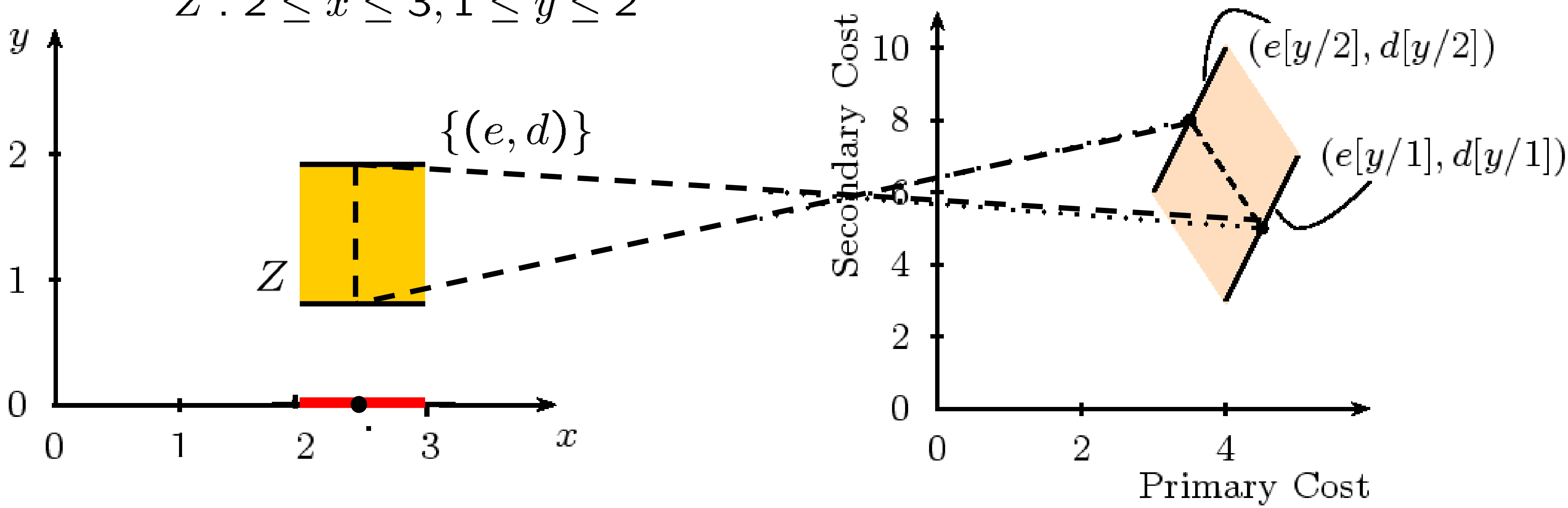
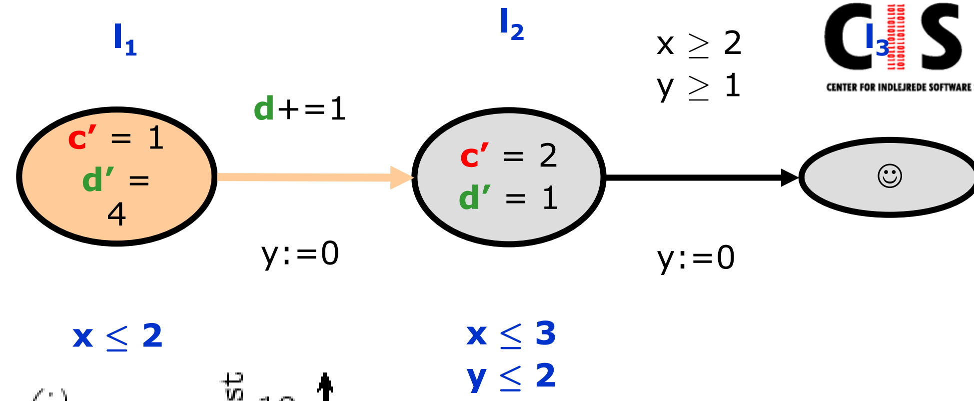


$$C = \{(x+1, 4x-2), \\ (x+2, 4x-5)\}$$

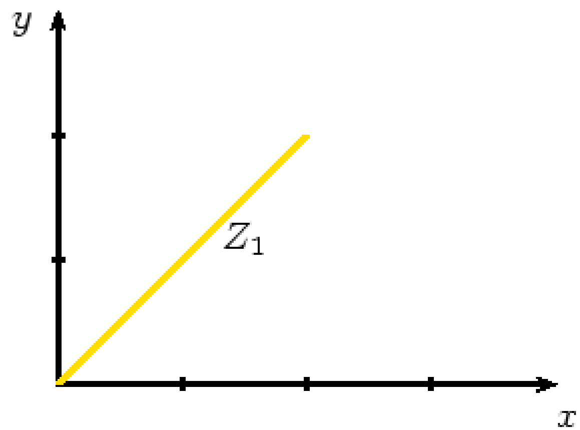
UCb

CISS
CENTER FOR INDLEJREDE SOFTWARE SYSTEMER

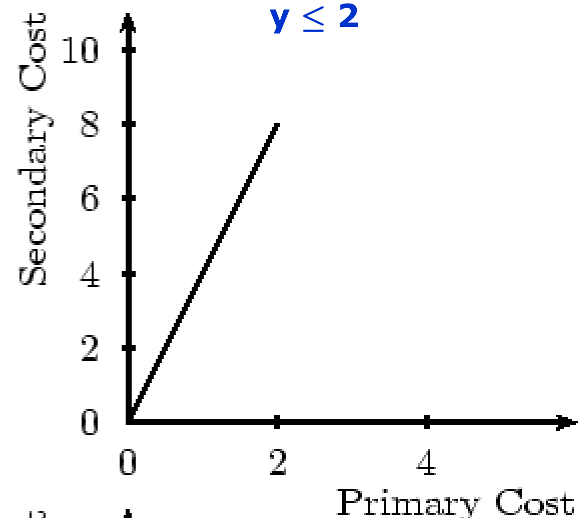
Exploration



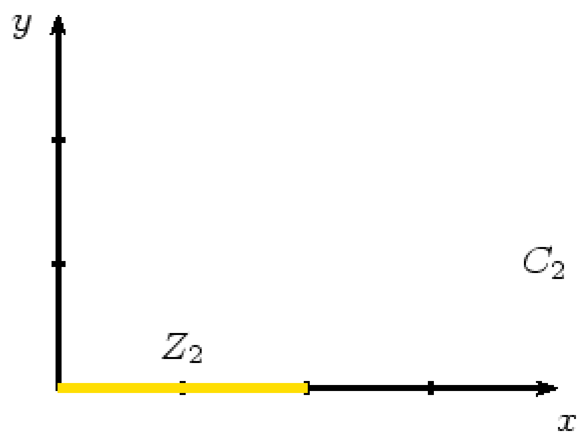
(i)



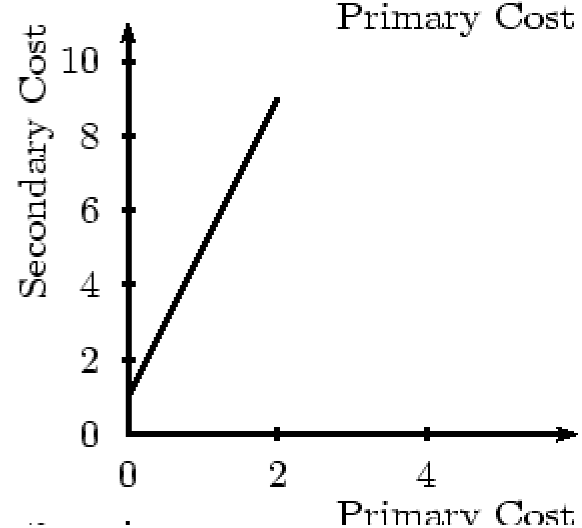
$$C_1 = \{(x, 4x)\}$$



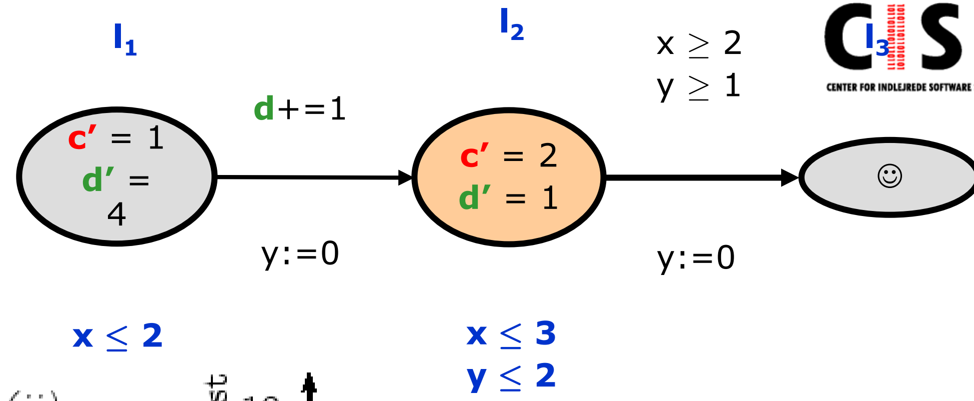
(ii)

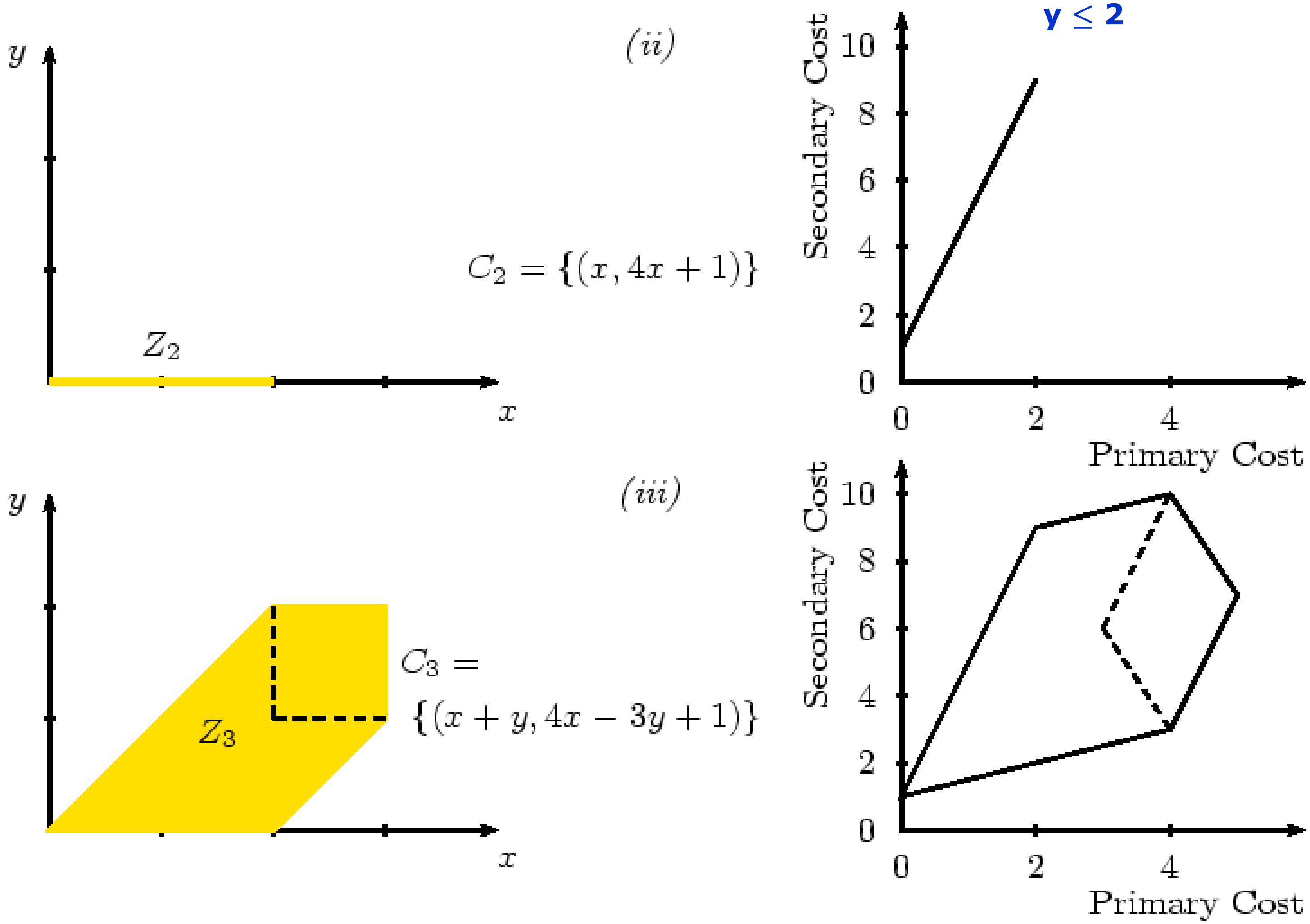


$$C_2 = \{(x, 4x + 1)\}$$

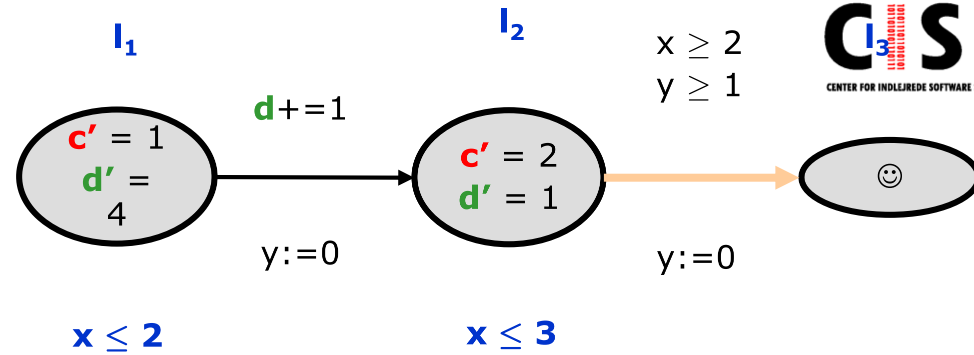


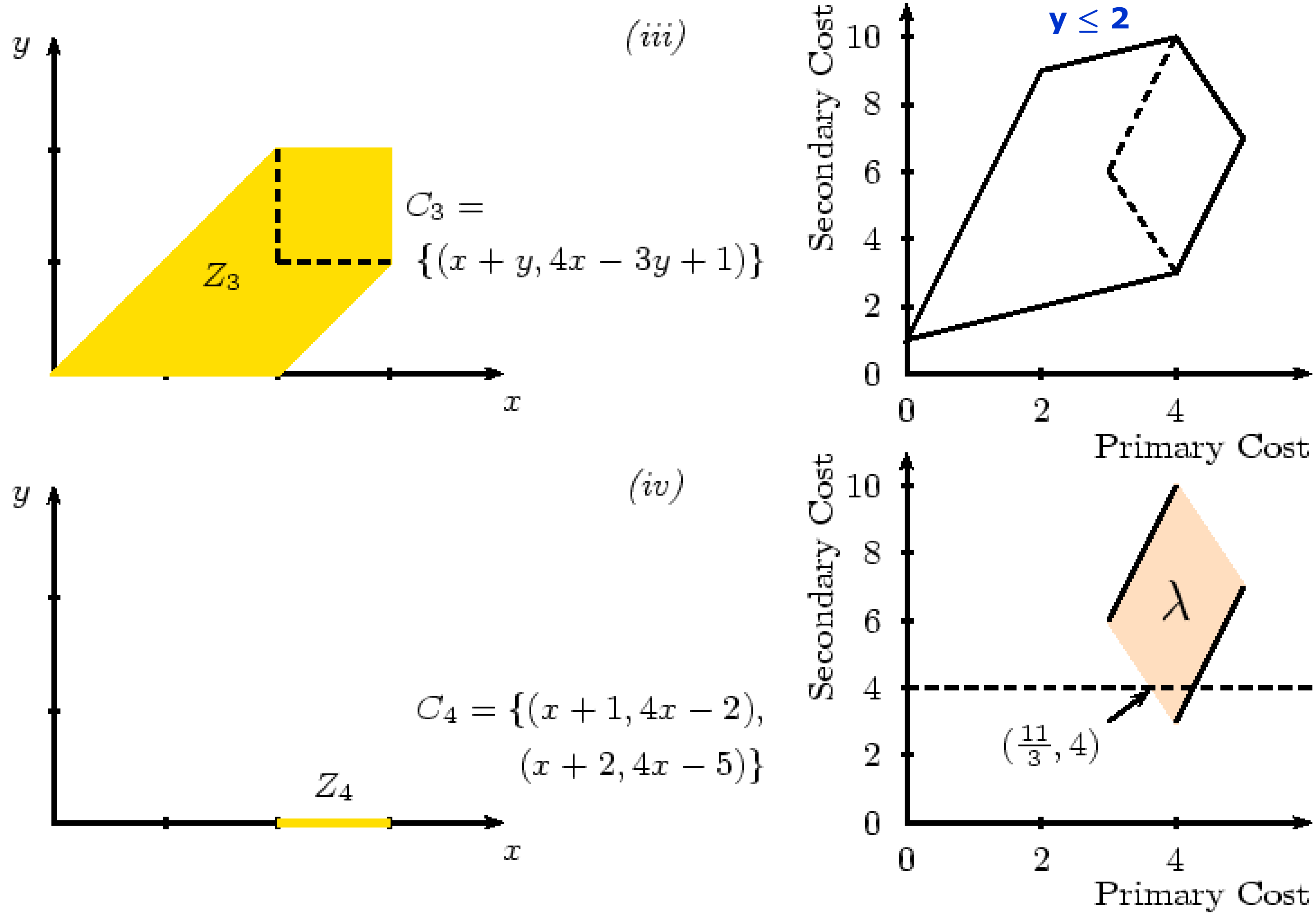
Exploration





Exploration





Termination

Definition

Let (Z, C) and (Z', C') be two dual-priced zones.

Then $(Z, C) \sqsubseteq (Z', C')$ iff

i) $Z' \subseteq Z$, and

ii) for any $(e', d') \in C'$ there exists $(e, d) \in C$

s.t. $e \leq_{Z'} e'$ and $d \leq_{Z'} d'$

Theor

If $(Z,$

$\forall(c'_1,$ $\ldots \leq c_2$

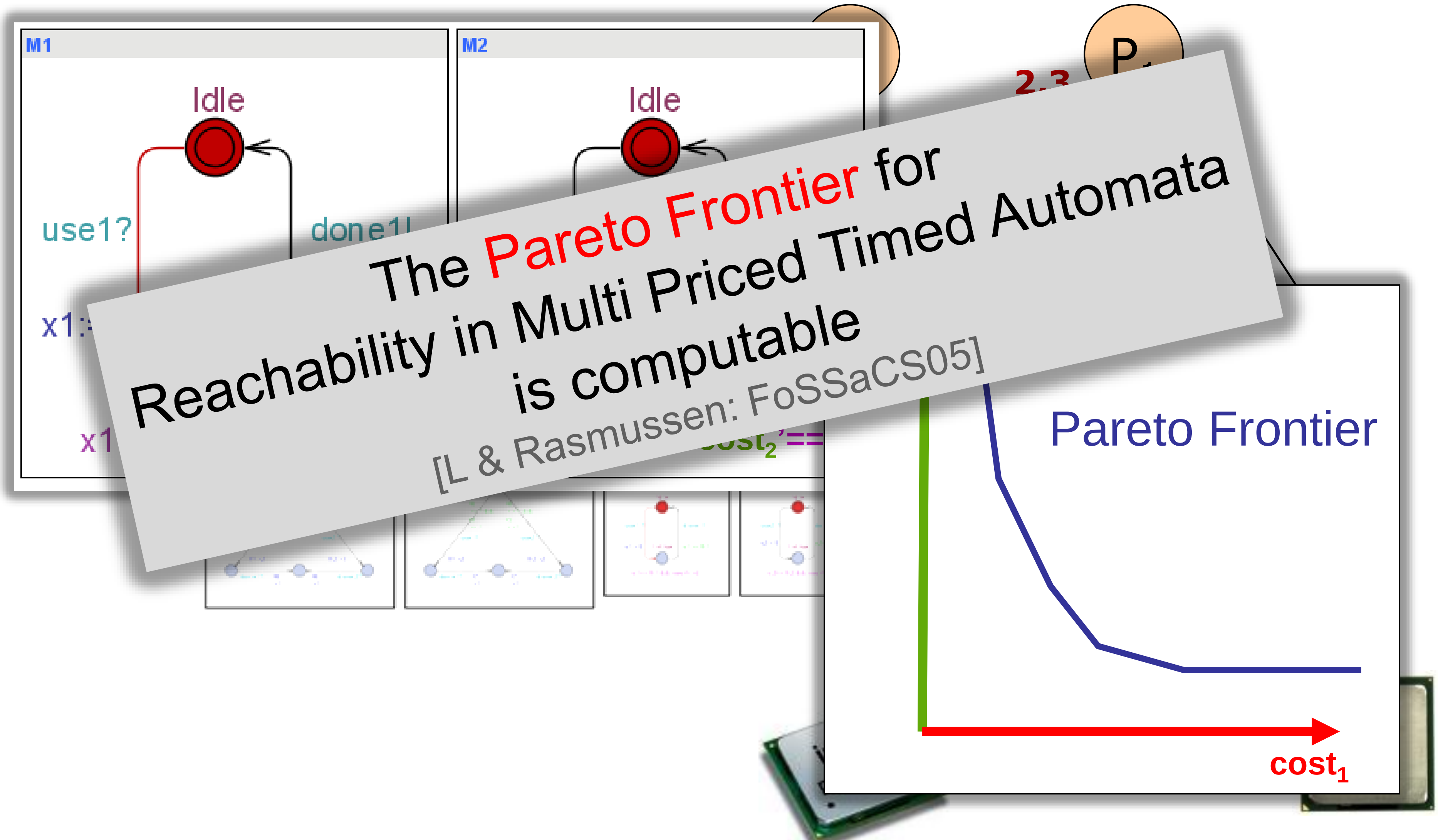
THEOREM

Optimal conditional reachability for multi-priced TA is computable.

Theor

$\sqsubseteq$ is a well-quasi ordering.

Multiple Objective Scheduling

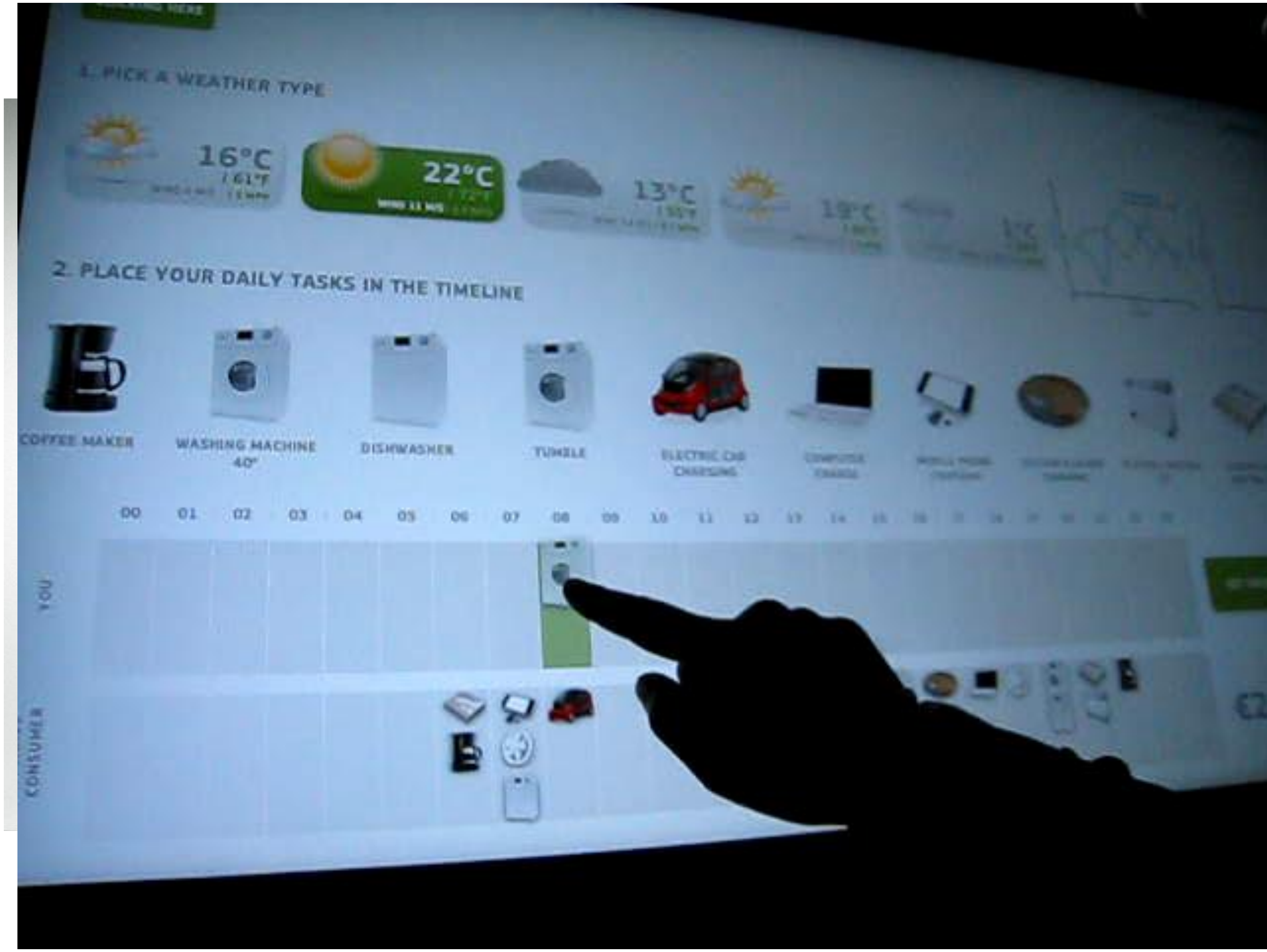


The Pareto Frontier for Reachability in Multi Priced Timed Automata is computable

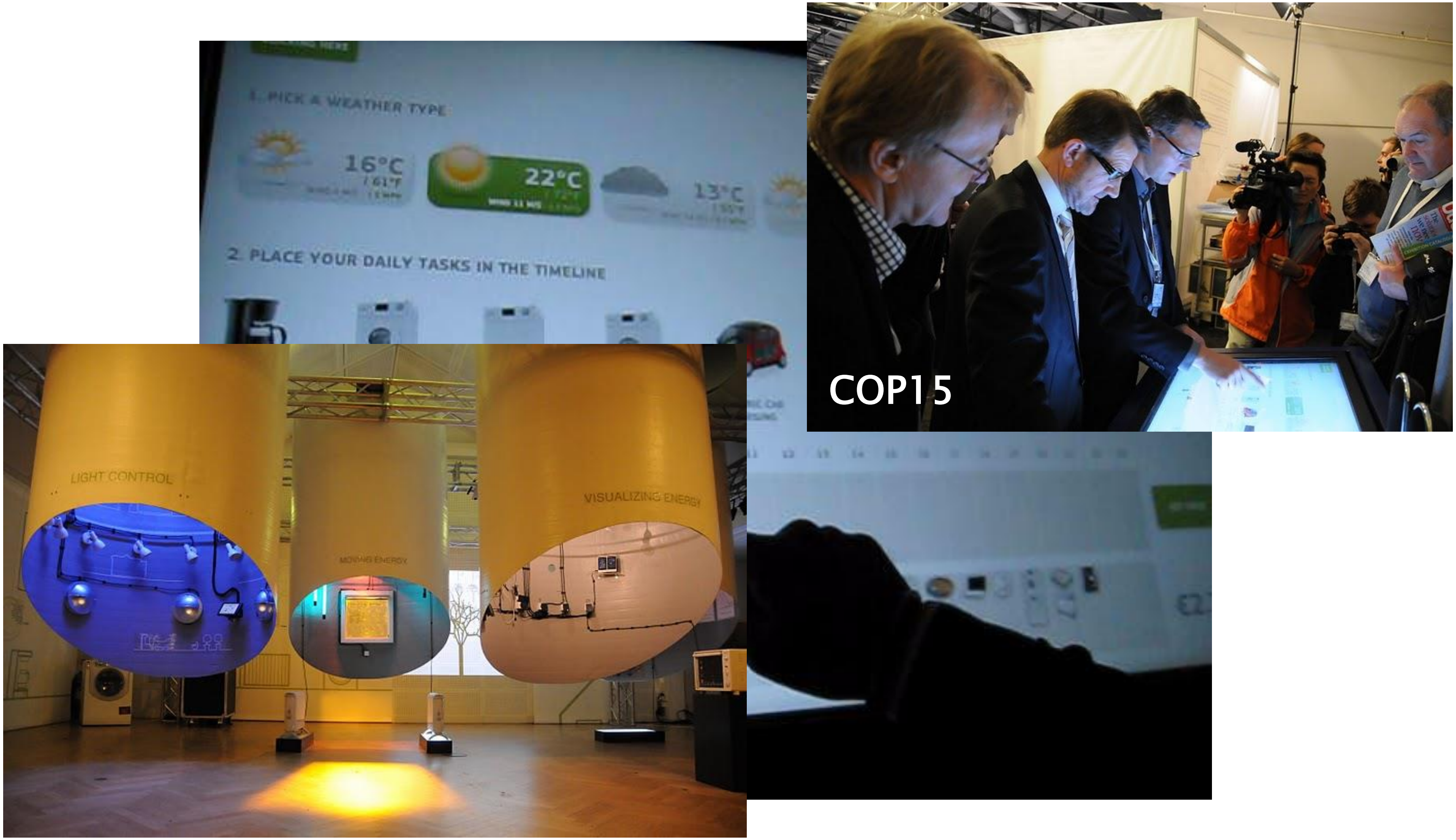
[L & Rasmussen: FoSSaCS05]

Applications

“Experimental” Results



"Experimental" Results

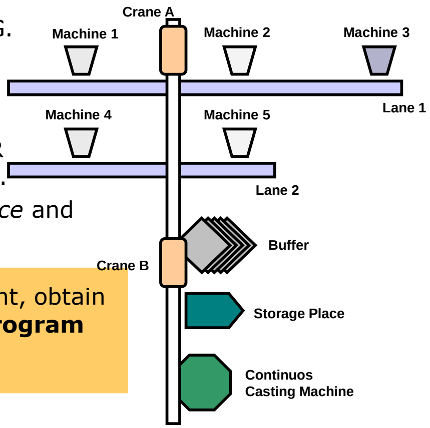


SIDMAR Production (2002) VHS

Steel Production Plant

CISS

- 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*.

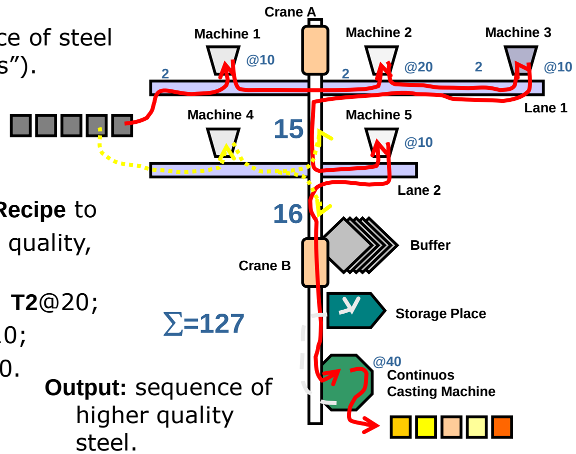


Objective: model the plant, obtain **schedule** and control **program** for plant.

Steel Production Plant

CISS

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

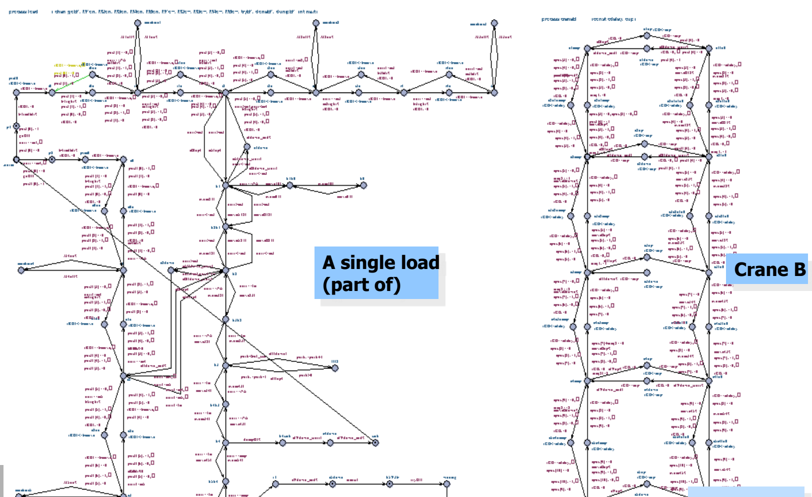


Load follows **Recipe** to obtain certain quality, e.g:
start; **T1**@10; **T2**@20; **T3**@10; **T2**@10; end within 120.

$\sum=127$

Output: sequence of higher quality steel.

CISS

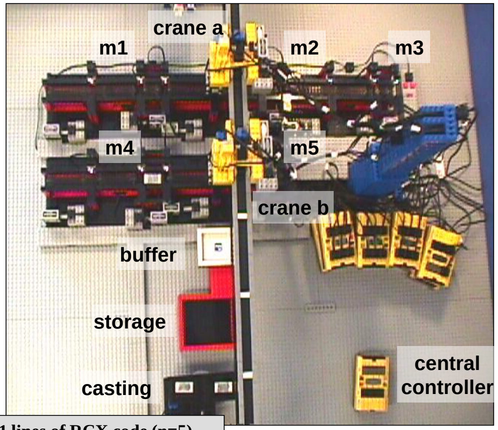


UCb

Controller Synthesis for LEGO Model

CISS

- 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

UCb

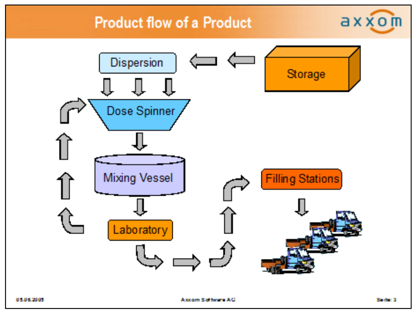
AXXOM Case Study (2005)

ARTEMIS

AXXOM Case study

Laquer Production Scheduling

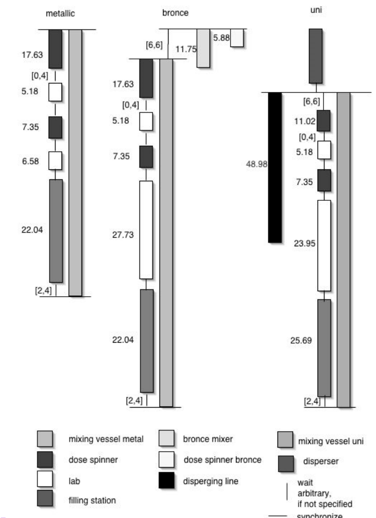
- 3 types of recipes
  - for uni/metallic/bronce
  - use of resources, processing times, timing
- 29 (73, 219) orders:
  - start time, due date, recipe
- extensions:
  - delay cost, storage cost, setup cost
  - weekend, nights



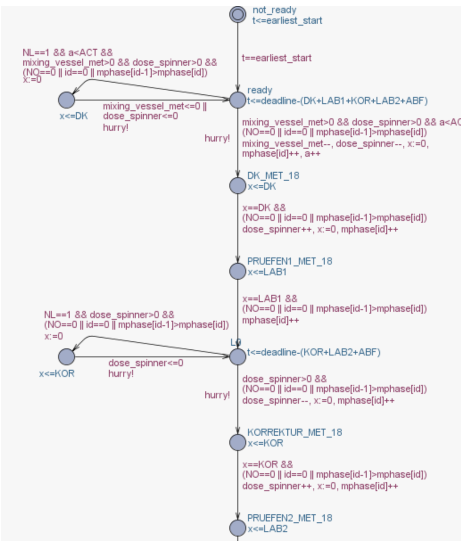
Behrmann, Brinksma, Hendriks, Mader
16th IFAC World Congress

UCb

Recipes



UPPAAL template for metal



Results Extended Case

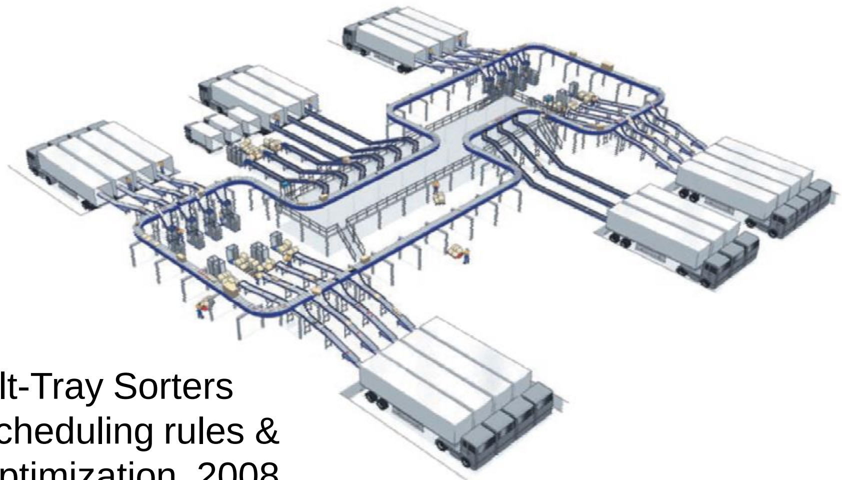
#jobs	work hrs	[illegible]istic	max orde[illegible]	cost
29	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
29	[illegible]	[illegible]	-	[illegible]4,87[illegible]
[illegible]	[illegible]	[illegible]0,[illegible]	-	2,263,496
[illegible]	[illegible]	no	4	192,881,129

Competitive with Orion-pi results

Orders of magnitude faster than MILP, GAMS/CPLEX

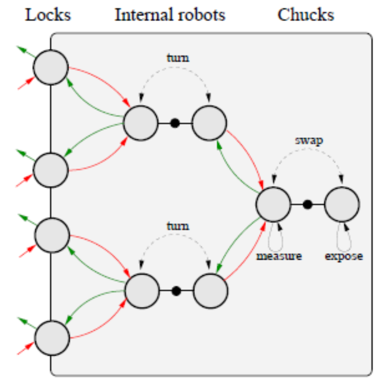
UCb

Embedded Systems Innovation BY TNO



Tilt-Tray Sorters
Scheduling rules &
Optimization, 2008

Océ Datapath, 2012



ASML, 2004:
Wafer Scanners
Optimization of
Throughput

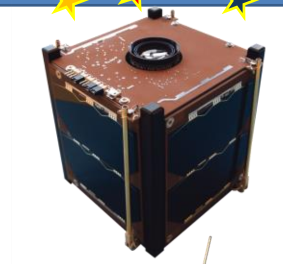
Philips: Indoor Lighting systems, 2014

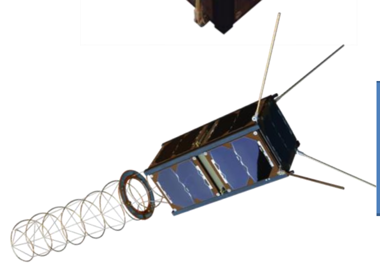
Within the Prisma project of TNO-ESI and Philips Lighting, research is done into the robustness and reliability of large-scale indoor lighting systems. The focus is on the robustness of the lighting control system. To analyse control system robustness, model checking is used. Timed automata models of lighting control systems have been created and checked with the model checker Uppaal. To validate

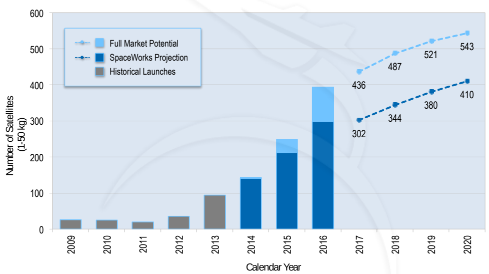
NANO Satellites (2015)

NanoSatellites

- Nanosatellite: 1 – 20 kg
  - Smaller
  - Cheaper
  - Faster
  - But also capable!



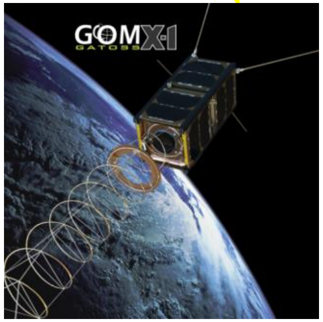




w
- Morten Bisgaard, GOMSPACE
- Holger Hermanns, Gilles Nies, Marvin Stenger, Saarbrücken

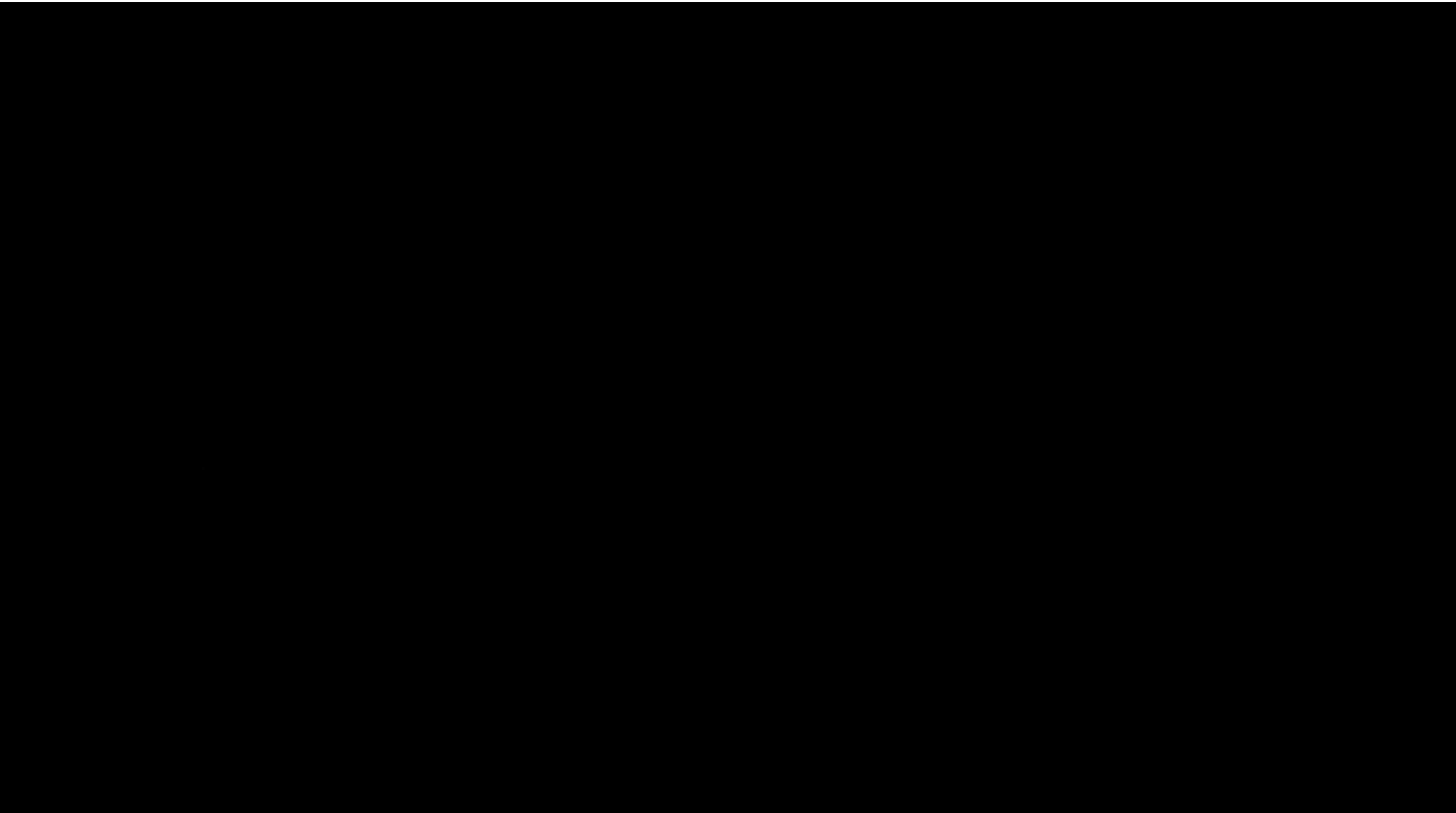
GomSpace Satellites

- 2U satellite -> 2013
- Tracking airplanes
- “Simple” mission

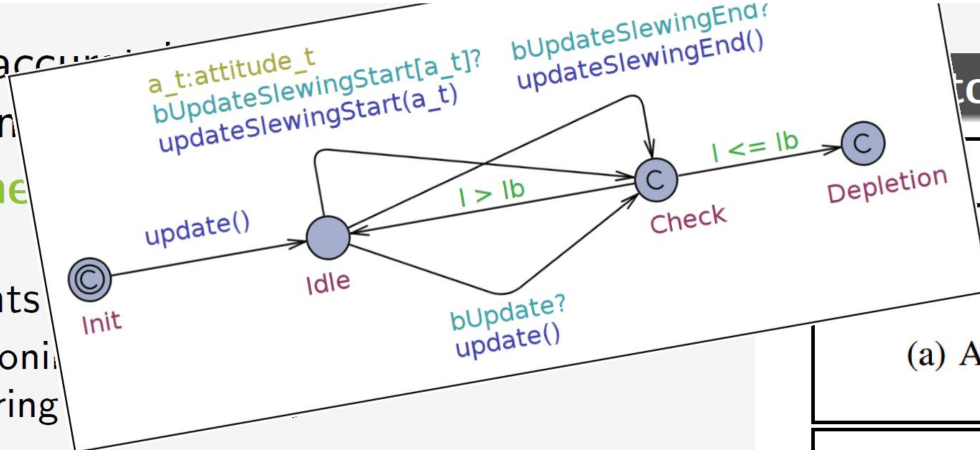


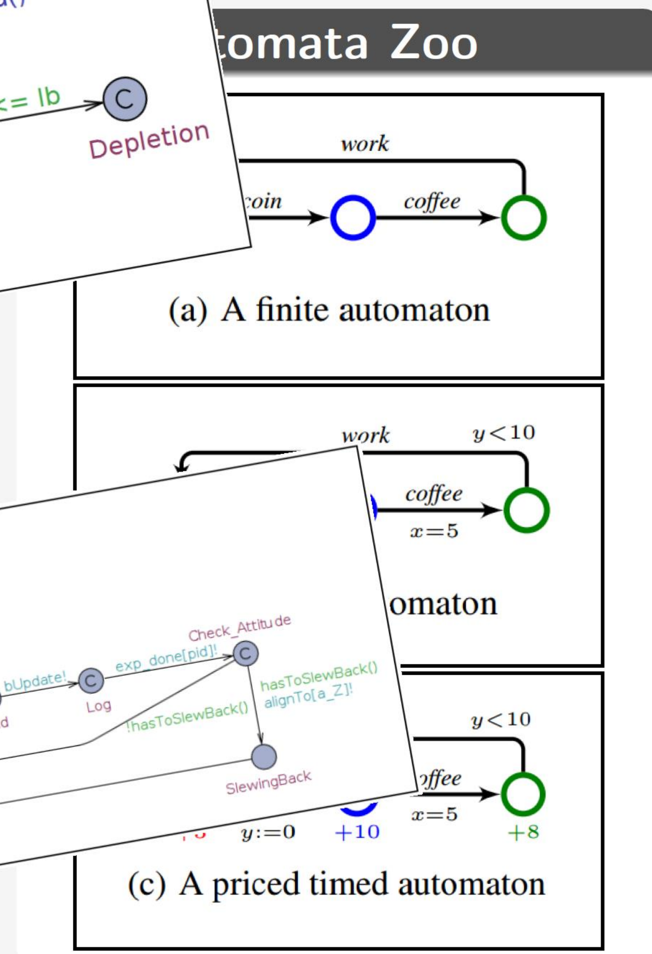
- 3U satellite -> 2015
- 3 major payloads
- Complex mission

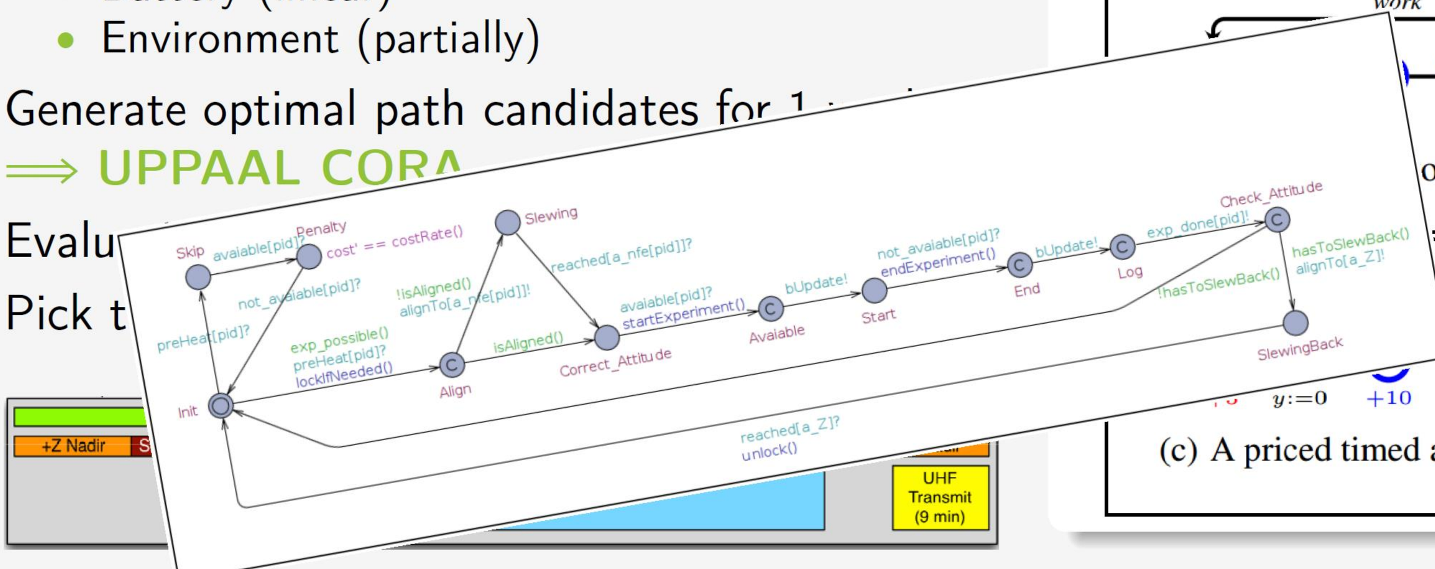
GOMX-3 Deployment



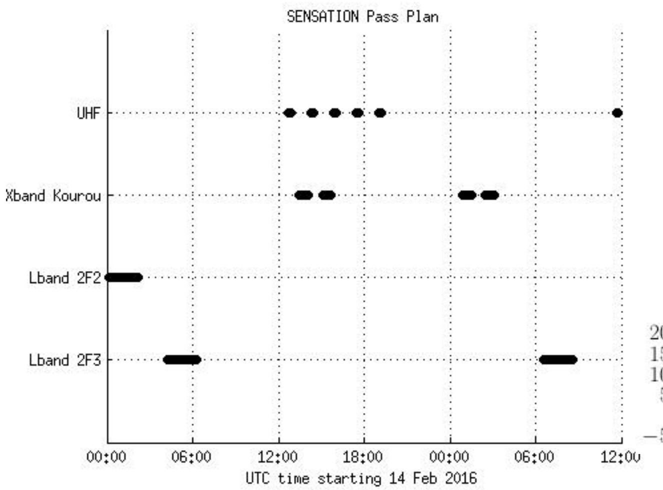
- Orbit can be accu
  ⟹ Experimen
- Network of line
  (LPTA)
  - Experiments
    - positioni
    - powering
  - Battery (linear)
  - Environment (partially)
- Generate optimal path candidates for 1
  ⟹ UPPAAL CORA
- Evalu
- Pick t

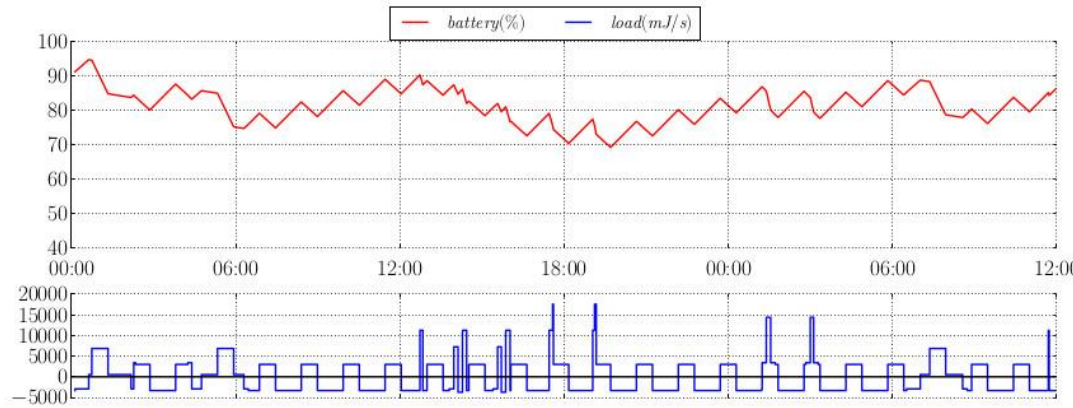


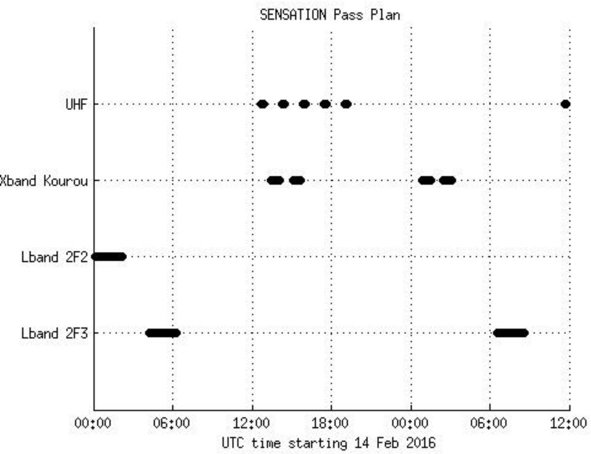


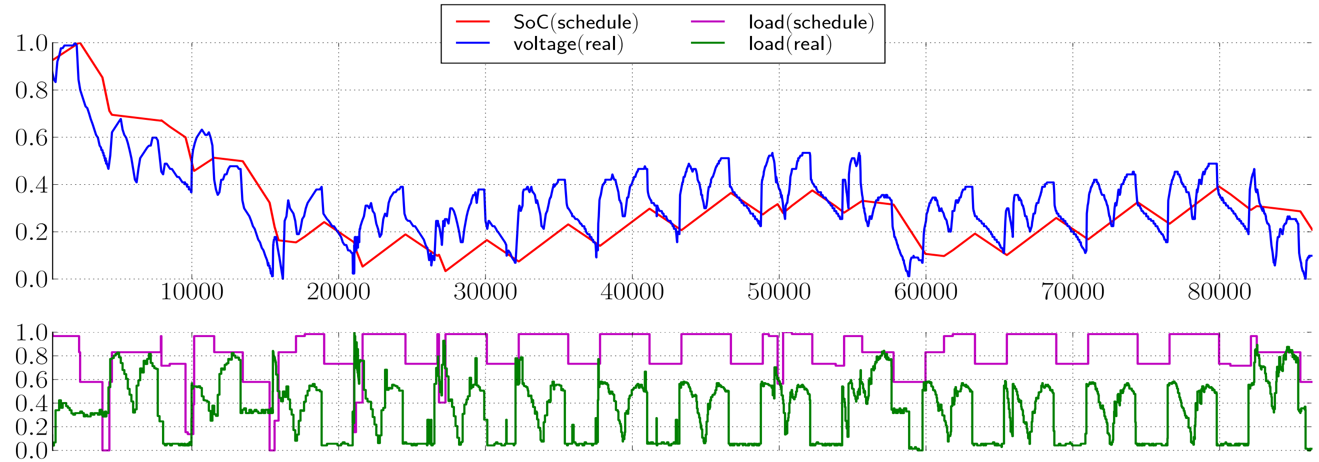


Derived Schedule






SENSATION Pass Plan
UHF
Xband Kourou
Lband 2F2
Lband 2F3
00:00
06:00
12:00
18:00
00:00
06:00
12:00
UTC time starting 14 Feb 2016


SoC(schedule)
voltage(real)
load(schedule)
load(real)
1.0
0.8
0.6
0.4
0.2
0.0
10000
20000
30000
40000
50000
60000
70000
80000

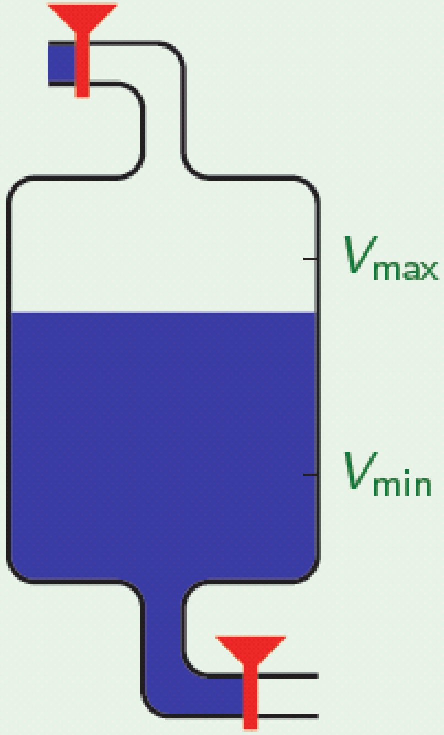
Energy Automata

Managing Resources

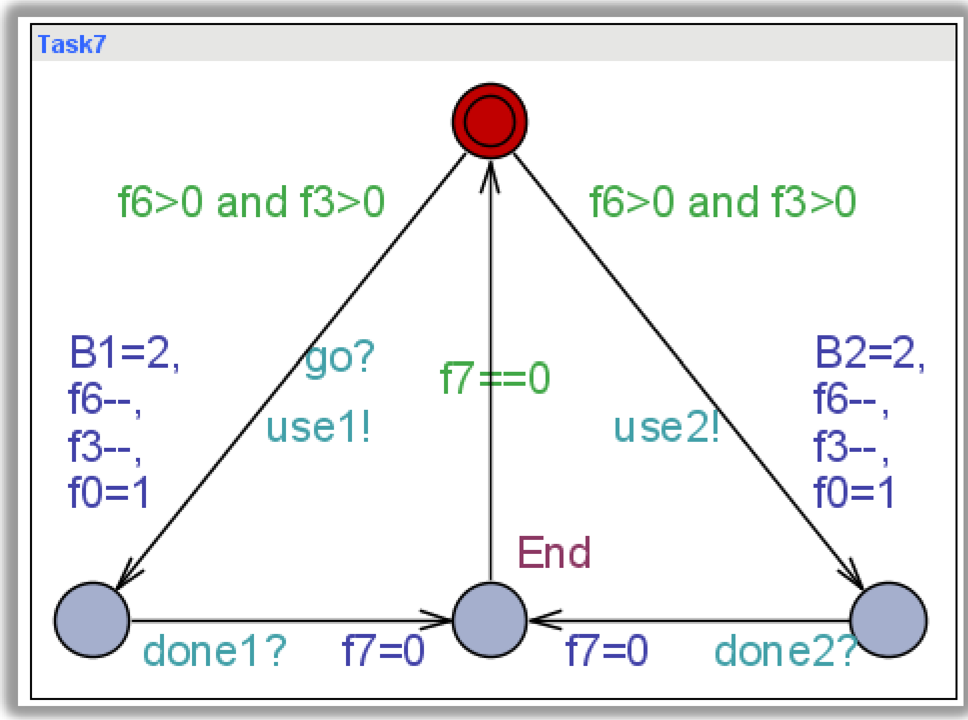
Example

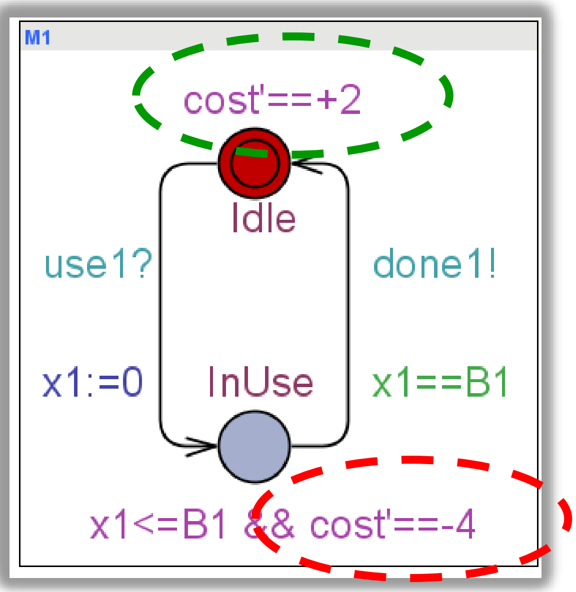
In some cases, resources can both be consumed and regained.

The aim is then to keep the level of resources within given bounds.



Consuming & Harvesting Energy

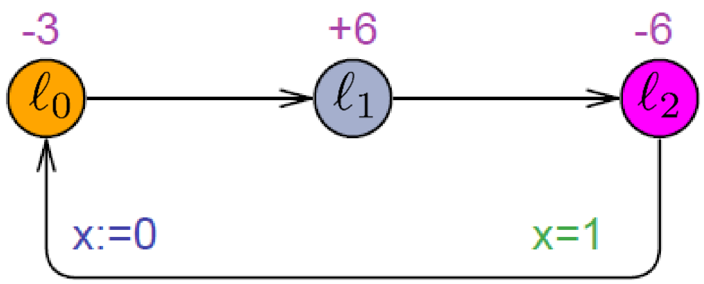


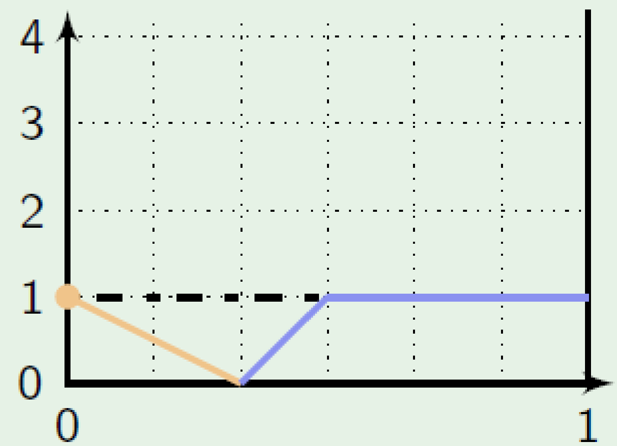


Maximize throughput
while respecting: $0 \leq \mathbf{E} \leq MAX$

Energy Constrains

- Energy is not only consumed but may also be regained
- The aim is to continously satisfy some energy constriants





lower-weak-upper-bound problem

One Weight Results

1 Clock	games	existential problem	universal problem
L	?	$\in$ P	$\in$ P
L+W	?	$\in$ P	$\in$ P
L+U	undecidable	decidable (flat)	?

1½ Clock	games	existential problem	universal problem
L	?	decidable	decidable
L+W	?	decidable	decidable

>3 Clocks	games	existential problem	universal problem
L	undecidable	undecidable	PSPACE-c
L+W	undecidable	undecidable	PSPACE-c

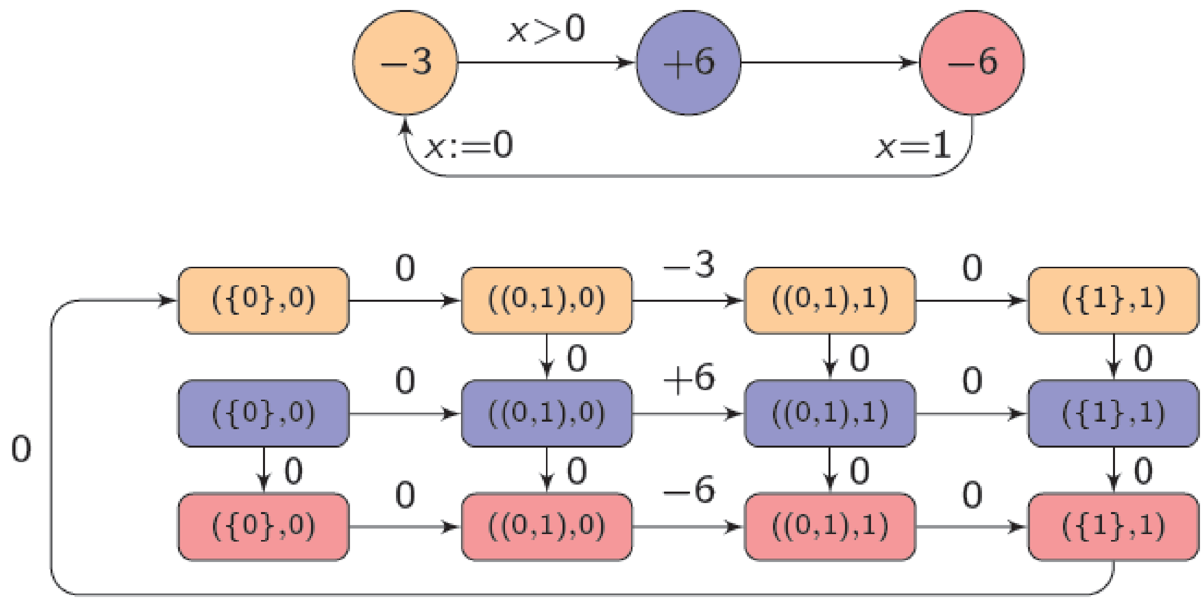
P Bouyer, U Fahrenberg, K Larsen, N Markey,.. . Infinite runs in weighted timed automata with energy constraints. 2008.
P. Bouyer, U. Fahrenberg, K. G. Larsen, N. Markey: Timed automata with observers under energy constraints. HSCC 2010
P. Bouyer, K. G. Larsen, and N. Markey. Lower-bound constrained runs in weighted timed automata. QEST 2012

L–Problem for 1–Clock Case

Theorem:
The L-problem is decidable in **PTIME** for **1**-clock PTAs

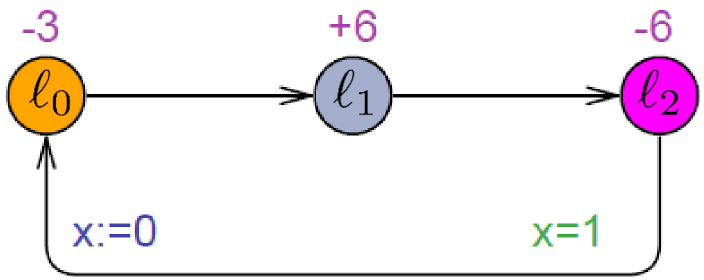
Proof.

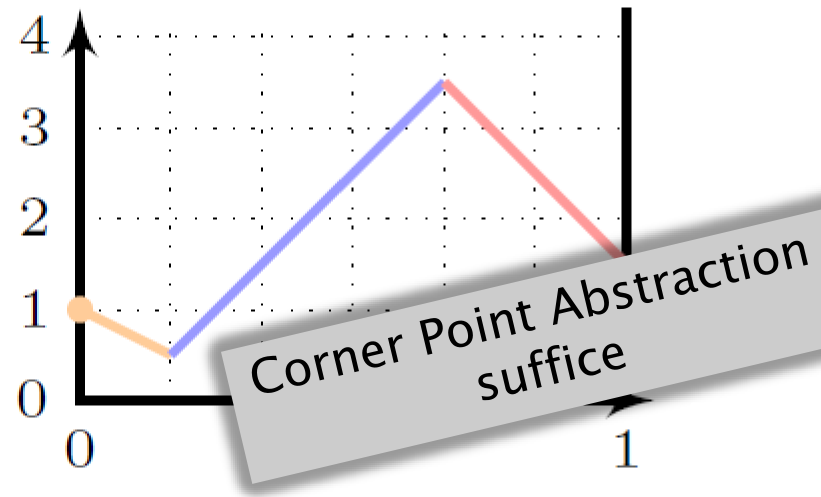
- Corner-point abstraction:

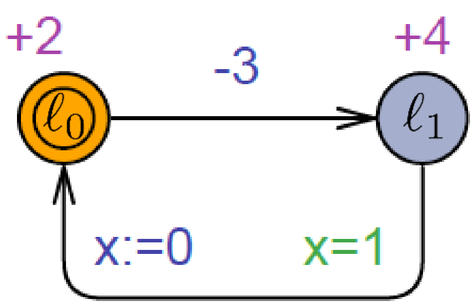


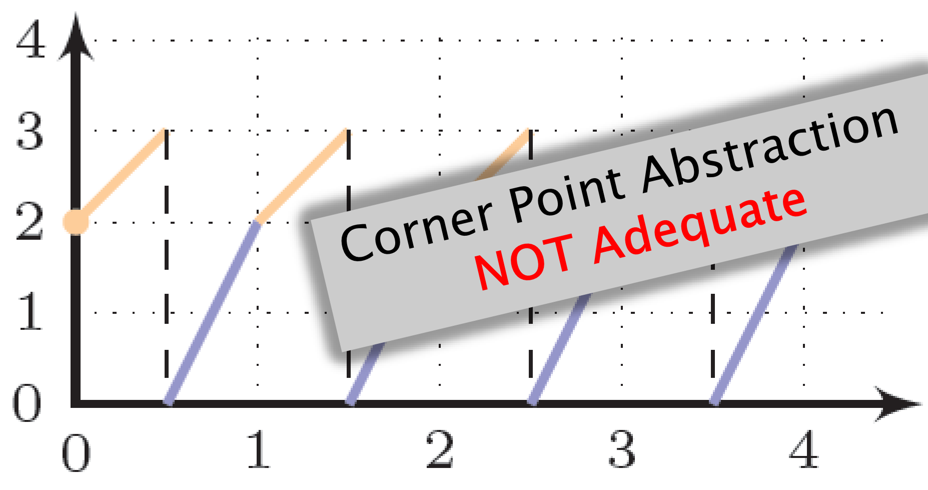
P Bouyer, U Fahrenberg, K Larsen, N Markey,.. . Infinite runs in weighted timed automata with energy constraints. 2008.

1½ Clocks = Discrete Updates

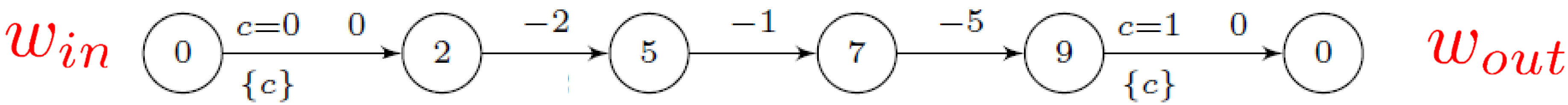




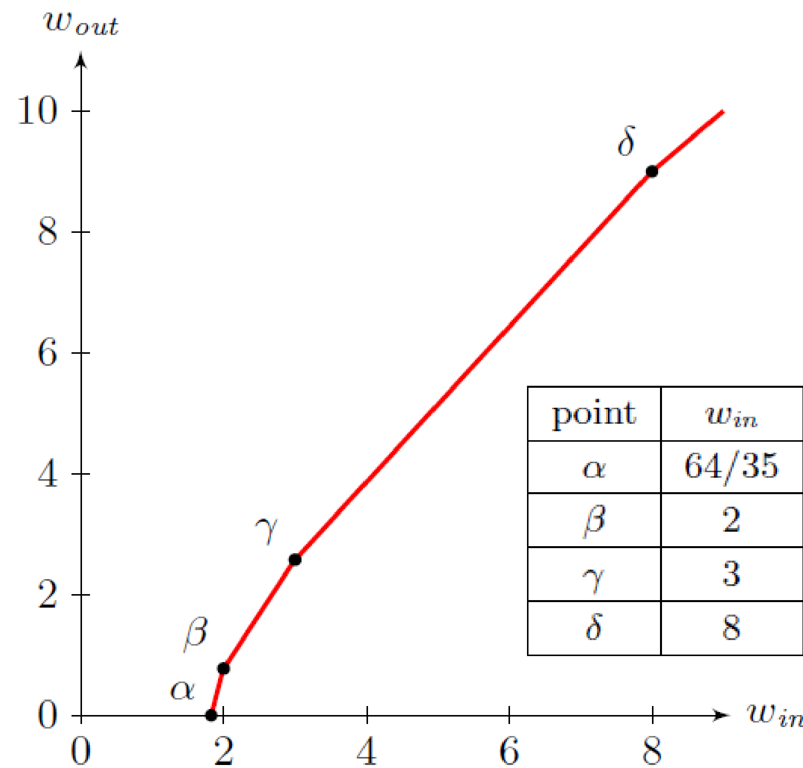




New Approach: Energy Functions



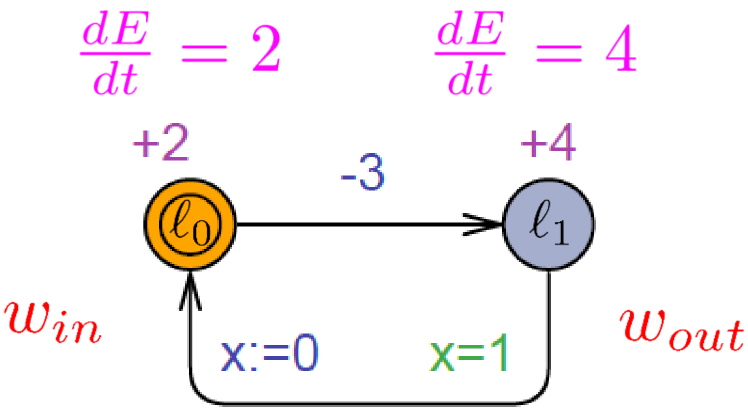
- Maximize energy along paths
- Use this information to solve general problem

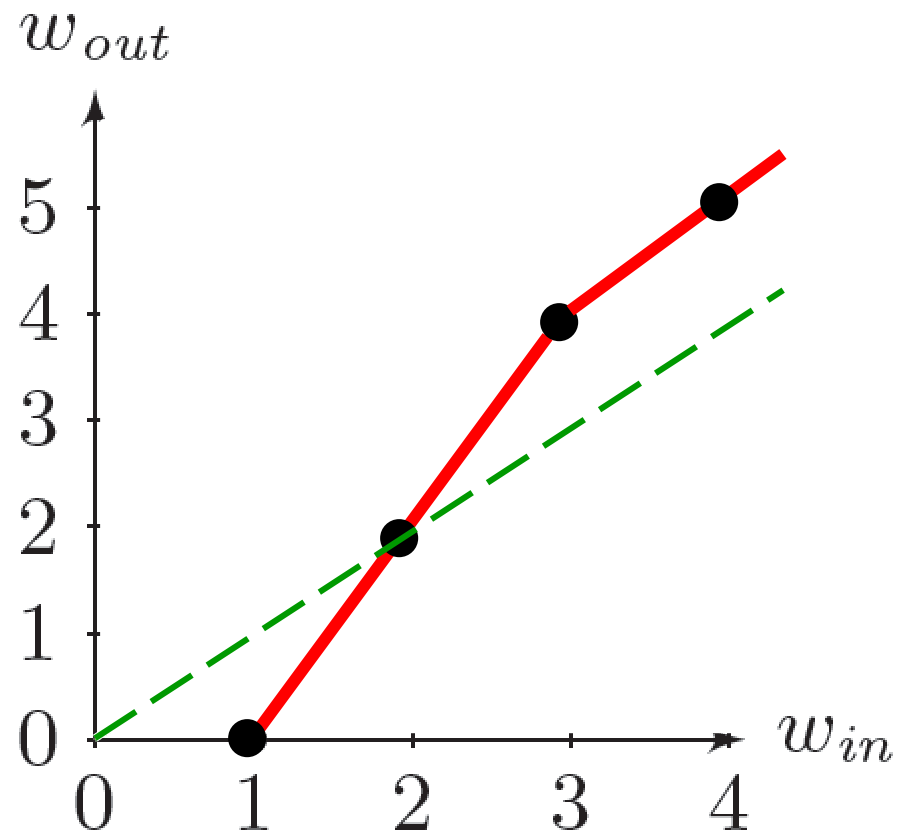


point	w_{in}	w_{out}
α	64/35	0
β	2	27/35
γ	3	18/7
δ	8	9

P. Bouyer, U. Fahrenberg, K. G. Larsen, N. Markey: Timed automata with observers under energy constraints. HSCC 2010

Energy Function

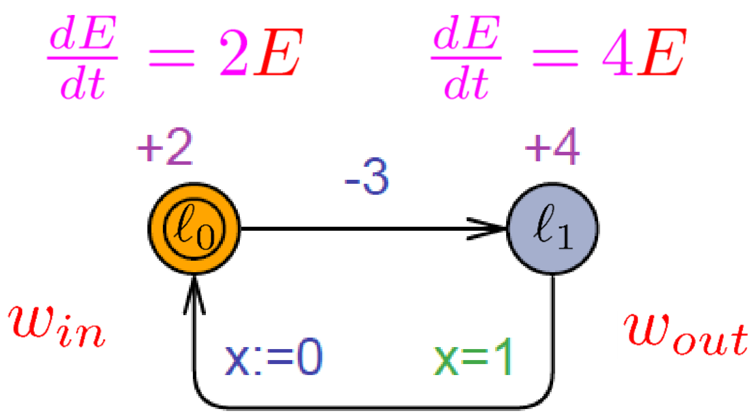


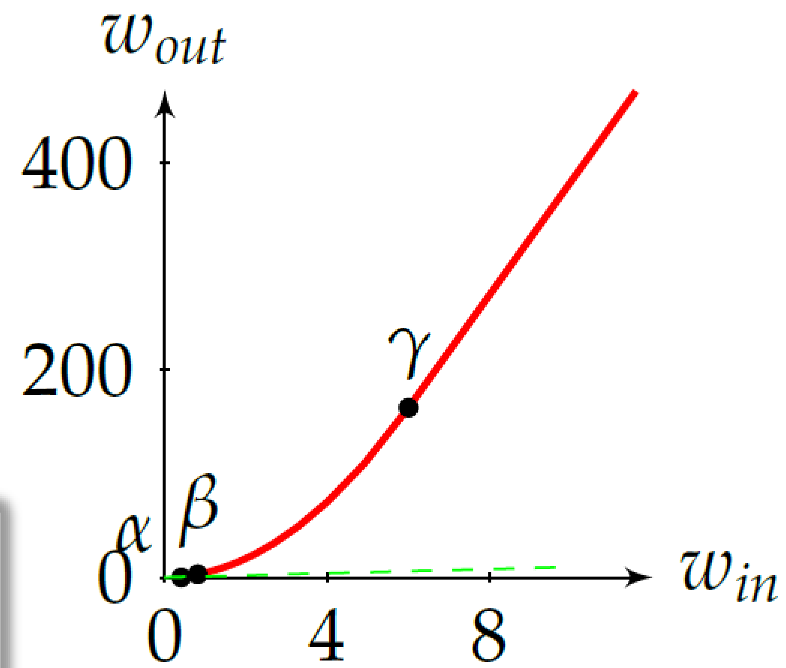


General Strategy
Spend just enough time
to survive the next negative
update

P. Bouyer, U. Fahrenberg, K. G. Larsen, N. Markey: Timed automata with observers under energy constraints. HSCC 2010

Exponential PTA





General Strategy
Spend just enough time
~~to survive the next negative update~~
so that after next negative update there is a certain positive amount !

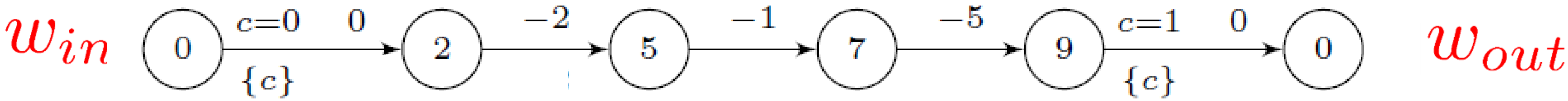
Minimal Fixpoint:

$$\frac{3}{e^2-1} \approx 0.47$$

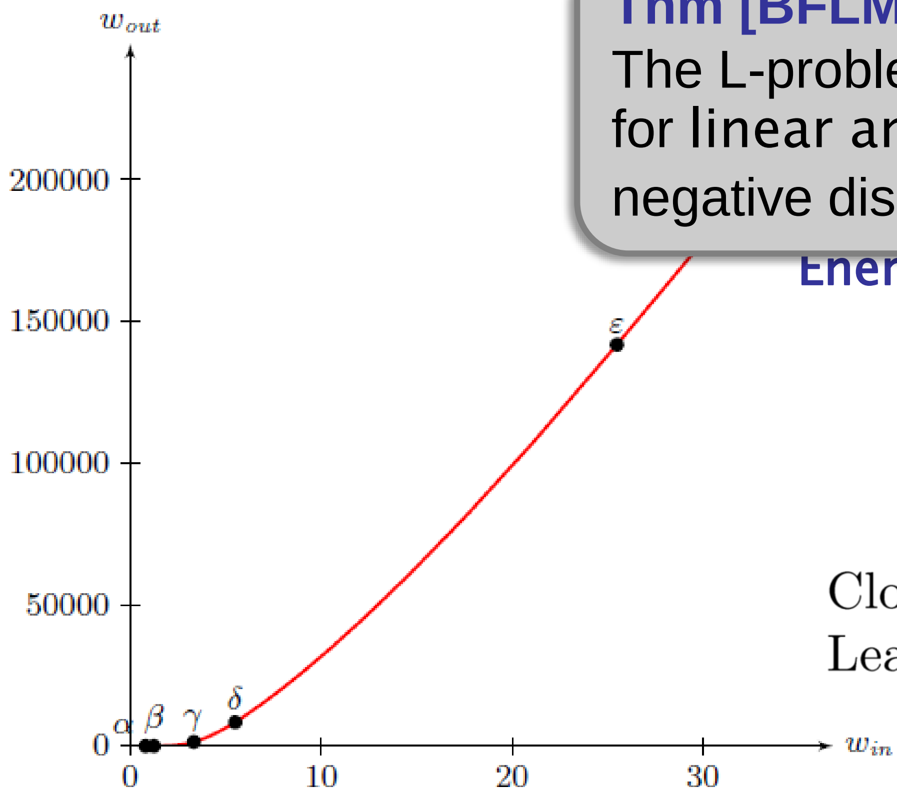
P. Bouyer, U. Fahrenberg, K. G. Larsen, N. Markey: Timed automata with observers under energy constraints. HSCC 2010

Exponential PTA

$$\frac{dE}{dt} = 2E$$



Thm [BFLM09]:
The L-problem is **decidable**
for linear and exponential 1-clock PTAs with negative discrete updates.



Energy Function

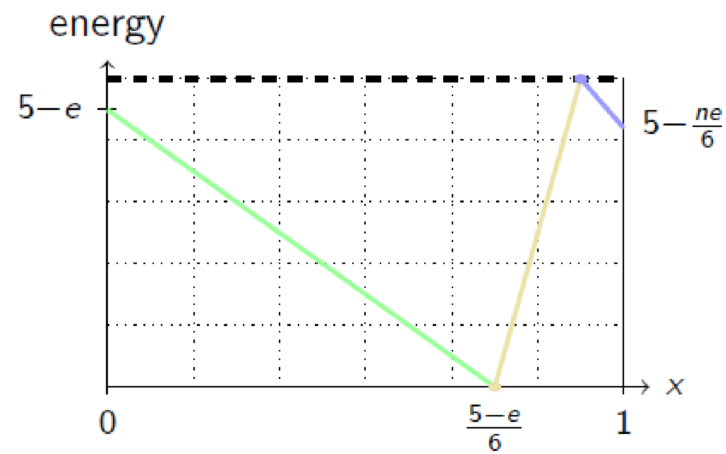
- $f : x \mapsto \alpha \cdot x^r + \beta$ where r is rational
- $\frac{df}{dt} \geq 1$

Closed under max and composition.
Least fixed point computable.

P. Bouyer, U. Fahrenberg, K. G. Larsen, N. Markey: Timed automata with observers under energy constraints. HSCC 2010

Multiple Costs & Clocks

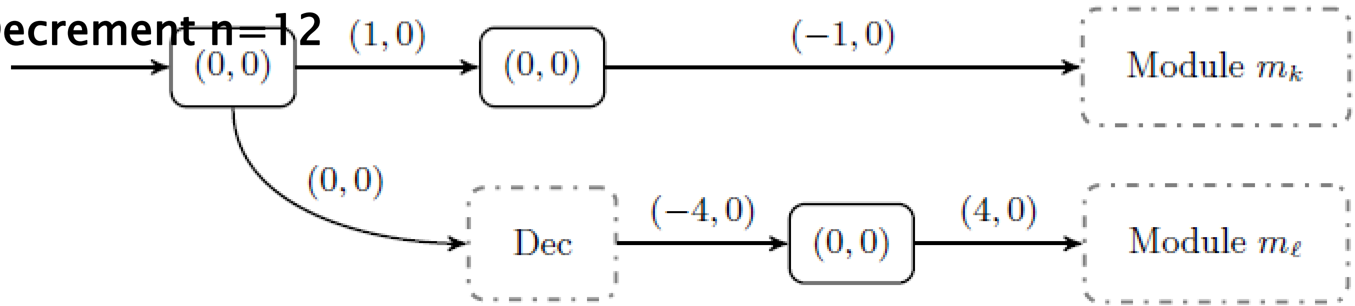
- LU Problem **Undecidable**
  - 2 clocks + 2 costs [1]
  - 1 clock + 2 costs [2]
  - 2 clocks + 1 cost [3]



Test-Dec / Update-Decrement

Increment n=3

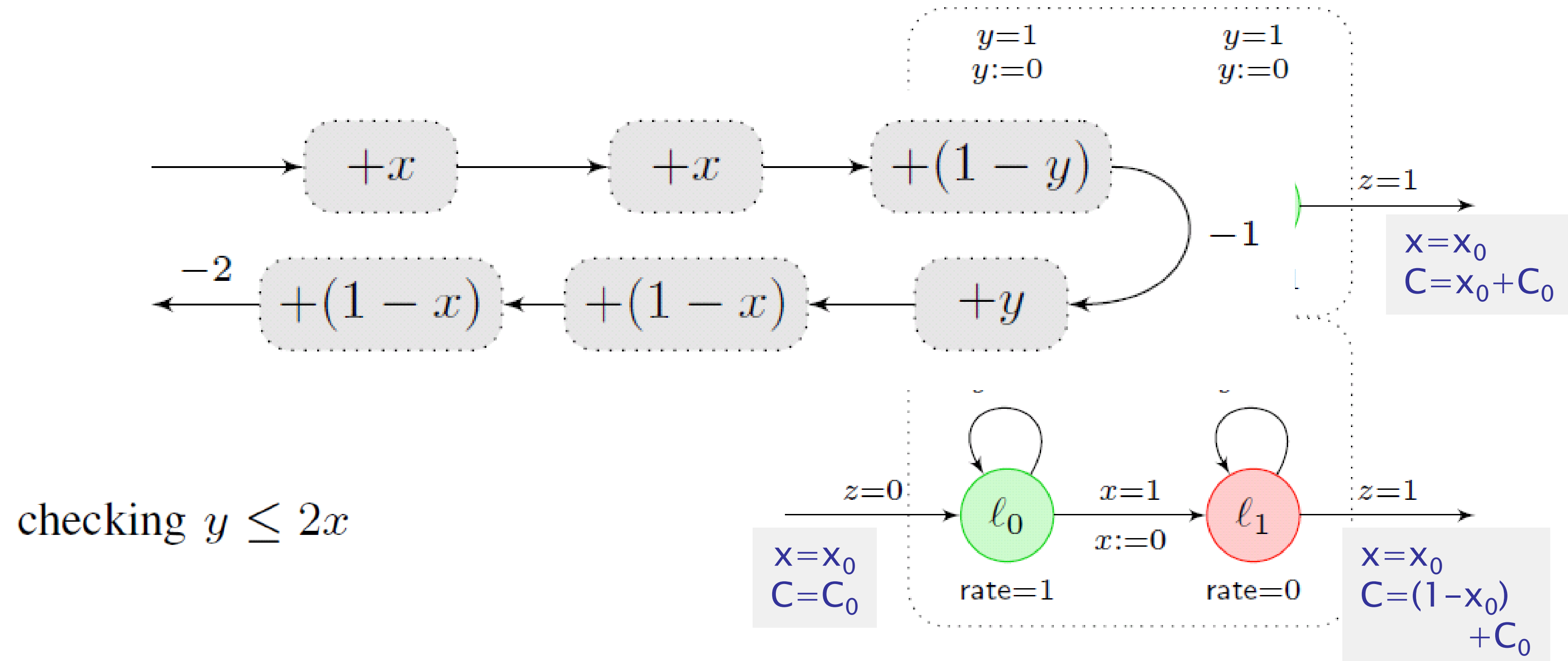
Decrement n=12



(1) Karin Quaas. On the interval-bound problem for weighted timed automata. 2011.
(2) Uli Fahrenberg, Line Juhl, Kim G. Larsen, and Jiri Srba. Energy games in multiweighted automata. 2011
(3) Nicolas Markey. Verification of Embedded Systems – Algorithms and Complexity. 2011.

Multiple Clocks & 1 Cost

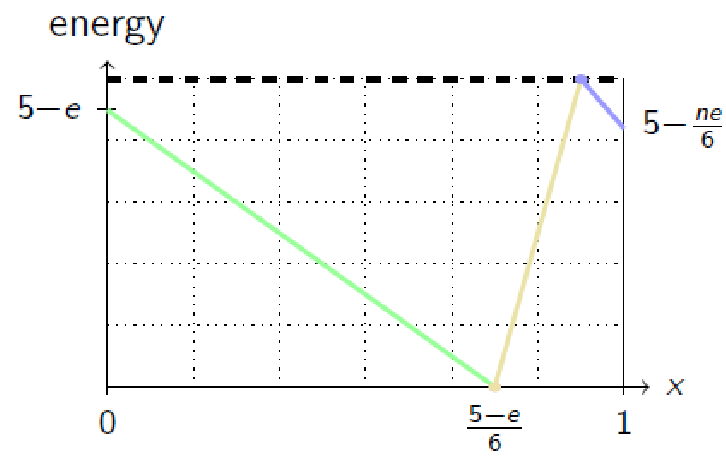
- L problem is **undecidable**
  - 4 clocks or more



P. Bouyer, K. G. Larsen, and N. Markey. Lower-bound constrained runs in weighted timed automata. QEST 2012

Upper Bounds

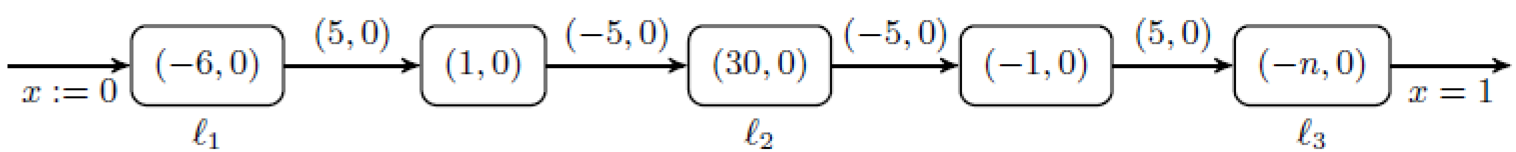
- LU Problem **Undecidable**
  - 2 clocks + 2 costs [1]
  - 1 clock + 2 costs [2]
  - 2 clocks + 1 cost [3]



Update c_1

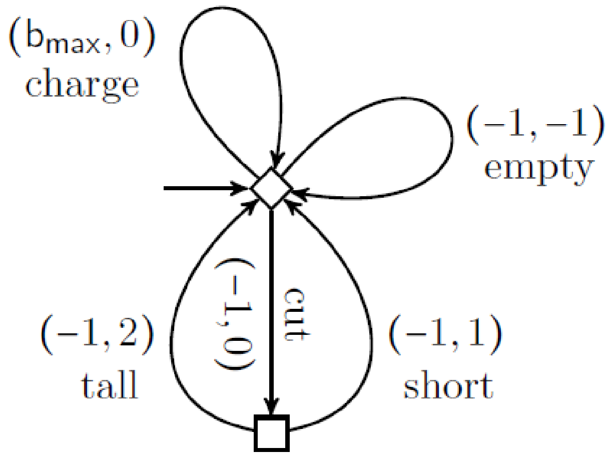
Increment n=3

Decrement n=12



(1) Karin Quaas. On the interval-bound problem for weighted timed automata. 2011.
(2) Uli Fahrenberg, Line Juhl, Kim G. Larsen, and Jirı Srba. Energy games in multiweighted automata. 2011
(3) Nicolas Markey. Verification of Embedded Systems – Algorithms and Complexity. 2011.

Multiple Costs & 0 Clocks

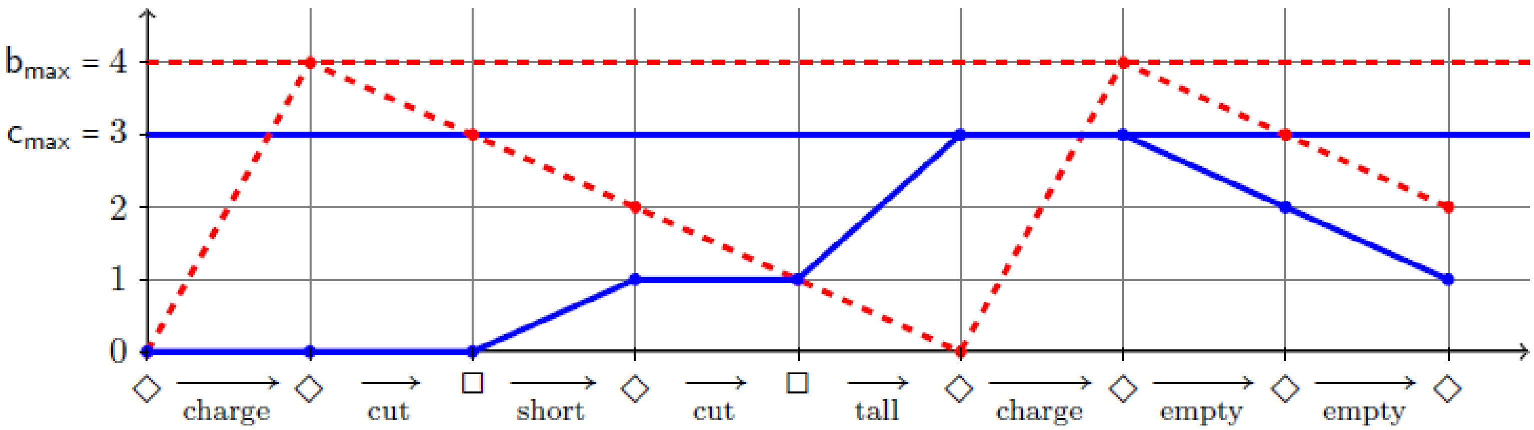


$b_{max} = 4$ (battery capacity)
$c_{max} = 3$ (container capacity)

if *battery* $= 0$ **then** charge

else if *battery* ≥ 2 **and** *container* ≤ 1 **then** cut

else if *battery* ≥ 1 **and** *container* ≥ 1 **then** empty



Uli Fahrenberg, Line Juhl, Kim G. Larsen, and Jirı Srba. Energy games in multiweighted automata. 2011

Multiple Costs & 0 Clocks

# weights	Bound	Existential	Universal	Game
One	L	$\in$ P [4]	$\in$ P [4]	$\in$ UP $\cap$ coUP [4]
	LW	$\in$ P [4]	$\in$ P [4]	$\in$ NP $\cap$ coNP [4]
	LU	NP-hard [4], $\in$ PSPACE [4]	$\in$ P [4]	EXPTIME-complete [4]
Fixed ($k > 1$)	L	**NP-hard**, $\in$ k-EXPTIME [3] (Remark 17)	$\in$ P (Remark 18)	**EXPTIME-hard**, $\in$ k-EXPTIME [3] (Remark 19)
	LW	**NP-hard**, $\in$ **PSPACE** **PSPACE-complete** for $k \geq 4$ (Remark 20)	$\in$ P (Remark 18)	**EXPTIME-complete** (Remark 21)
	LU	**PSPACE-complete** (Remark 20)	$\in$ P (Remark 18)	**EXPTIME-complete** (Remark 21)
Arbitrary	L	**EXPSPACE-complete** (Theorem 9)	$\in$ P (Remark 18)	**EXPSPACE-hard** (from EL) decidable [3]
	LW	**PSPACE-complete** (Theorem 9)	$\in$ P (Remark 18)	**EXPTIME-complete** (Remark 21)
	LU	**PSPACE-complete** (Theorem 9)	$\in$ P (Remark 18)	**EXPTIME-complete** (Remark 21)

Uli Fahrenberg, Line Juhl, Kim G. Larsen, and Jirı Srba. Energy games in multiweighted automata. 2011

Conclusion

- Priced Timed Automata a uniform framework for modeling and solving dynamic ressource allocation problems!
- Not mentioned here:
  - Model Checking Issues (ext. of CTL and LTL).
- Future work:
  - Zone-based algorithm for optimal infinite runs.
  - Approximate solutions for priced timed games to circumvent undecidablity issues.
  - Open problems for Energy Automata.
  - Approximate algorithms for optimal reachability