UPPAAL **now, next, and future**

meet a family of model checkers

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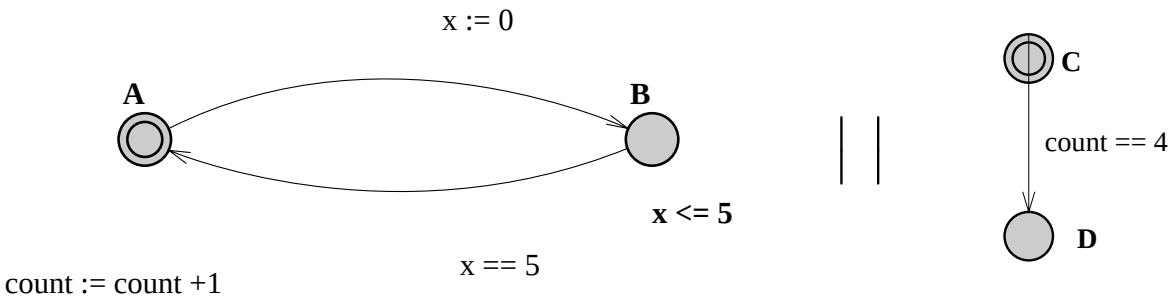
Outline:

1. Model-checking with UPPAAL
2. Internal Optimizations
3. Extensions of the timed automata model
4. Some recent case studies

UPPAAL: Model checking Timed Automata



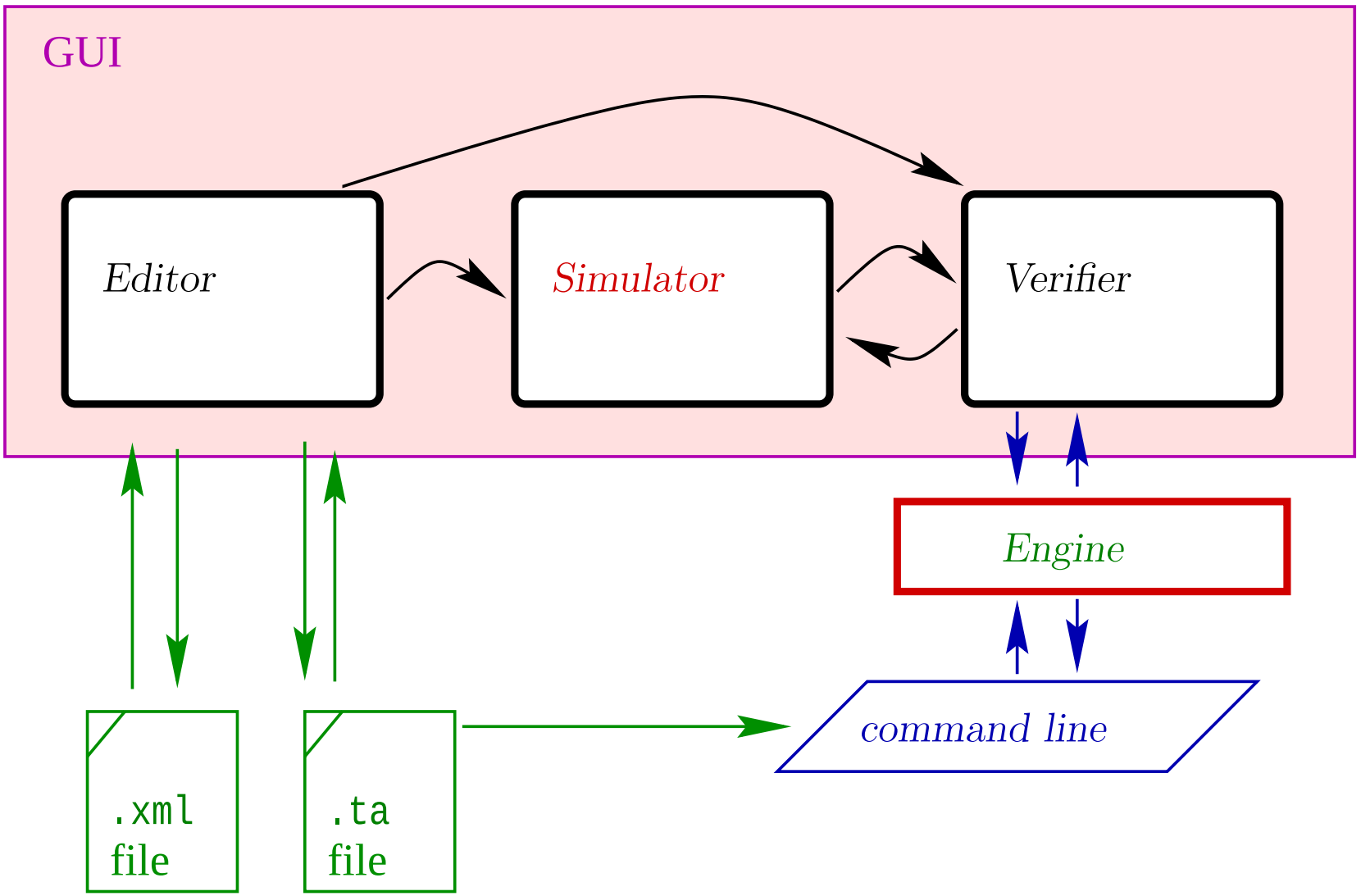

```
clock x; int count
```

Only subset of TCTL supported:

`E<>` φ	reachability
`A[]` φ	safety (invariantly φ)
`E[]` φ	possibly always φ
`A<>` φ	inevitably φ
`A[]` $\varphi \Rightarrow$ `A<>` ψ	unbounded response

φ, ψ : propositional formula over locations and (existing) clocks

Architecture of UPPAAL



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 $\vec{l} \xrightarrow{g,r} \vec{l'}$

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

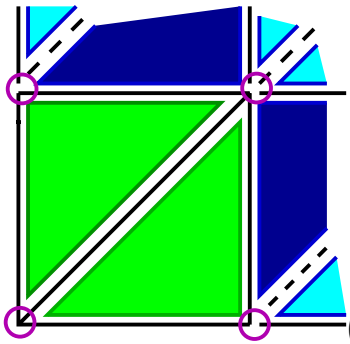
$v' \neq \varnothing$

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

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

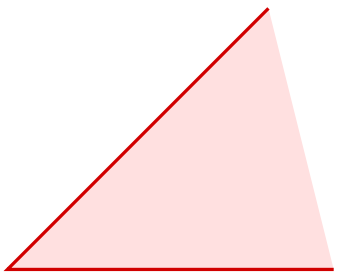
Sets of Clock-Evaluations

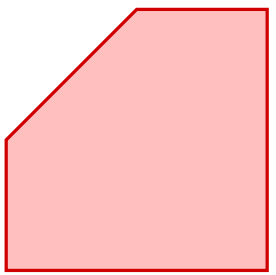
- regions: smallest distinguishable sets



(24 here)

- zones: unions of regions:





  For zones (or unions of them), there exist various data structures DBMs, CDDs, DDDs, ...

- basic operations:

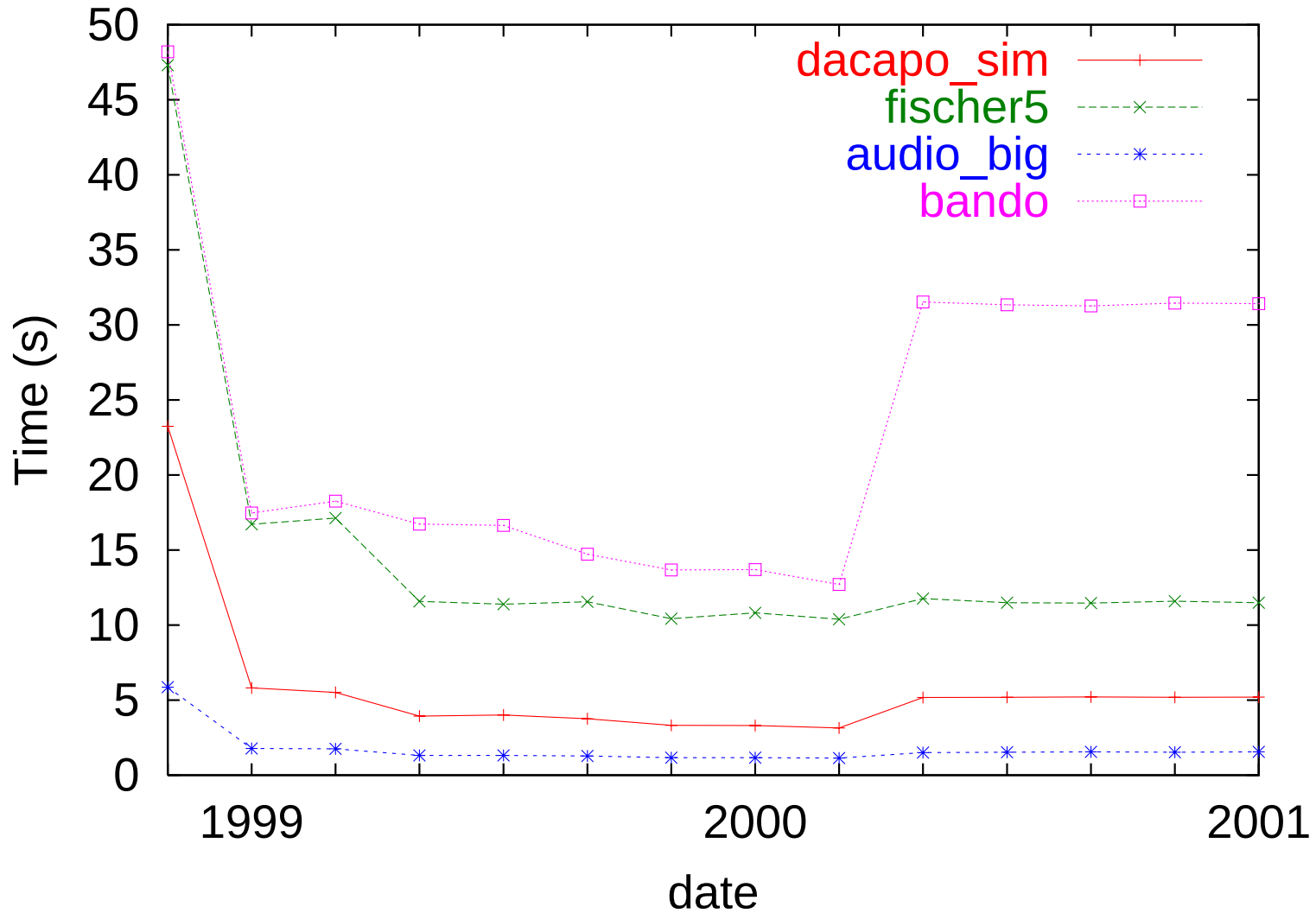
$. \cap .$	$: R \times R \rightarrow R$	intersection
$.^{\uparrow}$	$: R \rightarrow R$	delay
$. \subseteq .$	$: R \times R \rightarrow \mathit{bool}$	containment

Internal Optimizations

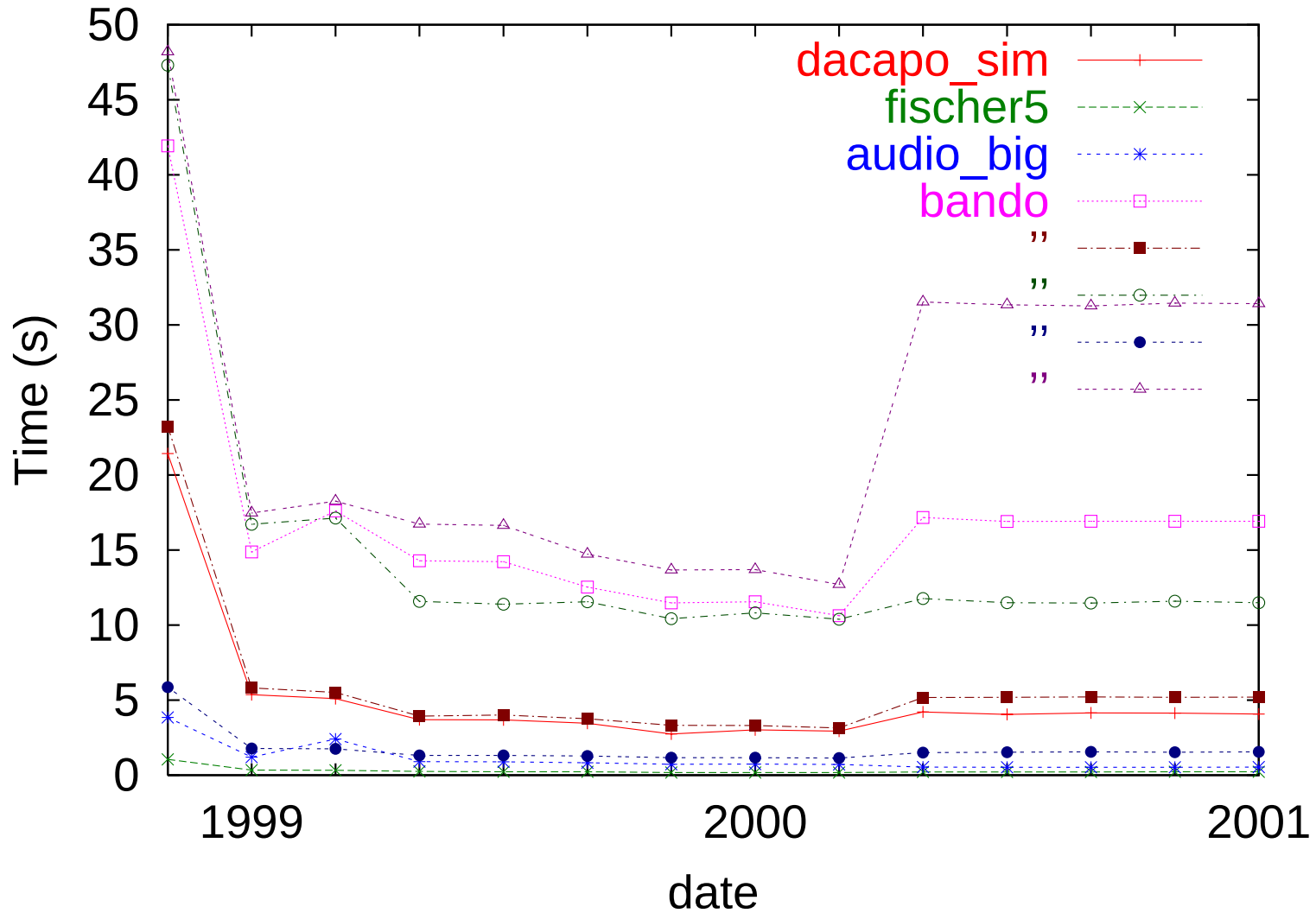
- × committed locations (to reduce interleavings)
- × active clock reduction
- × variation of search order
- × local reduction (compact DBM representation)
- × global reduction (remove covered states from *Passed*)
- ≈ convex hull over-approximation [safe]
- ≈ bit-state hashing [sound]

... and of course: *a lot of software engineering!*

Benchmarks (without optimizations)



Benchmarks (with optimizations)



Compact Data Structures

Each state encoded as a number, according to a multiply-and-add scheme:

(1) encode *both* location and DBM with this scheme

large space savings

expensive inclusion check

(2) encode DBMs as bit-strings for bounds

only small space savings

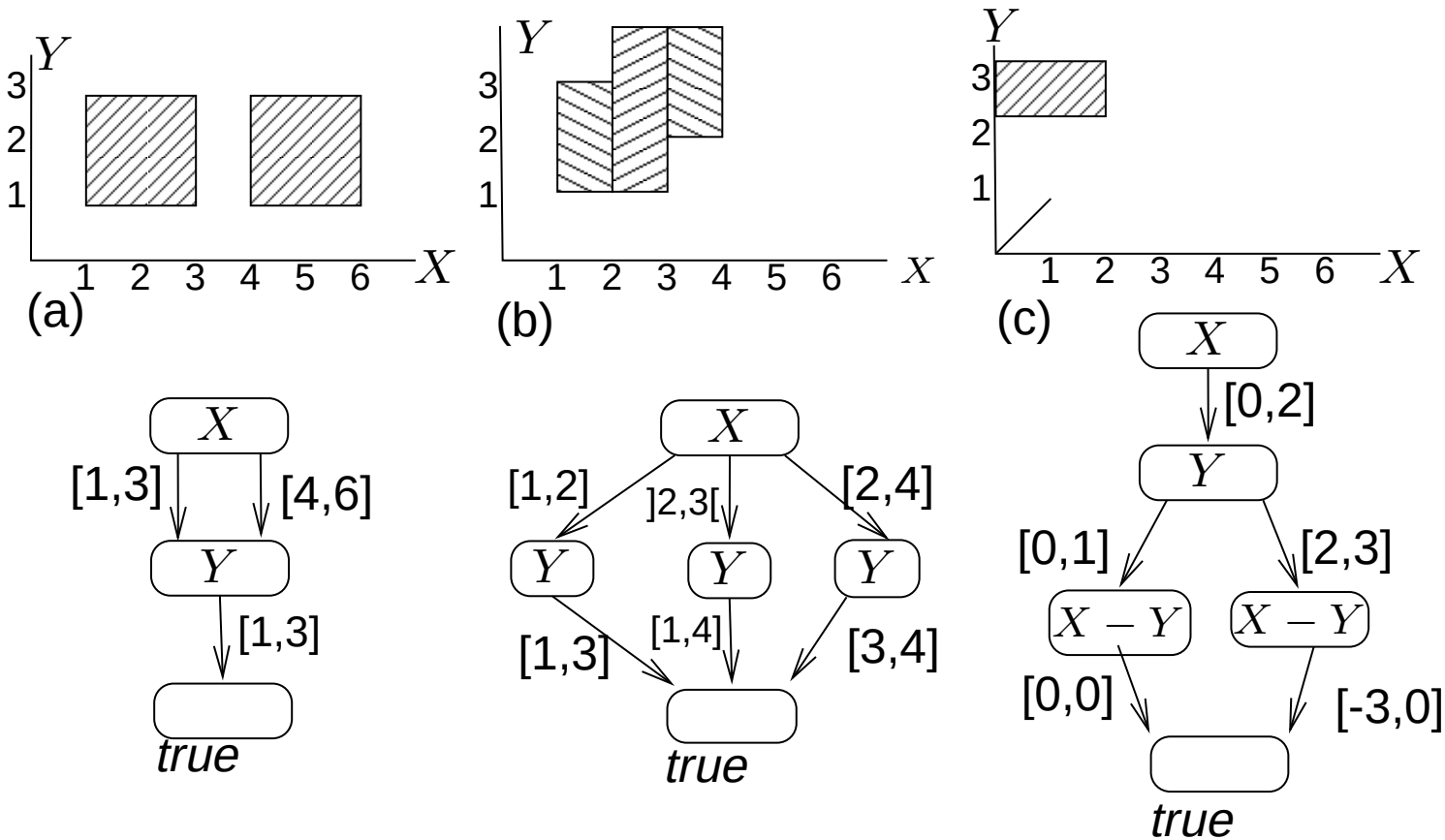
cheap inclusion check

Clock Difference Diagrams (CDDs)

Data structure to express disjunction of zones

- $\rightarrow$ similar to BDDs
- $\rightarrow$ rooted, directed, acyclic graph
- $\rightarrow$ every node labeled x or $x - y$
- $\rightarrow$ every edge labeled with an interval
- $\rightarrow$ order of labels fixed
- $\rightarrow$ one terminal node: $\mathbf{true}$
- $\rightarrow$ missing edges lead to $\mathbf{false}$
- ⚠ *not canonical*

Clock Difference Diagrams (CDDs) (2)



Distributed Execution of UPPAAL

Forward state-space exploration: spends most of the time browsing *Passed*

no strong interaction of steps

Idea: run state-space exploration on a cluster of machines

Difficulties: distribute work evenly

keep communication between nodes small

Approach: hash according to discrete part of state

order states locally according to smallest distance

Surprising: speed up usually close to linear

- and sometimes even *better*

Approximation by Dynamic Partitioning

Convex-hull approximation: over-approximates clock regions

Discrete part of the state: untouched

Idea: Group together *similar* control locations

Mayor Difficulty: Adjust the *level* of approximation

Approach: based on abstract interpretation
abstract lattice combines boolean and numerical properties
start with coarse abstraction & re£ne

Related: techniques used in tool NB$_{AC}$

Extensions of the Modeling Language

- → Stopwatch extension
- → Probabilistic timed automata
- → Hierarchical timed automata
- → Parameters on clock constraints
- → Cost-Optimal timed automata
- → Executable timed automata

Stopwatch UPPAAL

timed automaton + stopwatches = SWA

Fact: Any *timed language* accepted by a *linear hybrid automaton* can also be accepted by a *stopwatch automaton*

linear hybrid automaton —*translate*→ SWA

Problem: reachability analysis of SWA is undecidable

Observation: often it suffices to *over-approximate* reachability

Approach: run DBM-based SWA, with *approximative future*
(only differences of *two* stop-watches considered)

Notes: *way* to *translate* effects accuracy
more sophisticated translations could preserve *termination*

Probabilistic UPPAAL

Example Problem:

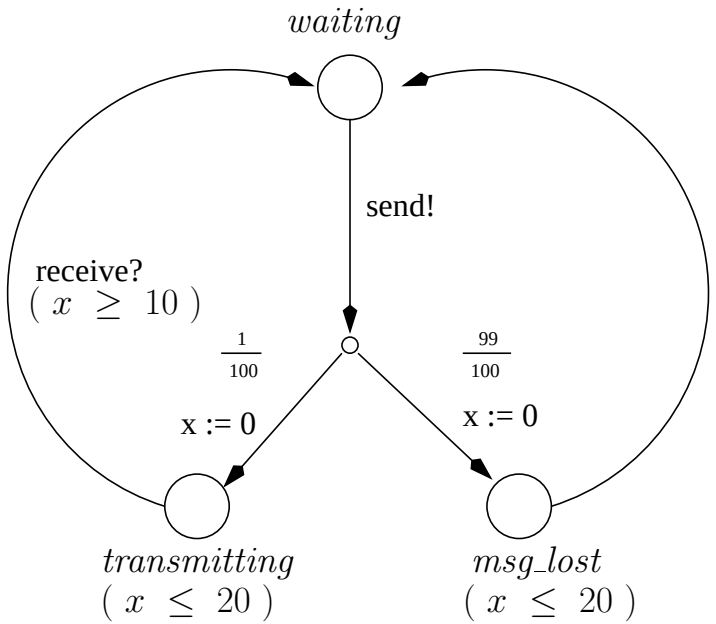
Lossy channel with known probabilites

Cannot prove:

in time X, message will arrive

But:

$P_{\geq 95\%}(\ \forall\Box_{\leq 1000}$ *received*)



existing Approaches: Jensen 96, Kwiatkowska et al. 99

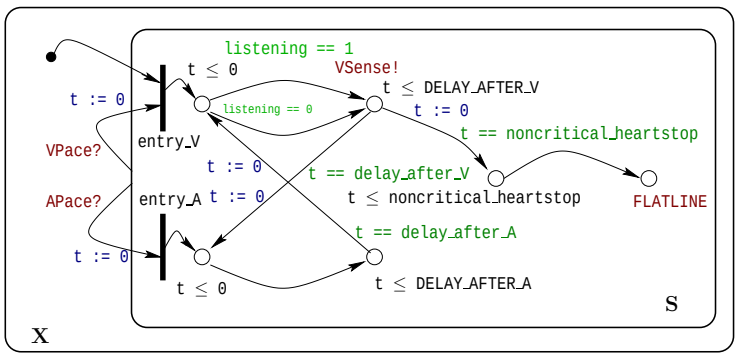
Problem: based on region graph construction

new Approach: use minimization techniques to obtain stable *probabilistic zone graphs*

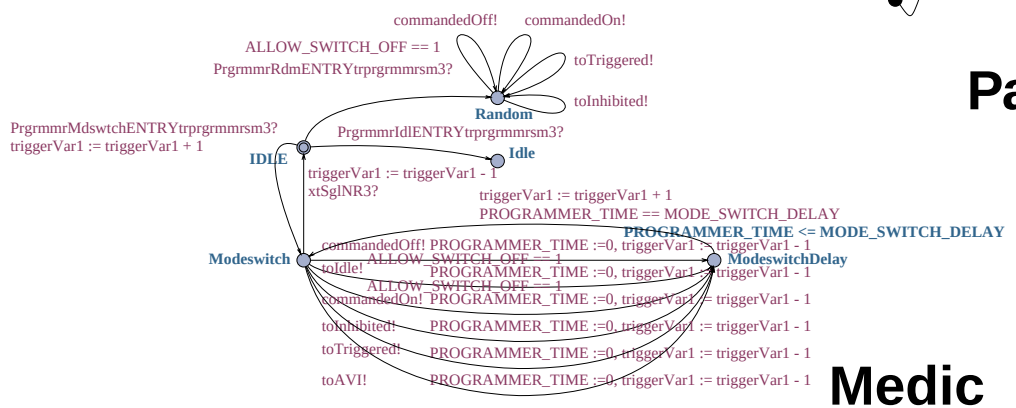
use matching data structure

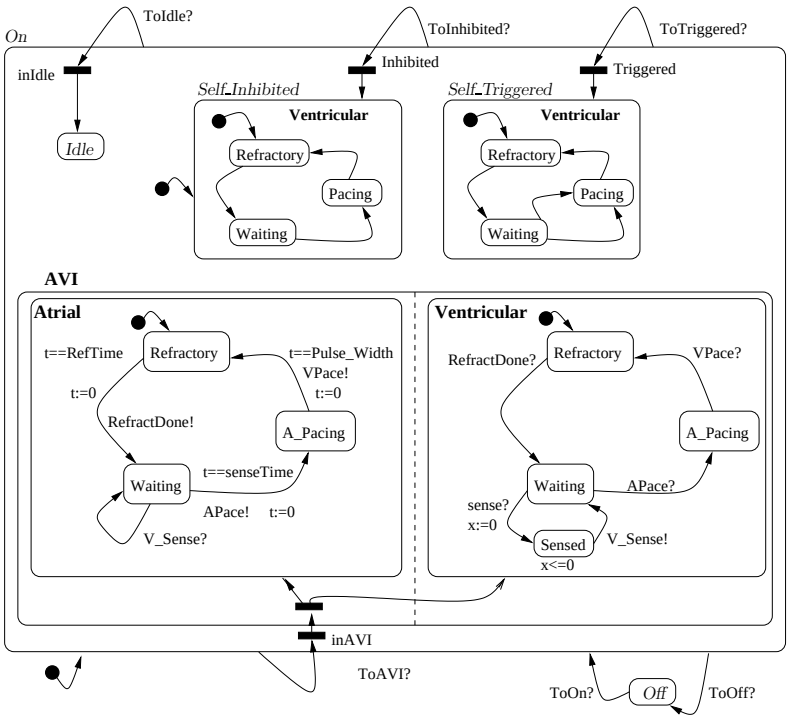
Hierarchical UPPAAL

Use hierarchical timed automata:



Human Heart





Pacemaker

Medic

Flattened Version of the Pacemaker

HTA model	# XML tags	564	$\longrightarrow$	1191	UPPAAL model
	# proper control locations	35	$\longrightarrow$	45	

- SAFETY:
  `A[] ¬heart stops`
- LIVENESS:
  `A[] Vcontract => A<> Acontract`

Parameters:

```
REFRACTORY_TIME  = 50
SENSE_TIMEOUT    = 15

DELAY_AFTER_V = 50
DELAY_AFTER_A =  5

MODE_SWITCH_DELAY  = 66
```

E.g. for `MODE_SWITCH_DELAY  = 65`, `A[] ¬heart stops` is violated

Determining Parameters: *Parametric-Uppaal*

Parameters: in clock guards $x \bowtie p$, $x - y \bowtie p$

$\bowtie \in \{<, \leq, =, \geq, >\}$, p a linear expression

Fact: parameterized timed reachability undecidable for systems with $\geq$3 clocks [AHV93]

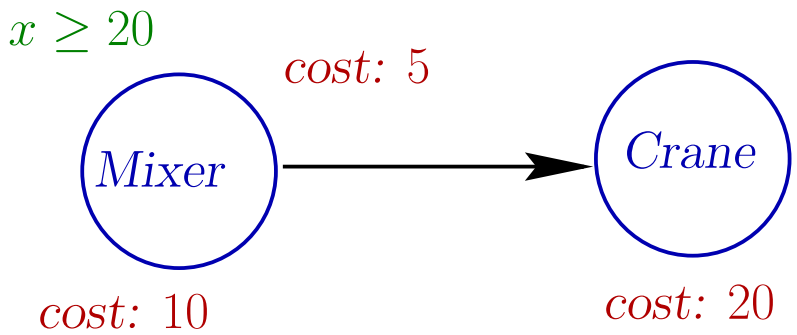
UPPAAL + LP solver (from PMC tool) = *semi*-algorithm

data-structure: parametric DBMs

modified algorithm: split, if the outcome of a comparison is dependent on parameter values

not guaranteed to terminate $\Rightarrow$ output partial solutions

Cost-Optimality



Idea: Add *cost* to locations and actions

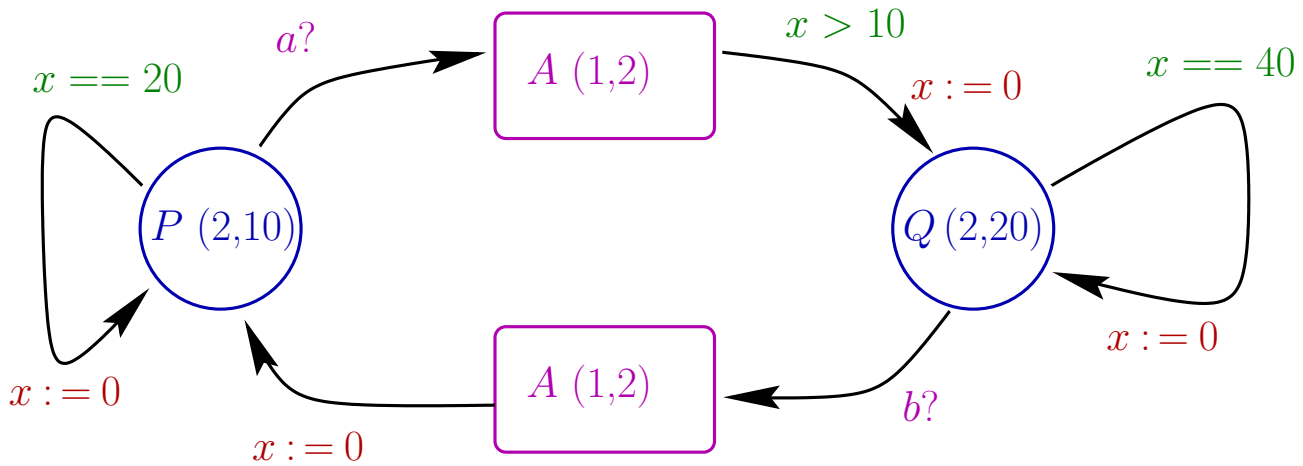
Starting Point: 'cost' not necessarily uniform

Approach: attach different (integer) prices to locations
treat algorithmically with *priced zones*

Applied: compute schedule for a steel batch plant in Ghent
and a LEGO model of it [Feh99, HLP00]

Fact: Cost-Optimal trace is computable

Executable Timed Automata



Periodic Tasks P, Q Spontaneous Tasks A, B

Parameters: worst-case execution time, deadline

Delay transition	$\equiv$	execute task with earliest deadline
Action transition	$\equiv$	releases a new task
Automaton schedulable	$\Leftrightarrow$	every $a!, b!$-sequence schedulable

Fact: added *Preemption* is as expressive as TAs with stop watches

Recent Case Studies

[LAM99] **part of ADA run-time complex formally verified**

- ⋆ uses Ravenscar Tasking Profile to implement concurrency part (to eliminate most implementation)
- ⋆ prove fourteen properties with UPPAAL
  one depends directly on an upper bound on a real-time clock value

[DY00] **commercial field bus communication protocol AF100**

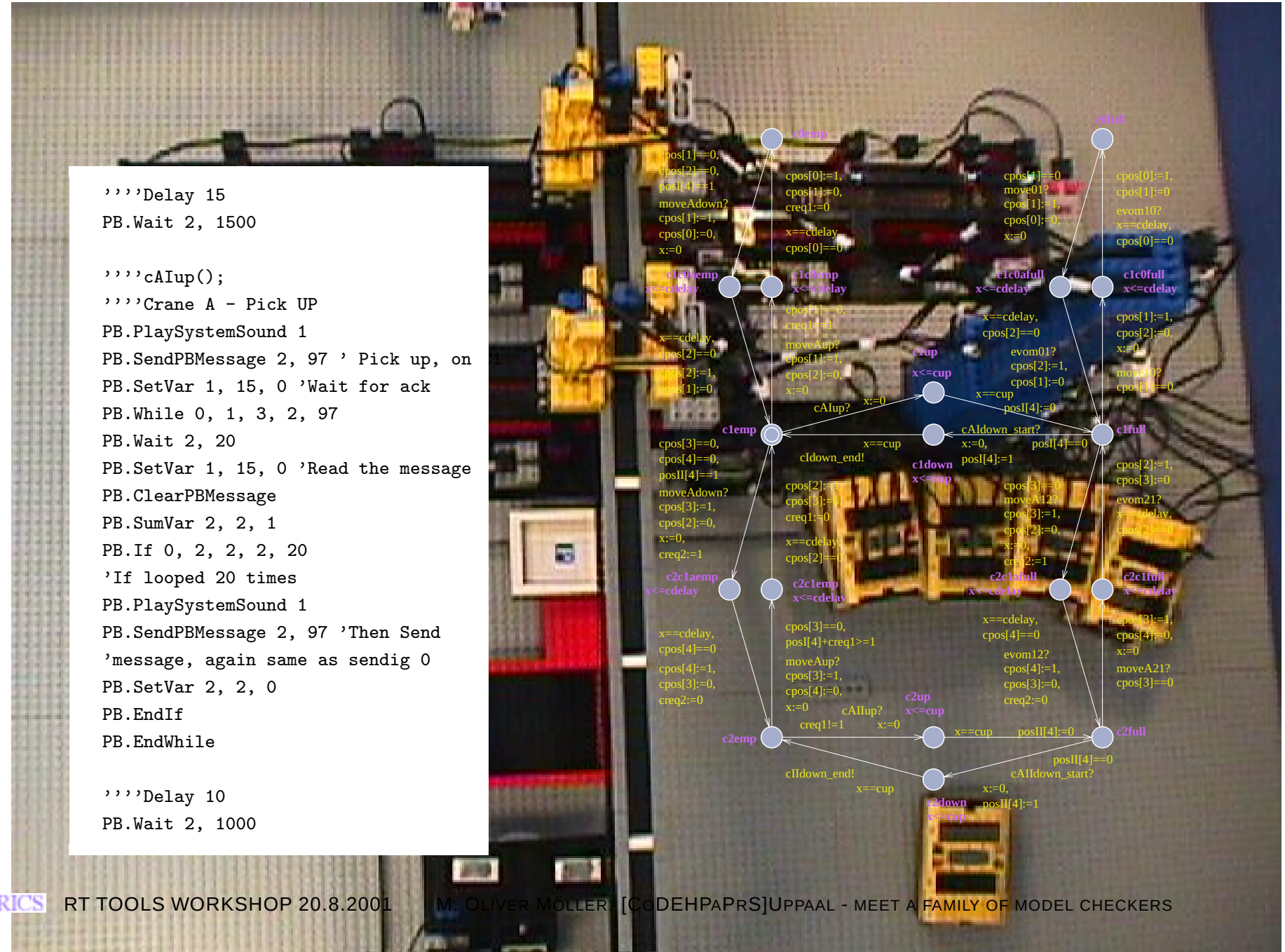
- ⋆ developed for safety-critical applications
- ⋆ been running all over the world for > 10 years
- ⋆ shows occasionally unexpected behaviors
- ⋆ ¤aws in protocol logic and implementation found

A case study with a LEGO plant

```
''''Delay 15
PB.Wait 2, 1500

''''cAIup();
''''Crane A - Pick UP
PB.PlaySystemSound 1
PB.SendPBMessage 2, 97 ' Pick up, on
PB.SetVar 1, 15, 0 'Wait for ack
PB.While 0, 1, 3, 2, 97
PB.Wait 2, 20
PB.SetVar 1, 15, 0 'Read the message
PB.ClearPBMessage
PB.SumVar 2, 2, 1
PB.If 0, 2, 2, 2, 20
'If looped 20 times
PB.PlaySystemSound 1
PB.SendPBMessage 2, 97 'Then Send
'message, again same as sendig 0
PB.SetVar 2, 2, 0
PB.EndIf
PB.EndWhile

''''Delay 10
PB.Wait 2, 1000
```



Ongoing Case-Study

[AJ01] **Saab Car Locking System**

- ⋆ UPPAAL applied to model and analyze
- ⋆ derived from functional requirements
- ⋆ communication network attached to the physical hardware to lock or unlock doors, trunk lid, etc
- ⋆ distributed over several nodes
- ⋆ input sources: different kinds of remote controllers, speed sensors, automatic re-locking timeouts

... you will hear more about this later!

UPPAAL in the European WOODDES project

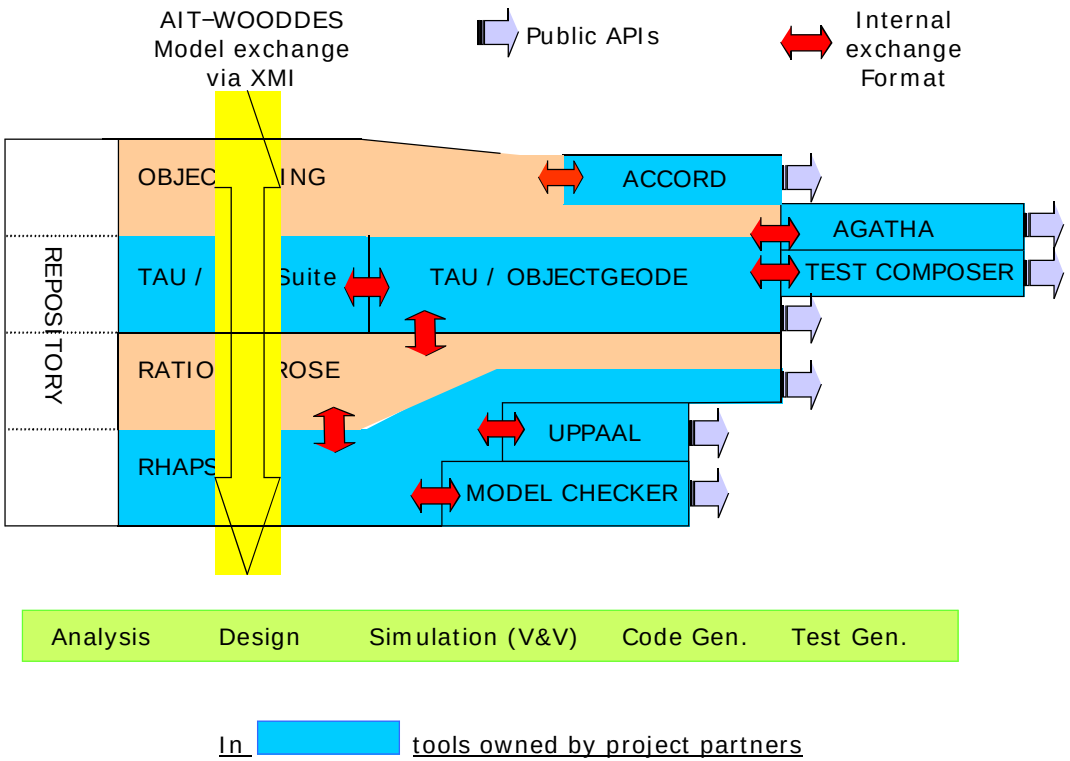
Workshop for Object-Oriented Design and Development of Embedded Systems

Partners:

- PSA
- Mecel
- CEA
- Telelogic
- I-Logix
- Intracom
- Offis
- Uppsala
- Aalborg

Objectives:

- UML Real-Time profile
- WOODDES methodology & tool platform



Completed Parts

- ✔ cost-optimal extension
- ✔ parametric extension
- ✔ distributed UPPAAL

Work in Progress

- → probabilistic extension
- → hierarchical extension
- → partial-order techniques
- → executable UPPAAL

Work Planned

- ⋆ dynamic partitioning
- ⋆ hybrid animation

Go, Get It!

UPPAAL2k (3.2beta) available for

Linux, SunOS, and MS Windows

`http://www.uppaal.com/`

Since July 1999: $>$ 800 downloads (from different users)

$>$ 60 countries

Open mailing list: `http://groups.yahoo.com/group/uppaal`

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