Statistical Model Checking in UPPAAL

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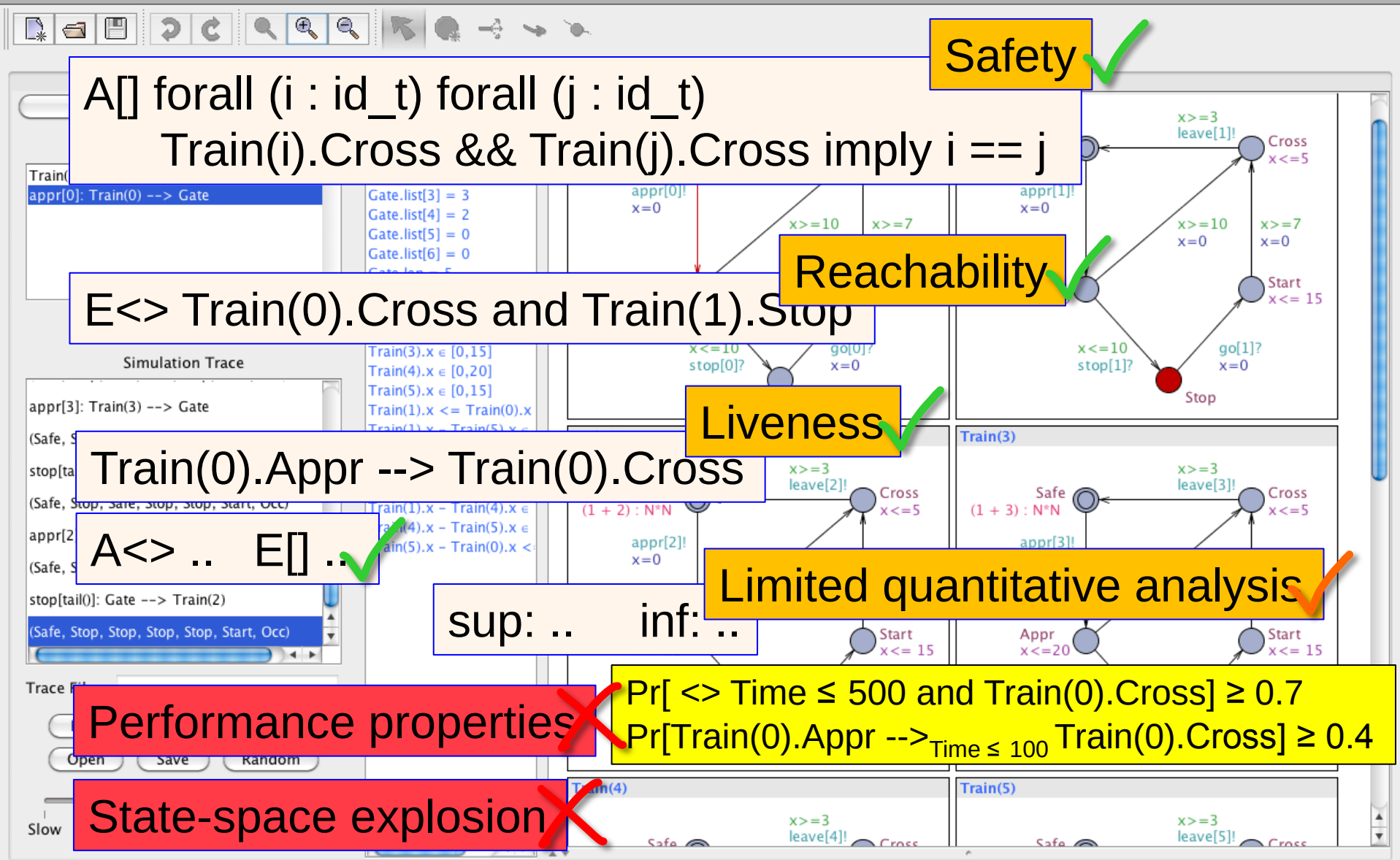
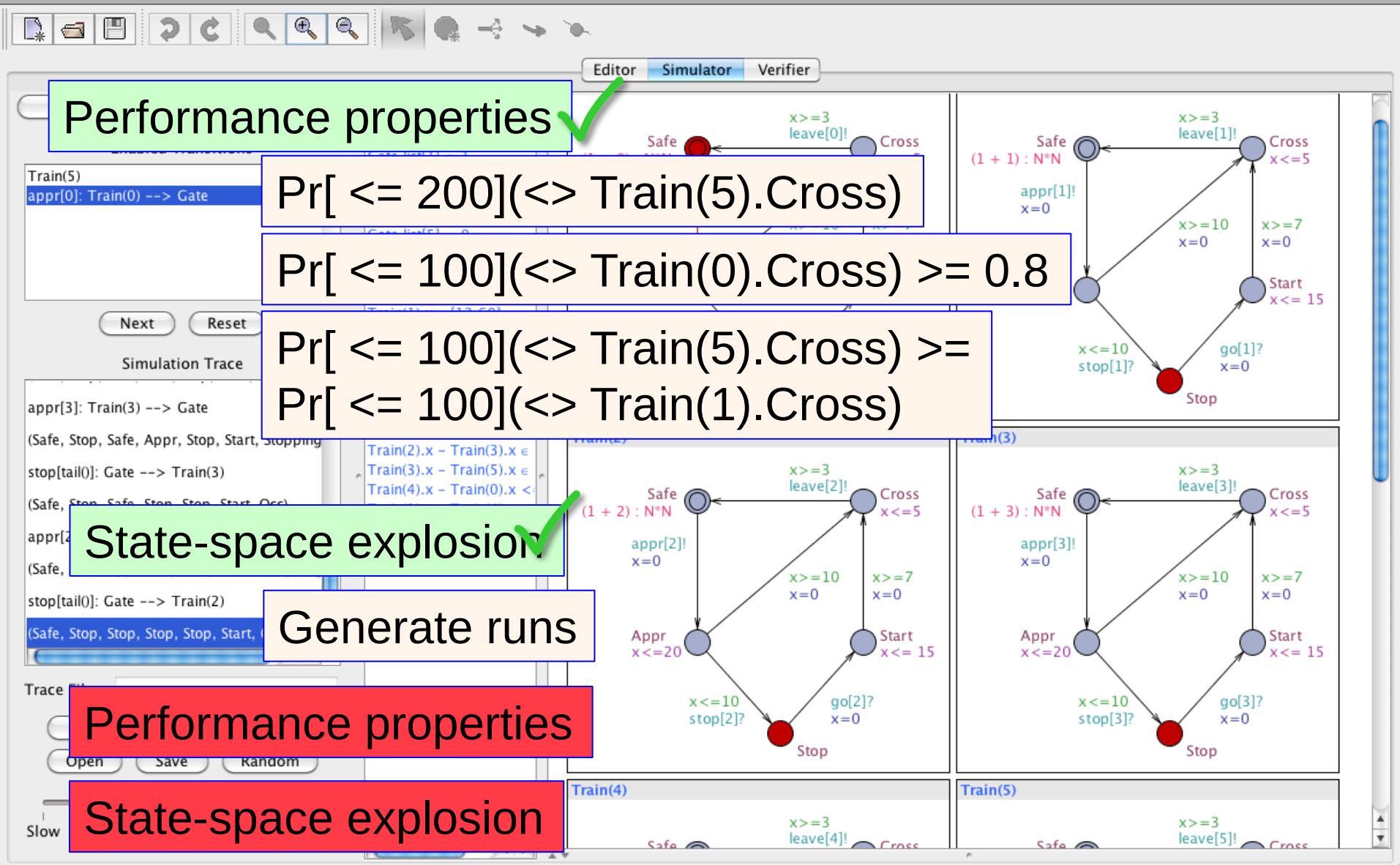
Dehui Du, Guangyuan Li

CAV 11, PDMC 11,FORMATS 11,
QAPL12, LPAR12, iWIGPL12, RV12,
FORMATS12, HBS12,ISOLA12,
SCIENCE China,NFM13,RV13,AVOCS13

UPPAAL


A[] forall (i : id_t) forall (j : id_t)
Train(i).Cross && Train(j).Cross imply i == j
Safety
E<> Train(0).Cross and Train(1).Stop
Reachability
Train(0).Appr --> Train(0).Cross
Liveness
A<> .. E[] ..
sup: .. inf: ..
Limited quantitative analysis
Performance properties
Pr[<> Time ≤ 500 and Train(0).Cross] ≥ 0.7
Pr[Train(0).Appr -->Time ≤ 100 Train(0).Cross] ≥ 0.4
State-space explosion
Simulation Trace
Train(0)
Train(1)
Train(2)
Train(3)
Train(4)
Train(5)
Cross
Start
Stop
Safe
Appr

UPPAAL SMC


Editor
Simulator
Verifier
Performance properties
Pr[<= 200](<> Train(5).Cross)
Pr[<= 100](<> Train(0).Cross) >= 0.8
Pr[<= 100](<> Train(5).Cross) >=
Pr[<= 100](<> Train(1).Cross)
State-space explosion
Generate runs
Performance properties
State-space explosion
Train(5)
appr[0]: Train(0) --> Gate
Next
Reset
Simulation Trace
appr[3]: Train(3) --> Gate
stop[tail()]: Gate --> Train(3)
stop[tail()]: Gate --> Train(2)
Open
Save
Random
Slow
Safe
Cross
Appr
Start
Stop
x>=3
leave[0]!
leave[1]!
leave[2]!
leave[3]!
leave[4]!
leave[5]!
(1 + 1) : N*N
(1 + 2) : N*N
(1 + 3) : N*N
appr[1]!
appr[2]!
appr[3]!
x=0
x>=10
x>=7
x<=5
x<=15
x<=20
x<=10
stop[1]?
stop[2]?
stop[3]?
go[1]?
go[2]?
go[3]?
Train(3)
Train(4)
Train(5)

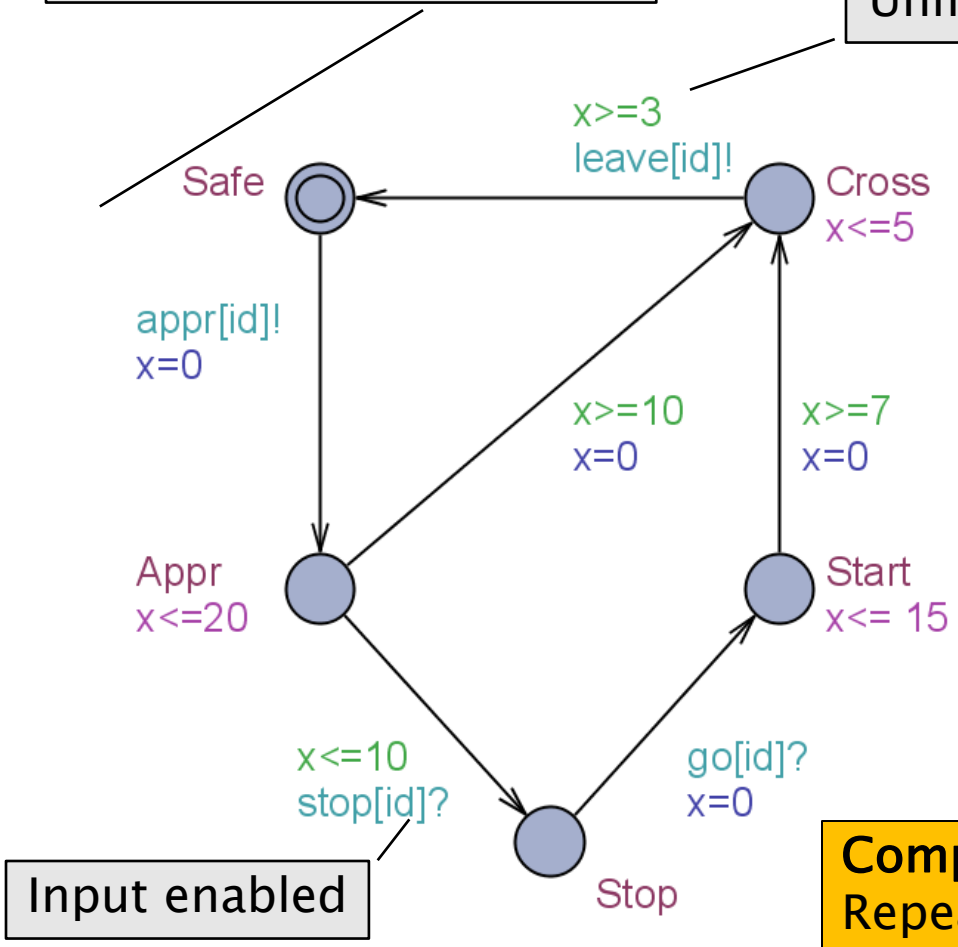
Overview

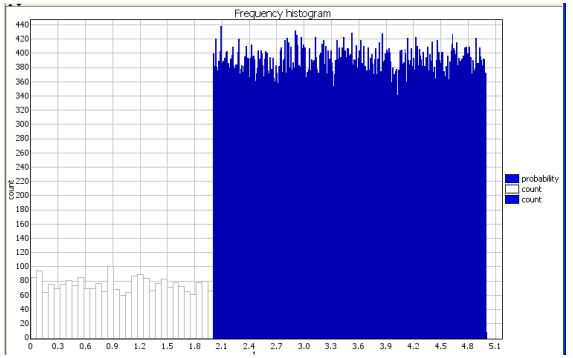
- Stochastic Semantics of Networks of Timed Automata
- Statistical Model Checking in UPPAAL
  - Estimation
  - Sequential Hypothesis Testing
  - Sequential Probability Comparison
  - Parameterized Probability Comparison
- SMC of Hybrid Automata
- Case Studies & Demo

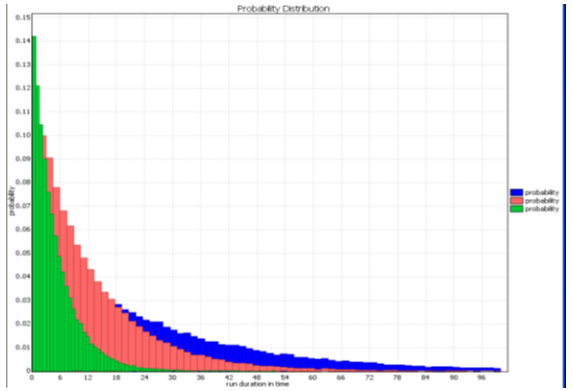
Stochastic Semantics of TA

Exponential Distribution

Uniform Distribution



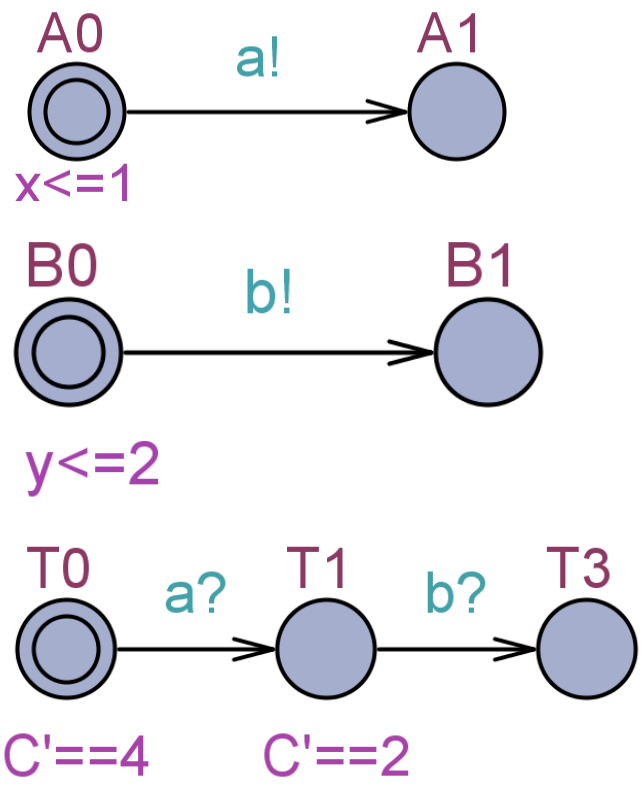




Input enabled

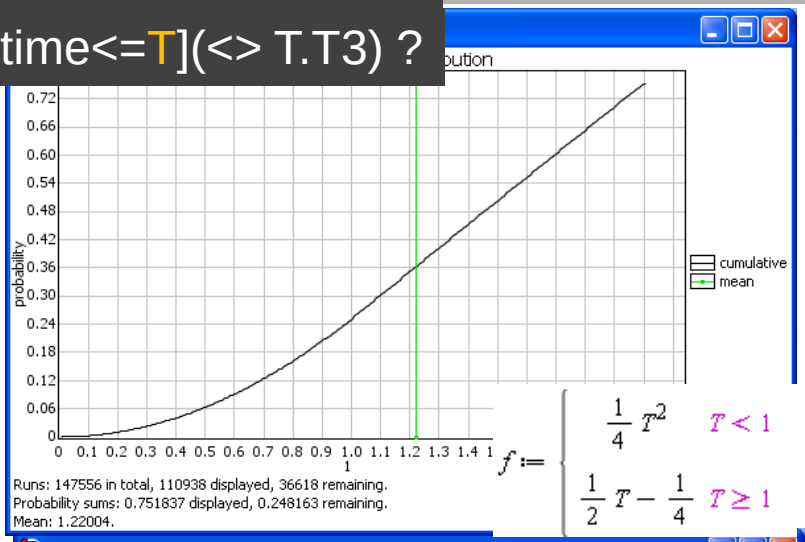
Composition =
Repeated races between components

Stochastic Semantics of Timed Automata

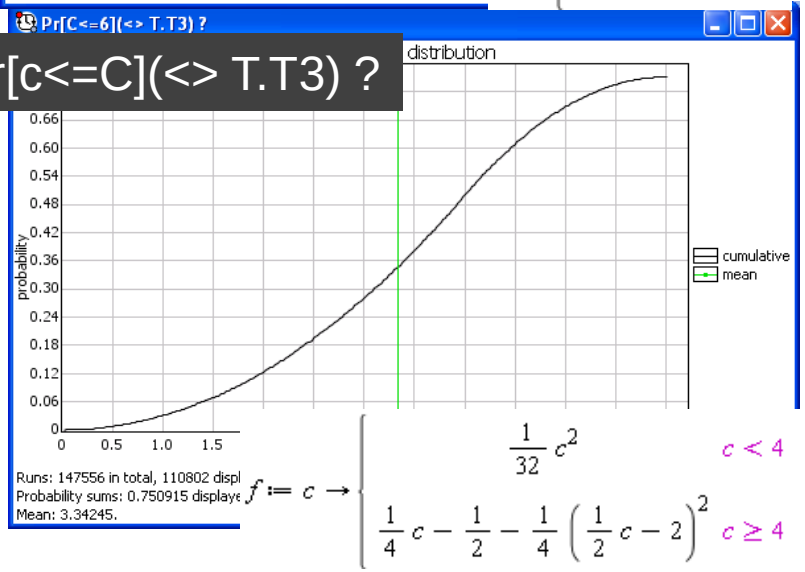


Composition = Race between components for outputting

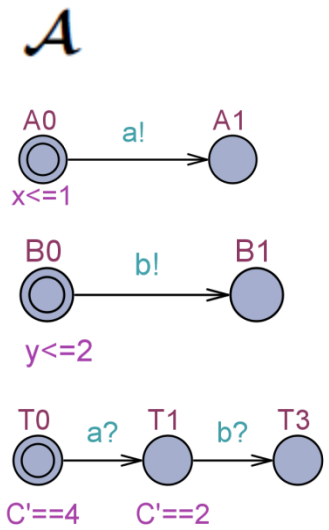
Pr[time<=T](<> T.T3) ?



Pr[c<=C](<> T.T3) ?



Stochastic Semantics of Timed Automata



Assumptions:
Component TAs are:
- Input enabled
- Deterministic
- Disjoint set of output actions

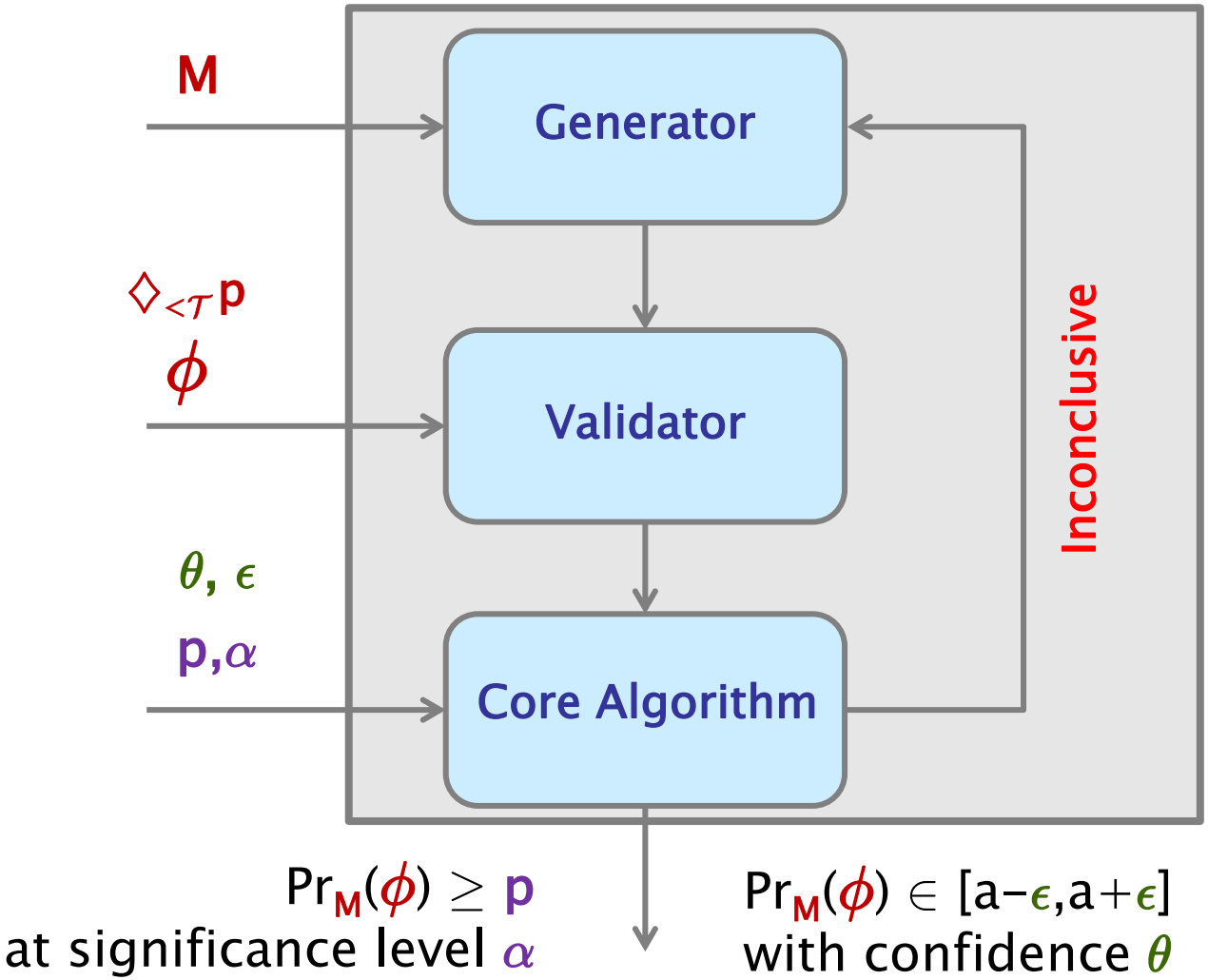
π (**s** , $a_1\ a_2\ \ldots.\ a_n$) :
the set of maximal runs from **s** with a prefix
$t_1\ a_1\ t_2\ a_2\ \ldots\ t_n\ a_k$
for some $t_1,\ldots,t_n \in \mathbf{R}$.

$$\mathbb{P}_{\mathcal{A}}\big(\pi(\mathbf{s},\, a_1 a_2 \ldots a_n)\big) =$$
$$\int_{t\geq 0} \mu_{s_c}(t) \cdot \Big(\prod_{j\neq c} \int_{\tau>t} \mu_{s_j}(\tau)\, d\tau\Big) \cdot \gamma_{s_c{}^t}(a_1) \cdot \mathbb{P}_{\mathcal{A}}\big(\pi(\mathbf{s}^t)^{a_1},\, a_2 \ldots a_n\big)\ dt$$

where $c = c(a_1)$, and as base case we take $P_{\mathcal{A}}(\pi(\mathbf{s}), \varepsilon) = 1$.

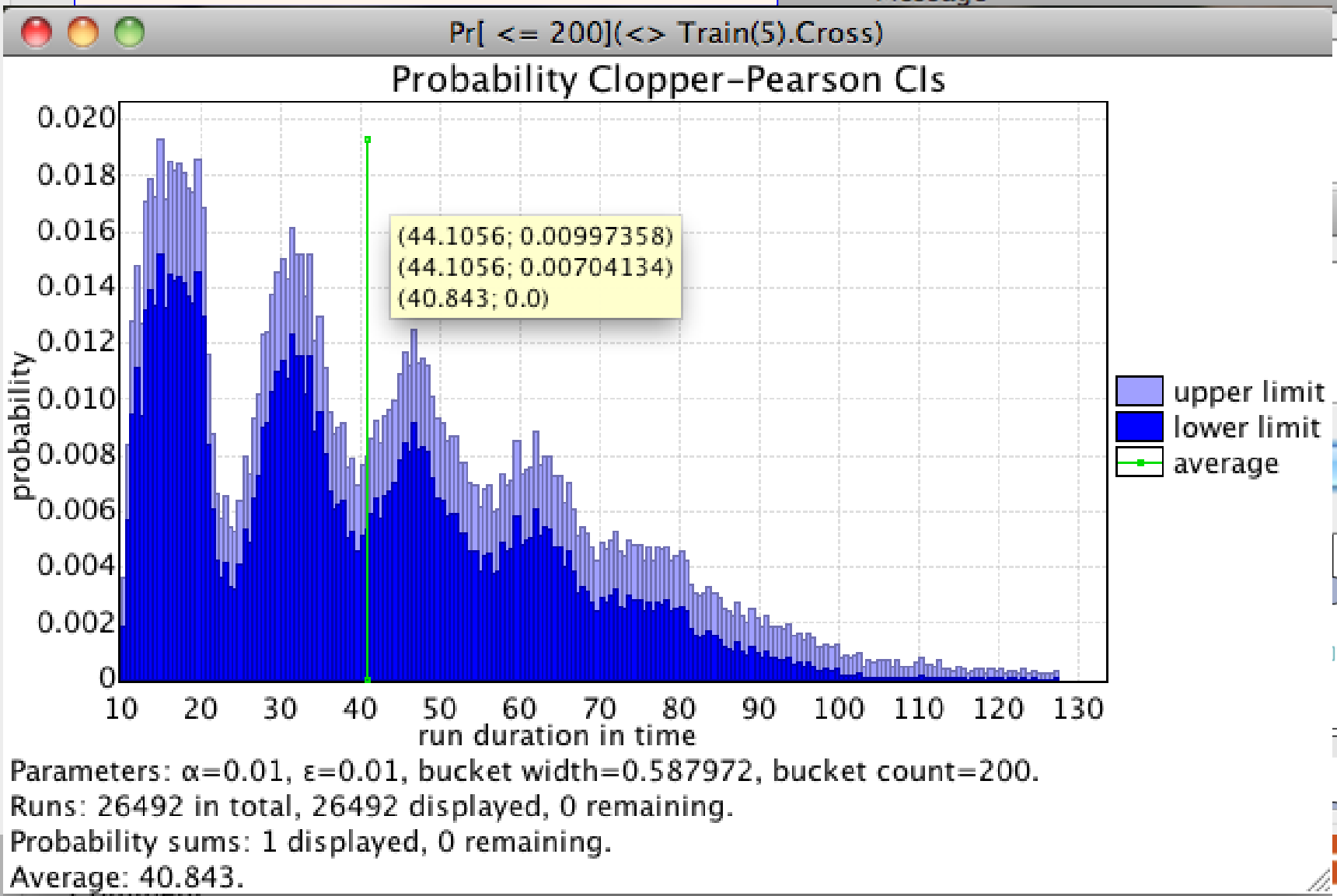
Statistical Model Checking

[FORMATS11, LPAR12, RV12]



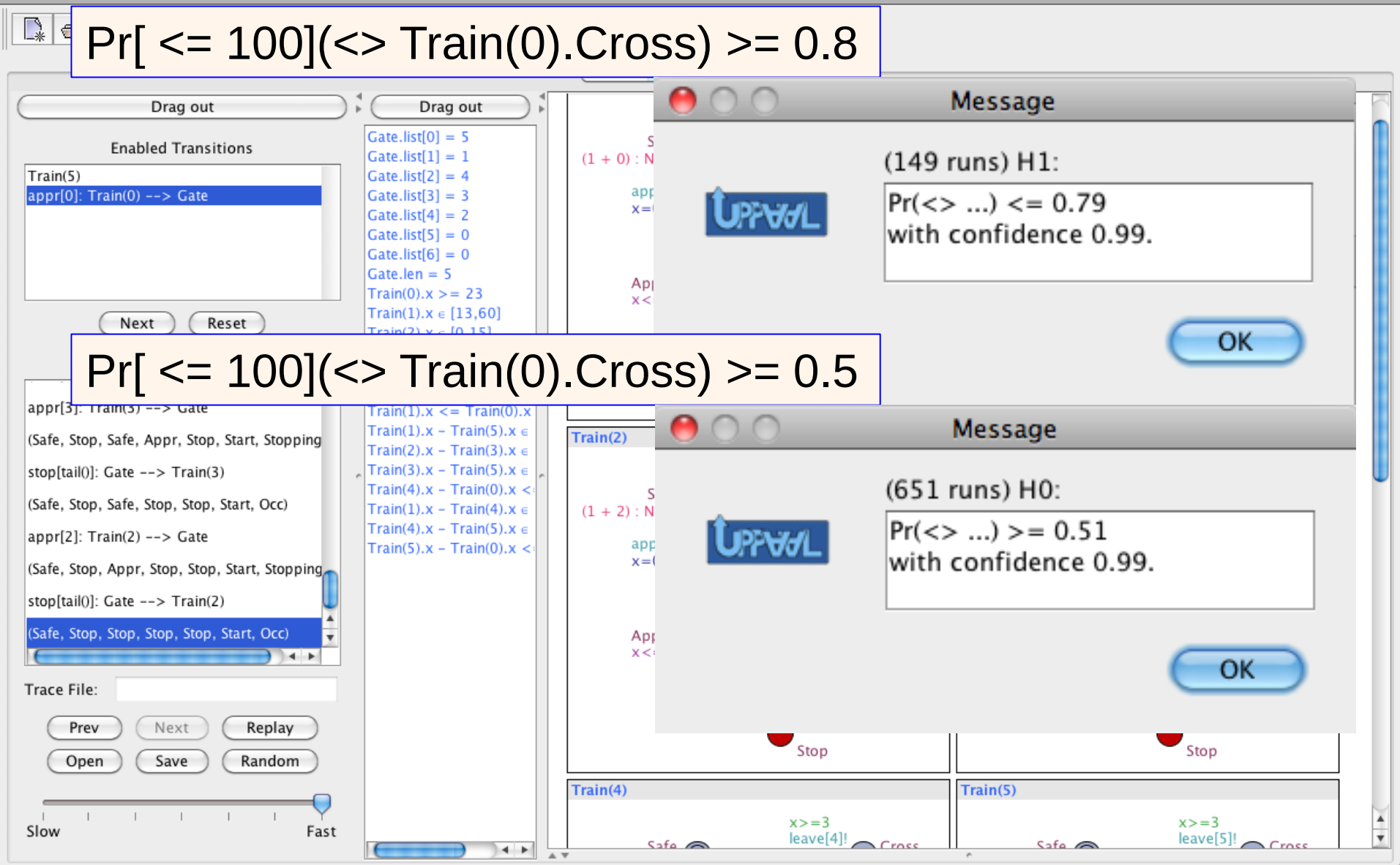
Queries in UPPAAL SMC

Pr[<= 200](<> Train(5).Cross)



Queries in UPPAAL SMC

Pr[<= 100](<> Train(0).Cross) >= 0.8



Pr[<= 100](<> Train(0).Cross) >= 0.5

Queries in UPPAAL SMC

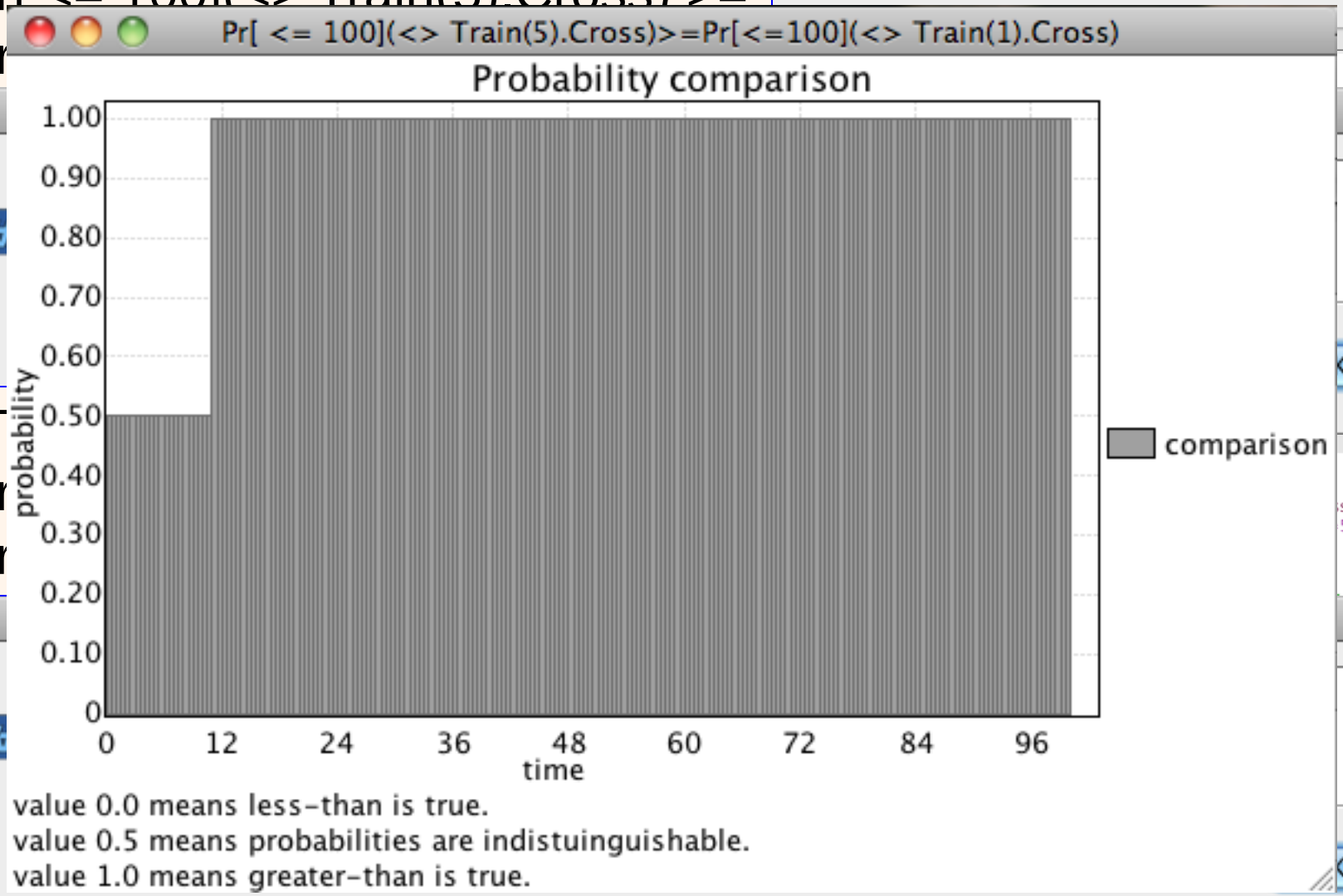
Pr[<= 100](<> Train(5).Cross) >=

Pr

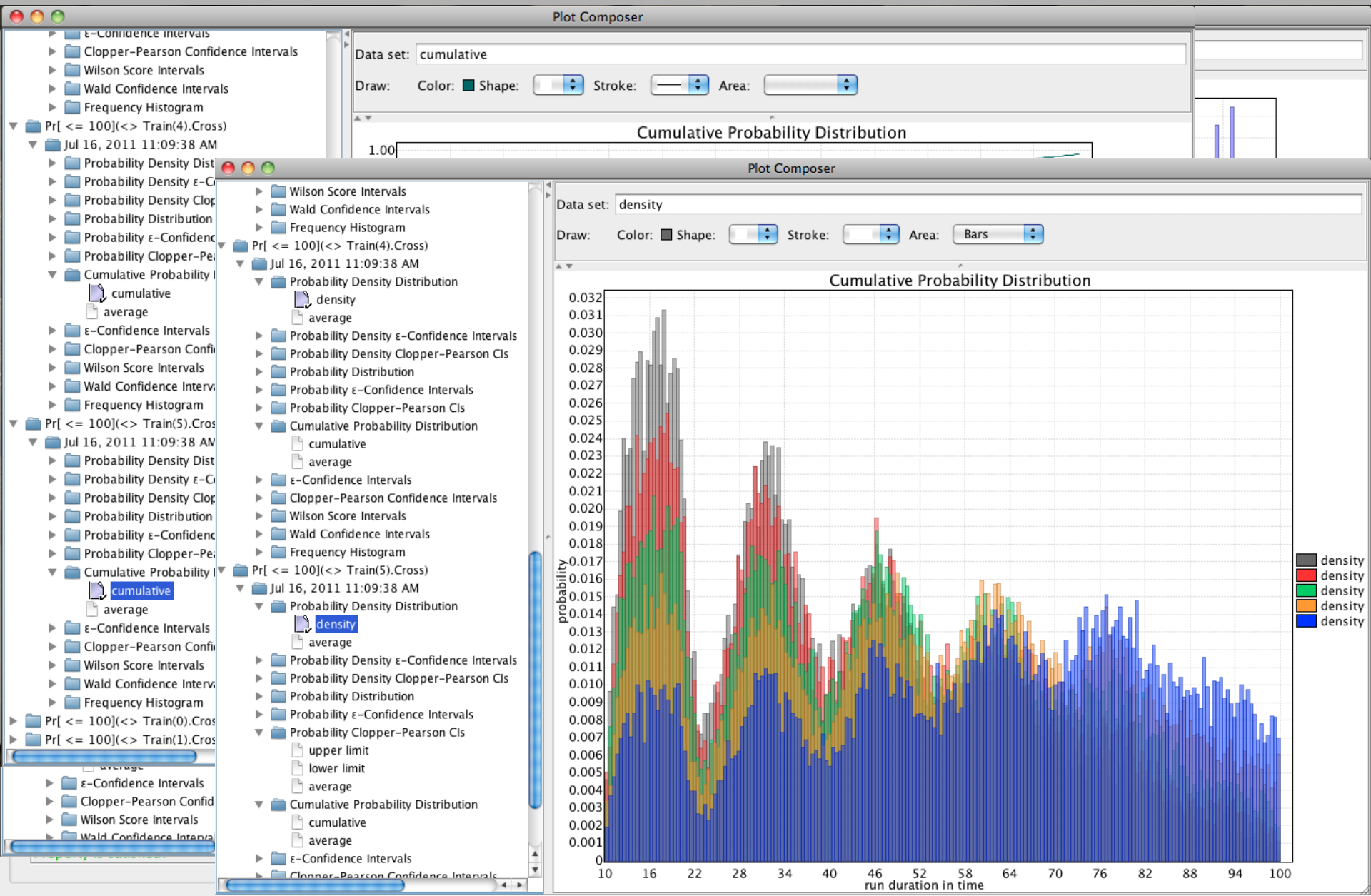
∀

Pr

Pr



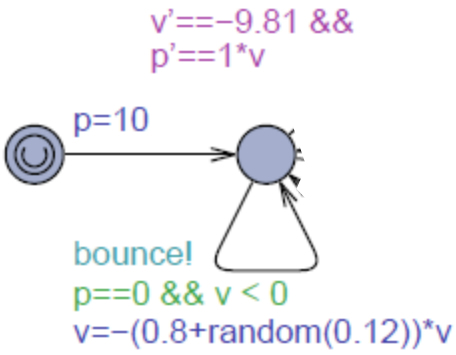
Analysis Tool: Plot Composer



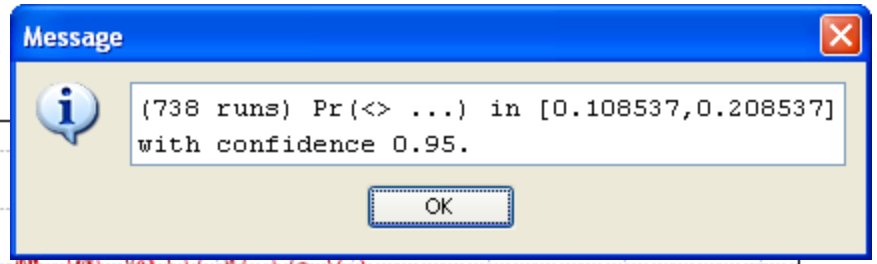
Demo

Stochastic Hybrid Systems

- A Bouncing Ball



Simulate 5 [<=20] {p}



Pr[<=20](<>(time >=12 && p >= 4))

Stochastic Hybrid Systems

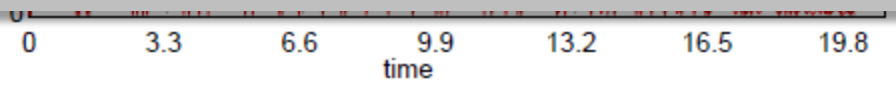
- A Bouncing Ball

UPPAAL SMC

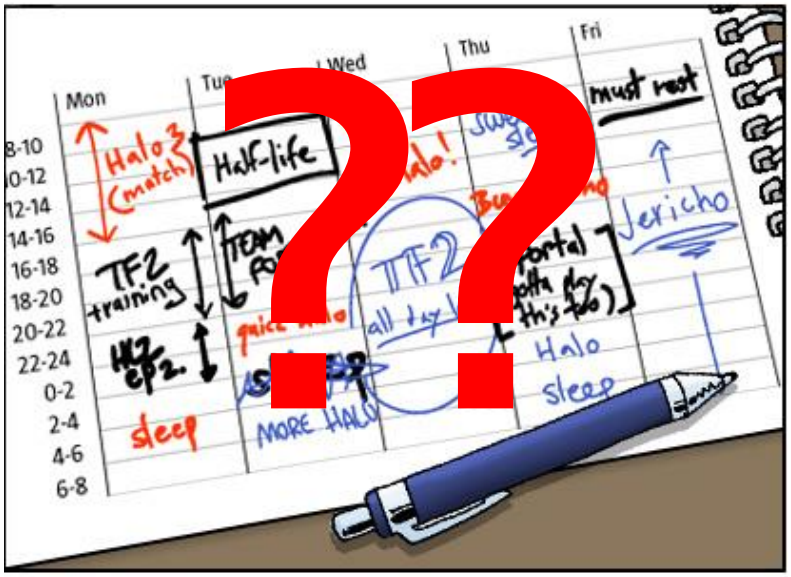
Uniform distributions (bounded delay)
Exponential distributions (unbounded delay)
Syntax for discrete probabilistic choice
Distribution on next state by use of `random`
Hybrid flow by use of ODEs
+ usual stuff (structured variables, user-defined types
  user-defined functions, ….)

Networks

Repeated races between components for outputting



Schedulability & Performance Analysis



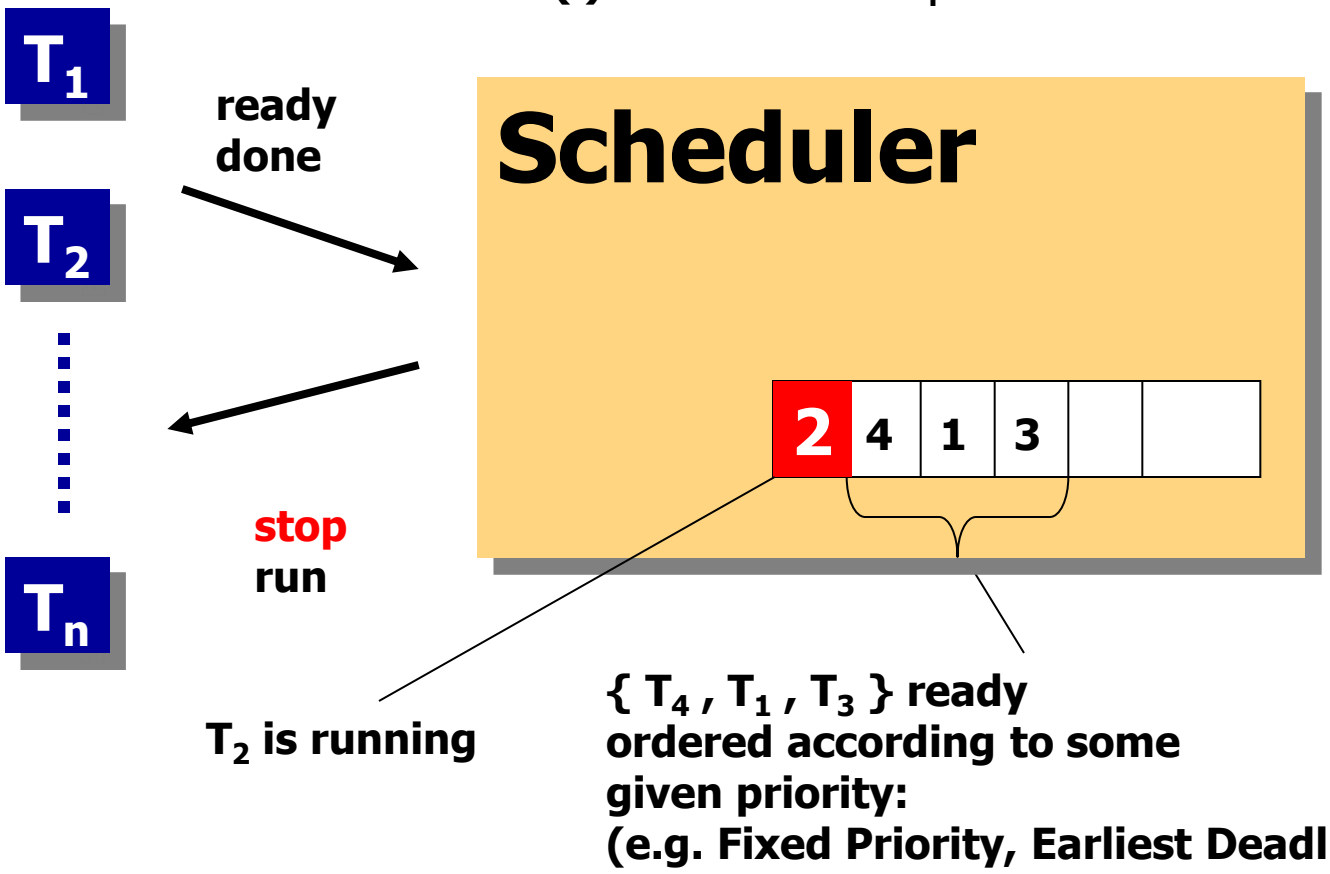
Task Scheduling

utilization of CPU

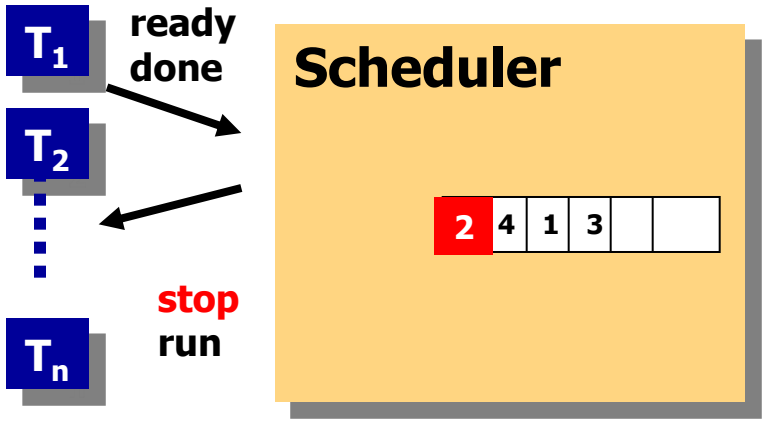
P(i), UNI[E(i), L(i)], .. : period or earliest/latest arrival or .. for T_i

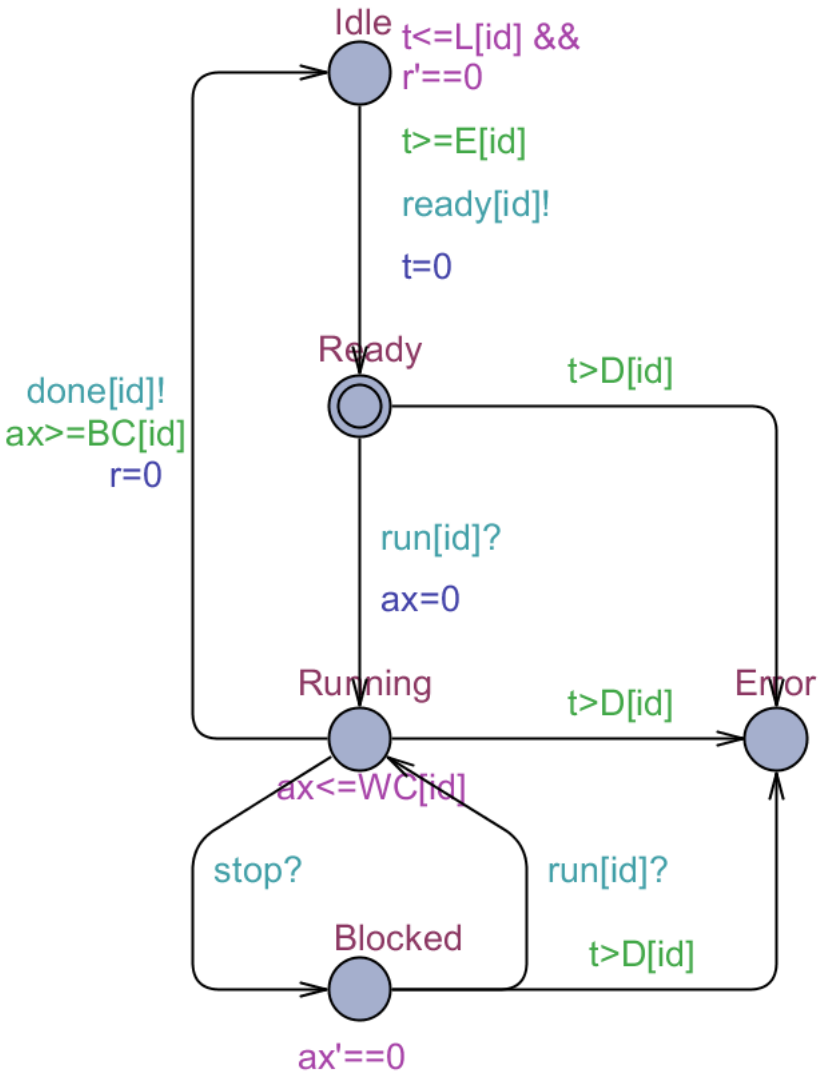
C(i), UNI[BC(i),WC(i)] : execution time for T_i

D(i): deadline for T_i

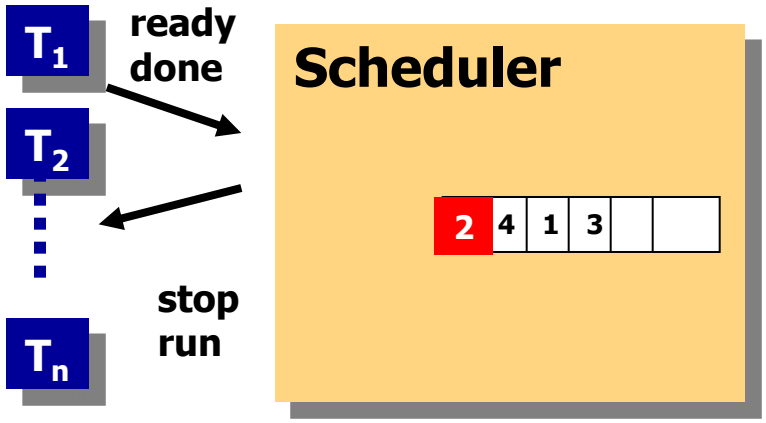


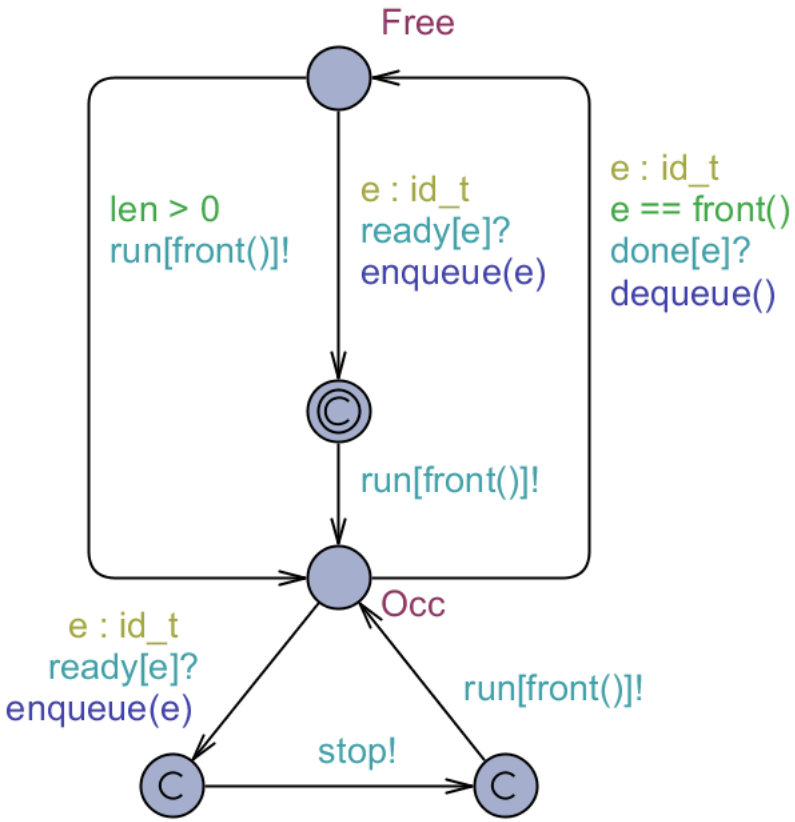
Modeling Task



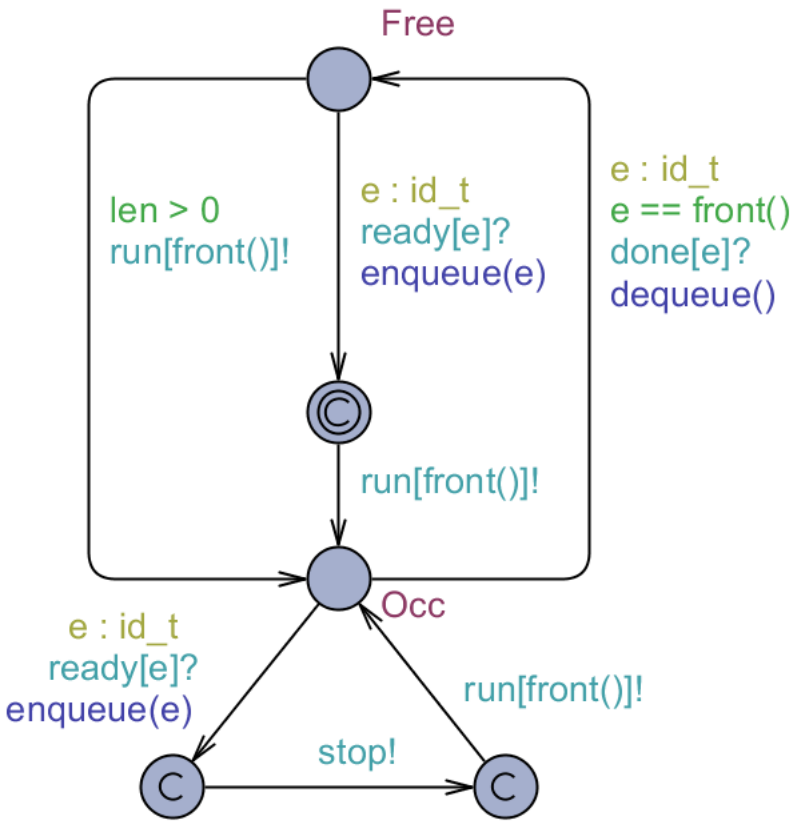


Modeling Scheduler





Modeling Queue



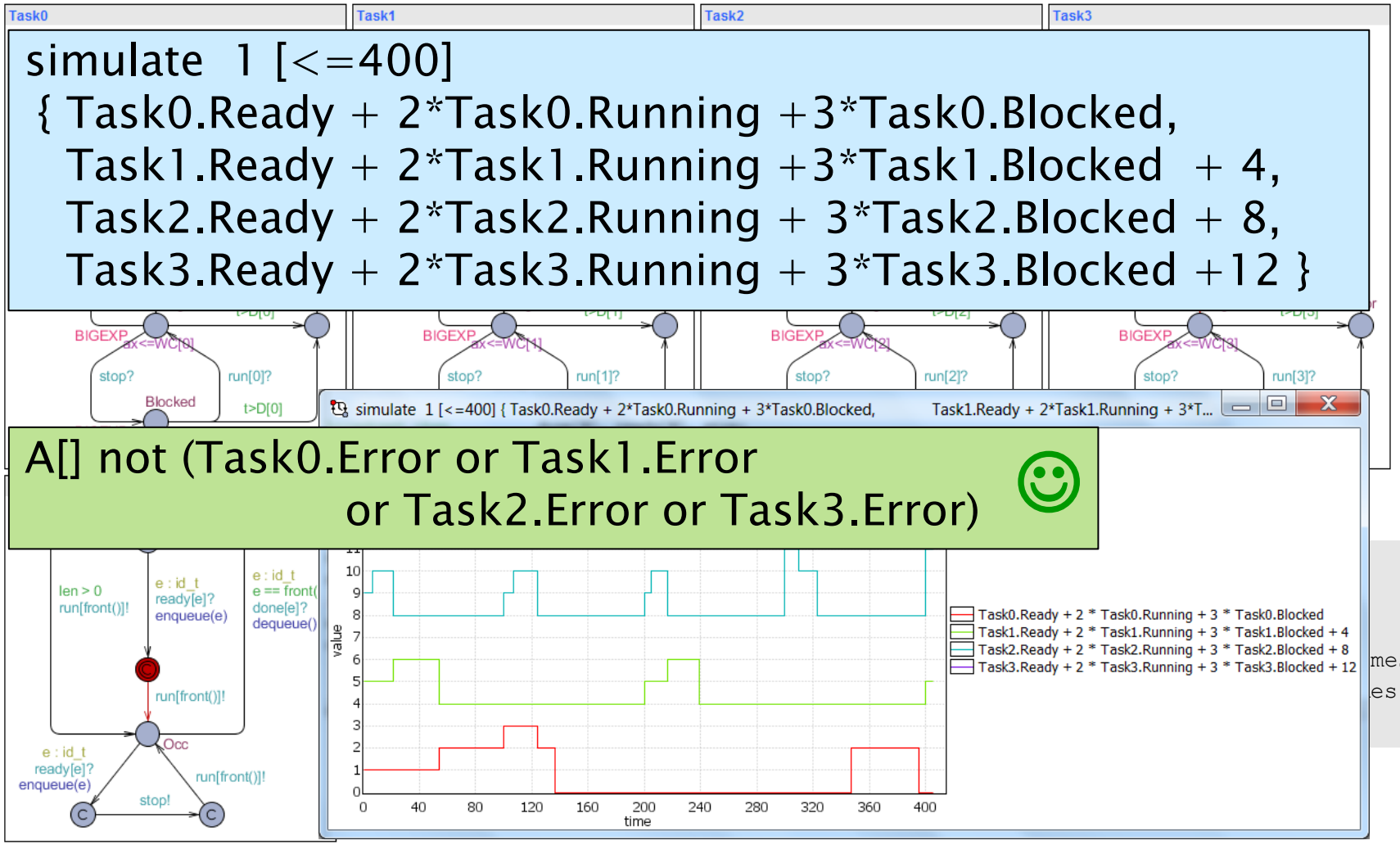

```
// Put an element at the end of the queue
void enqueue(id_t element)
{
int tmp=0;
list[len++] = element;
if (len>0)
{
        int i=len-1;
        while (i>1 && P[list[i]]>P[list[i-1]])
        {
                tmp = list[i-1];
                list[i-1] = list[i];
                list[i] = tmp;
                i--;
        }
}
}

// Remove the front element of the queue
void dequeue()
{
  ......
```

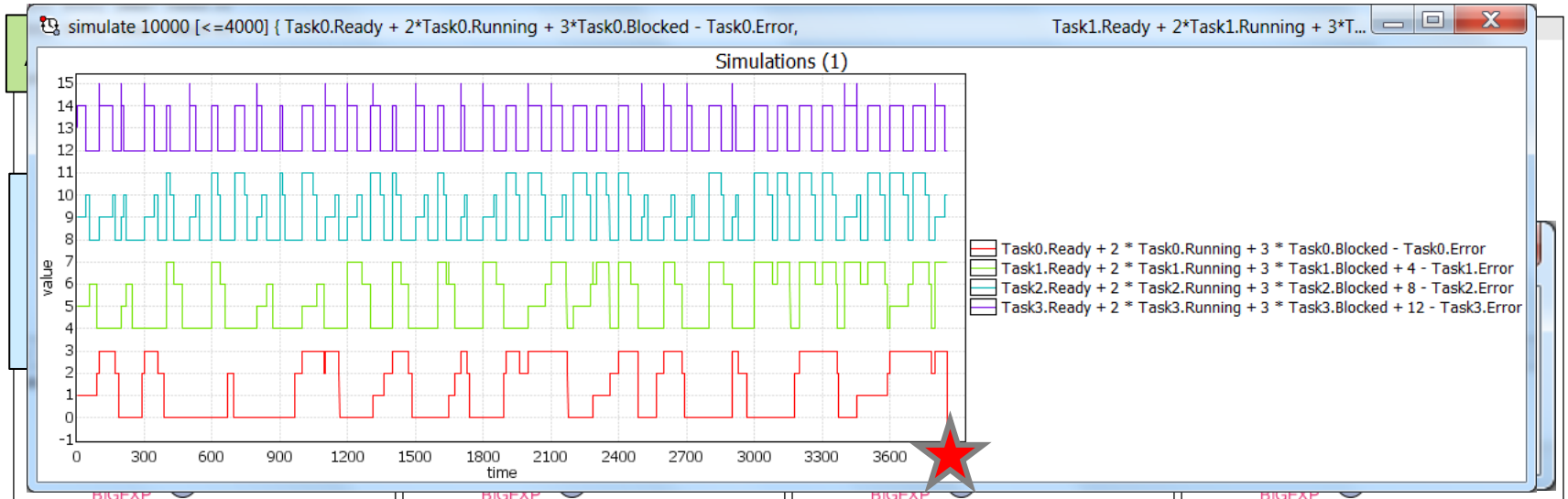
Schedulability Analysis

simulate 1 [<=400]
{ Task0.Ready + 2*Task0.Running +3*Task0.Blocked,
Task1.Ready + 2*Task1.Running +3*Task1.Blocked + 4,
Task2.Ready + 2*Task2.Running + 3*Task2.Blocked + 8,
Task3.Ready + 2*Task3.Running + 3*Task3.Blocked +12 }

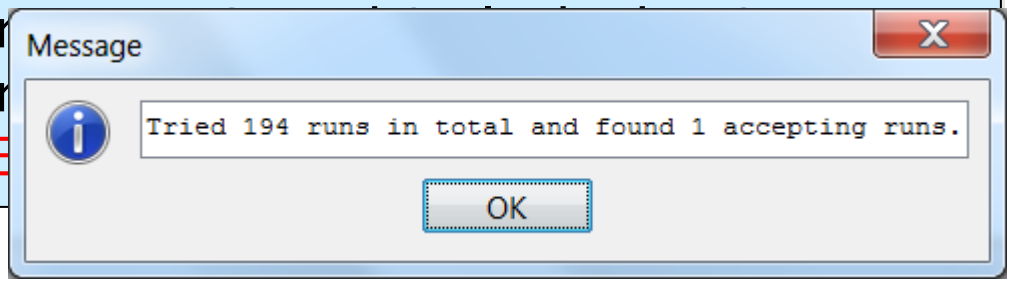
A[] not (Task0.Error or Task1.Error
or Task2.Error or Task3.Error)



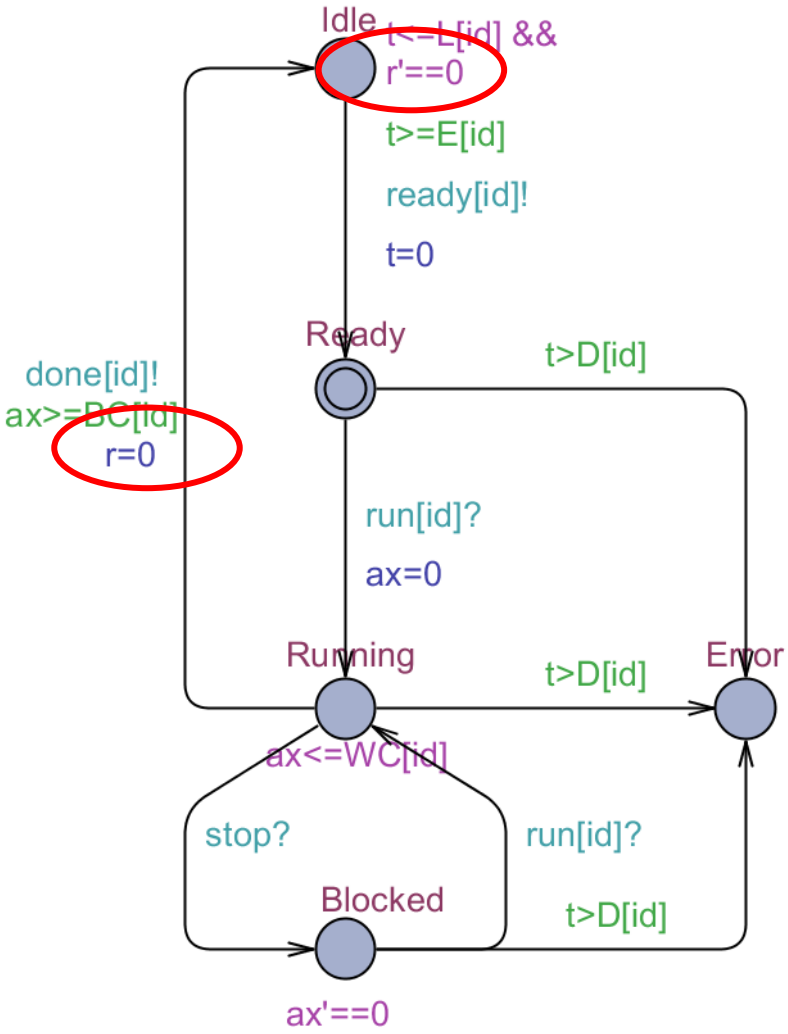
Schedulability Analysis



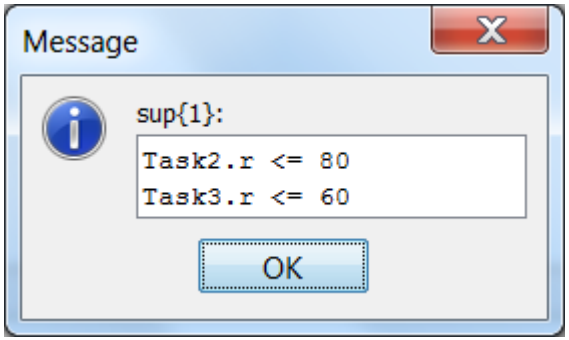
simulate 10000 [<=400]
{ Task0.Ready + 2*Task0.Running +3*Task0.Blocked,
Task1.Ready + 2*Task1.Running +3*Task1.Blocked + 4,
Task2.Ready + 2*Task2.Run
Task3.Ready + 2*Task3.Run
: 1 : (Task0.Error or Task1.E



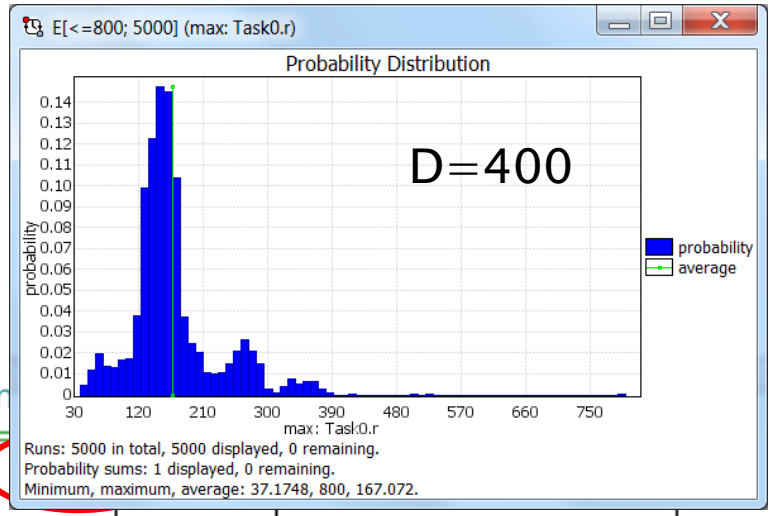
Performance Analysis

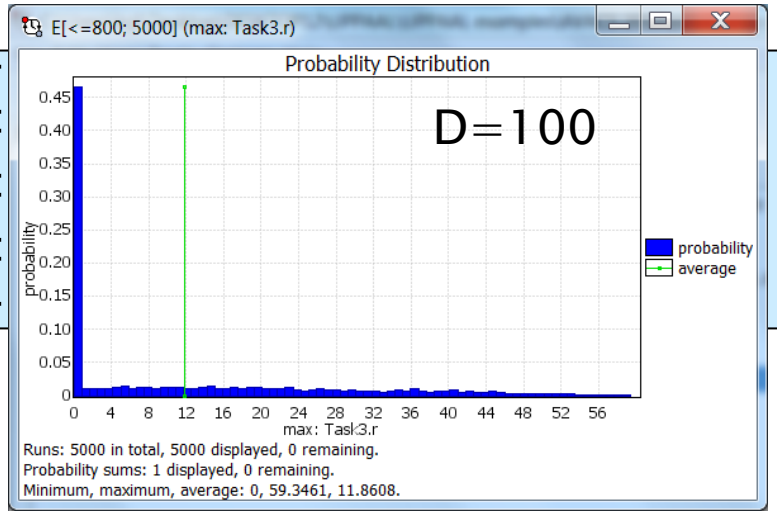


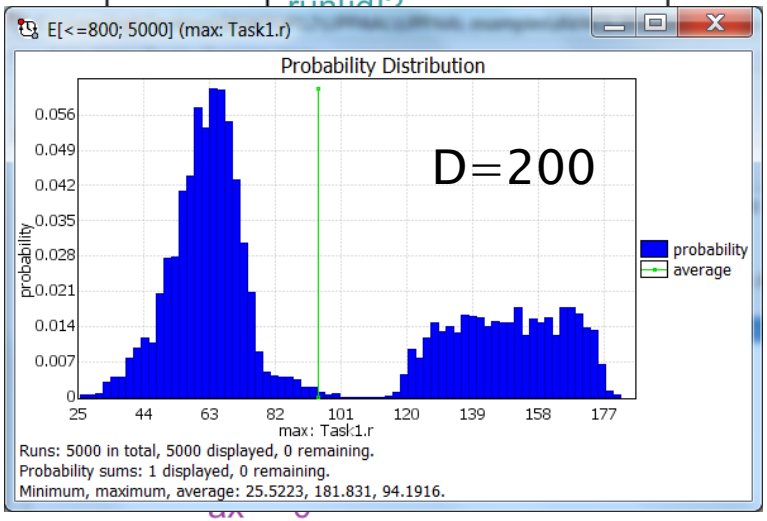
sup : Task2.r, Task3.r

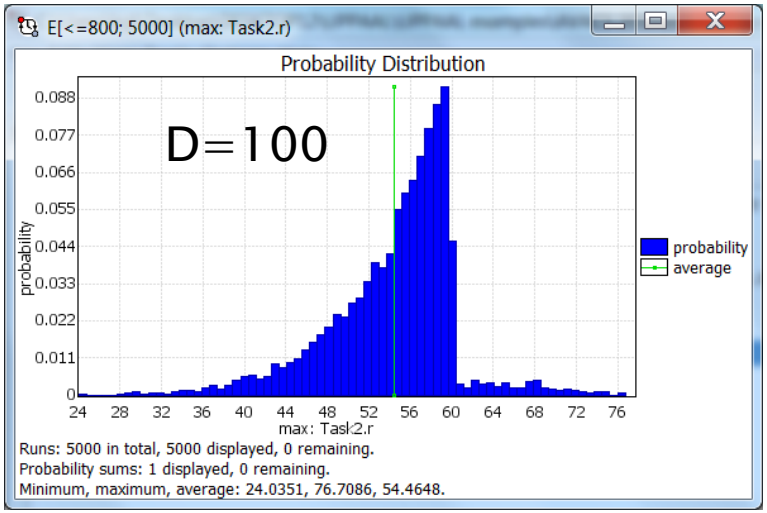


Performance Analysis







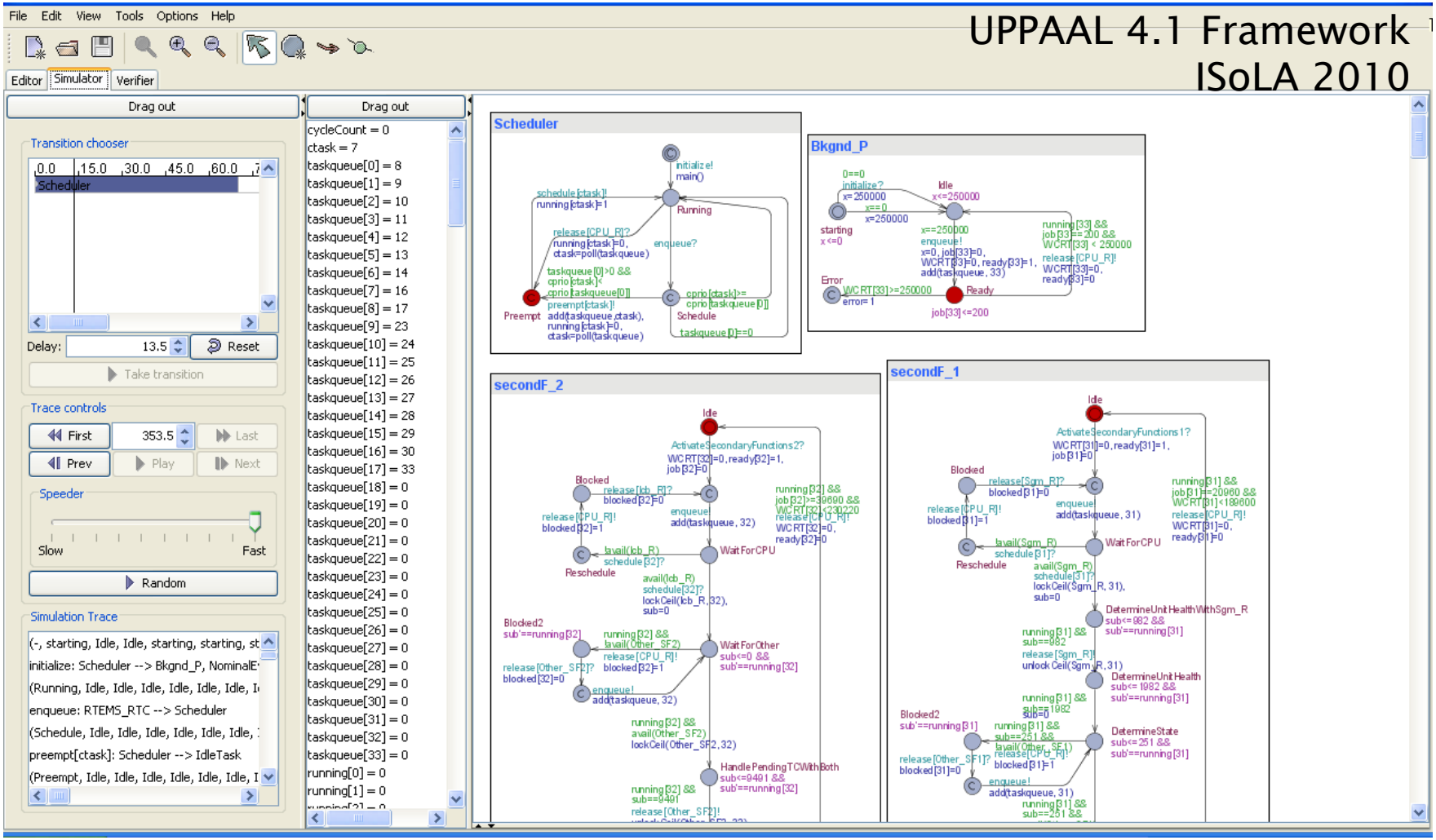


Herschel-Planck Scientific Mission at ESA

Attitude and Orbit Control Software
TERMA A/S Steen Ulrik Palm, Jan Storbank Pedersen, Poul Hougaard

Modeling in UPPAAL

TERMA



UPPAAL 4.1 Framework
ISoLA 2010

Symbolic MC vs. Statistical MC

Symbolic analysis:

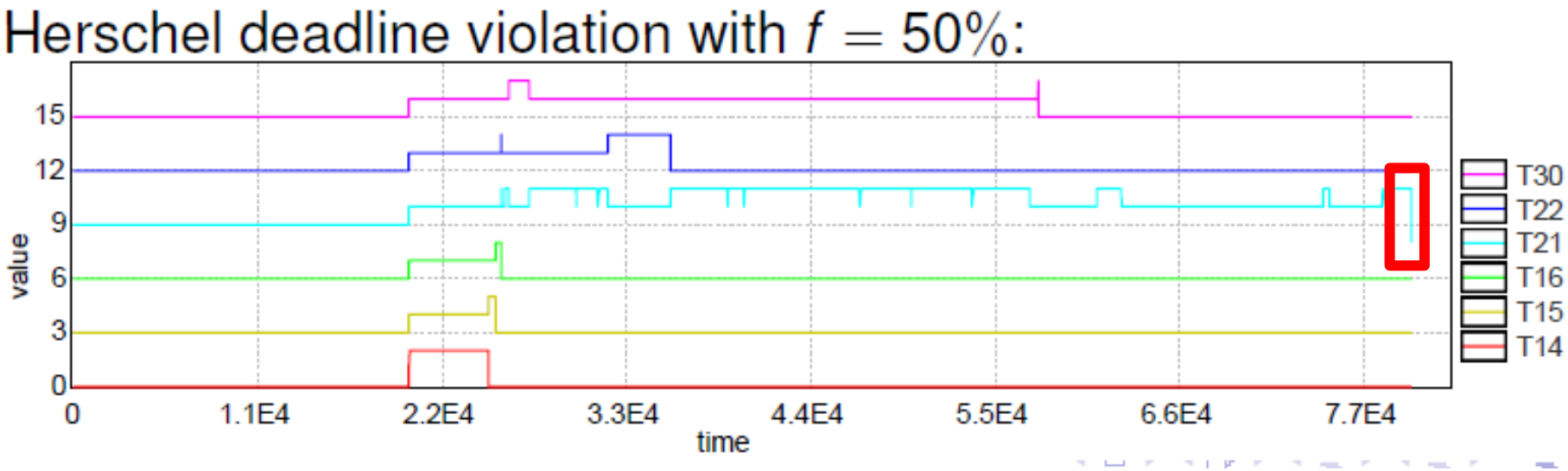
- Preemptive scheduler requires *stop-watches*.
- Exact reachability of stop-watch automata is *undecidable*.
- UPPAAL provides *over-approximation* for stop-watches.
- $\Rightarrow$ symbolic analysis may give spurious errors, but still suitable for *proving safety/schedulability*.

Statistical analysis:

- can show *presence of errors* but not absence.
- $\Rightarrow$ suitable for *disproving schedulability*.

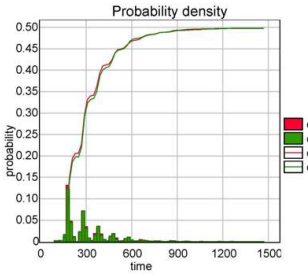
$f = \text{BCET}/\text{WCET}$:	0-71%	72-86%	87-89%	90-100%
Symbolic MC:	maybe	maybe	n/a	**Safe**
Statistical MC:	**Unsafe**	maybe	maybe	maybe

SMC Simulation to Find Error

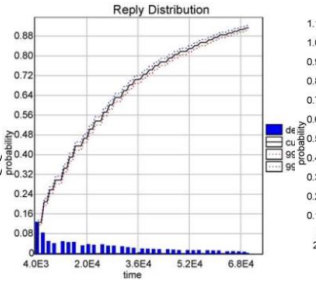


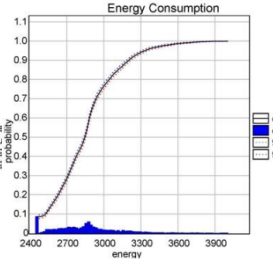

```
simulate 10000 [<=300] {
   (T(1).Ready+T(1).Computing+T(1).Release+runs[1]-2*T(1)
   (T(2).Ready+T(2).Computing+T(2).Release+runs[2]-2*T(1)
   (T(3).Ready+T(3).Computing+T(3).Release+runs[3]-2*T(1)
} : 1 : error
```

Other Case Studies

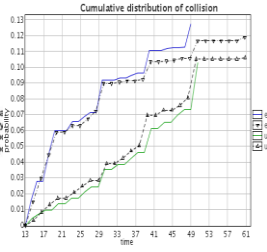


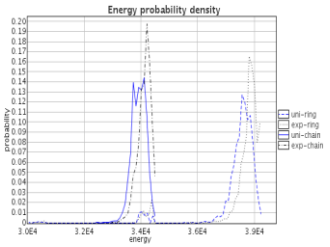
FIREWIRE



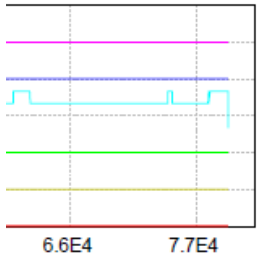


BLUETOOTH

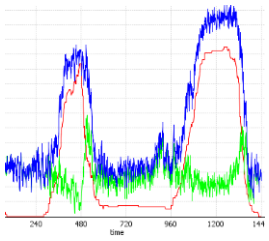




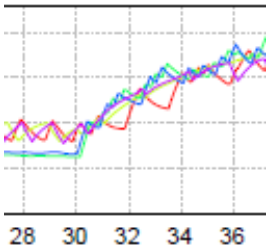
10 node LMAC



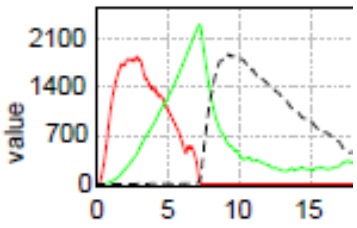
Schedulability Analysis for Mix Cr Sys



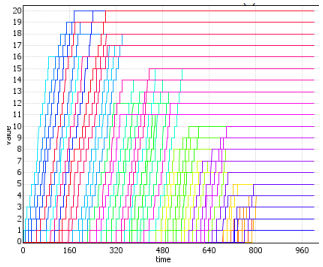
Smart Grid Demand / Response



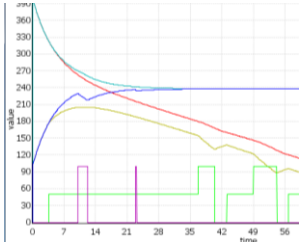
Energy Aware Buildings



Genetic Oscilator (HBS)



Passenger Seating in Aircraft



Battery Scheduling
(SENSATION)
Erik Wogensen

SMC Queries – Examples

- Pr[<=100](<> goal)
- Pr[#<=10]([] safe)
- Pr[x<=200](<> goal) >= 0.3
- E[<=100; 1000](min: expr)
- simulate 10 [<=100] { e1, e2, x1 }
- simulate 100 [<=10] { e } : 2 : goal

Exercise 28 (Jobshop scheduling part 2)