Statistical Model Checking in UPPAAL

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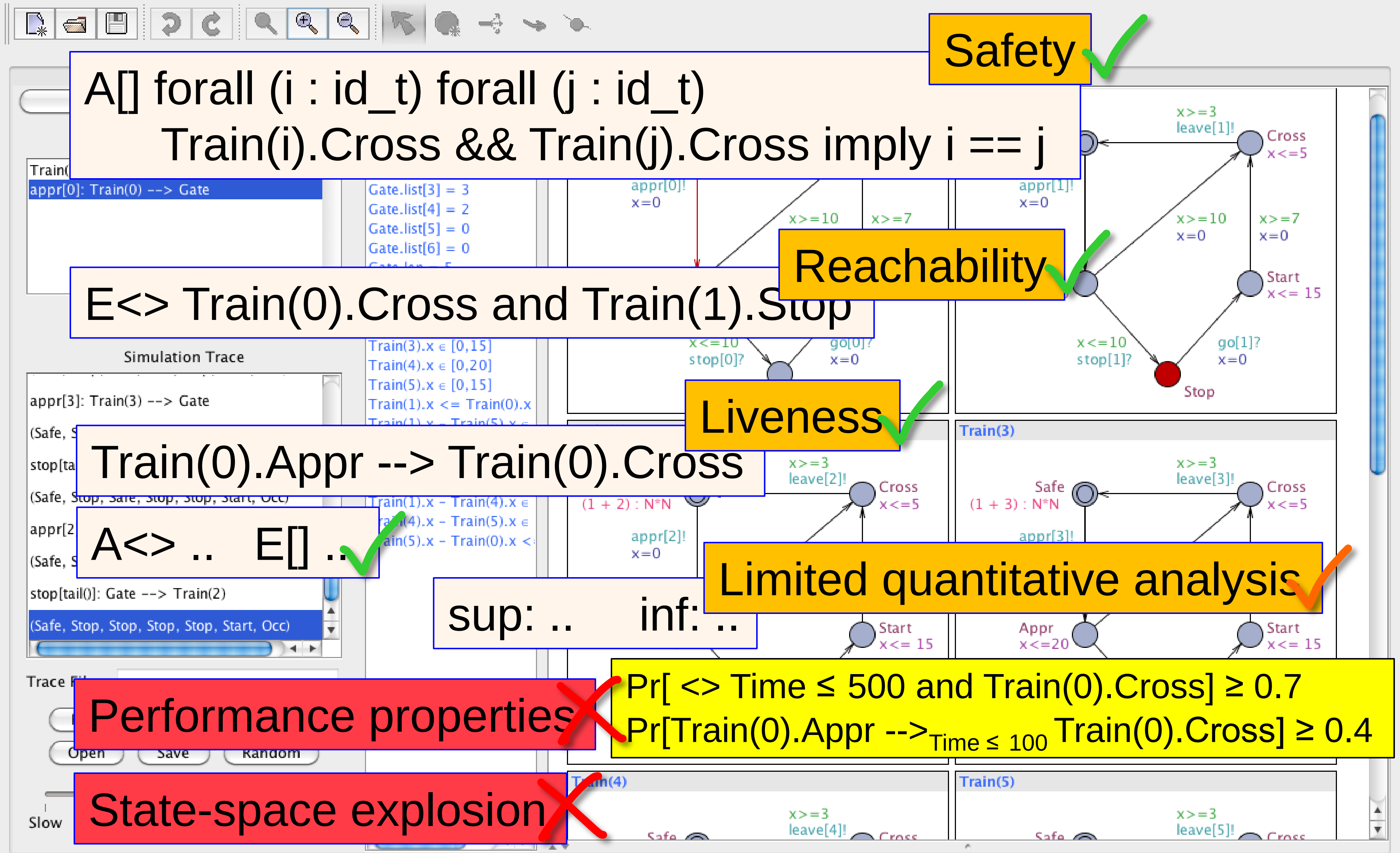
CAV 11, PDMC 11,FORMATS 11,
QAPL12, LPAR12, iWIGPL12,
RV12, FORMATS12, HBS12,
ISOLA12, SCIENCE China,
NFM13,RV13,AVOCS13

UPPAAL



Safety ✓

A[] forall (i : id_t) forall (j : id_t)
Train(i).Cross && Train(j).Cross imply i == j

Reachability ✓

E<> Train(0).Cross and Train(1).Stop

Liveness ✓

Train(0).Appr --> Train(0).Cross

A<> .. E[] .. ✓

sup: .. inf: ..

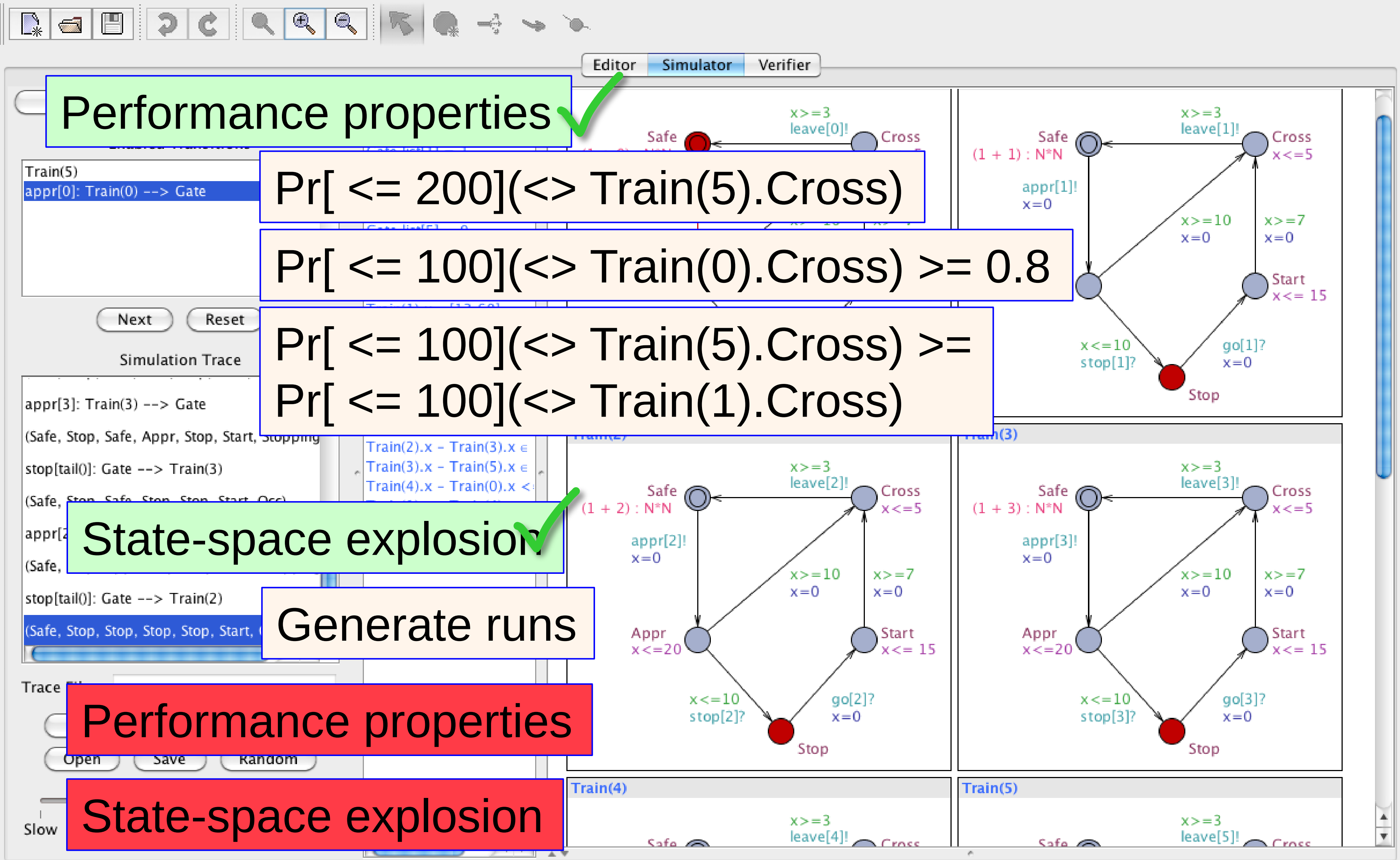
Limited quantitative analysis ✓

Performance properties ✗

Pr[<> Time ≤ 500 and Train(0).Cross] ≥ 0.7
Pr[Train(0).Appr $-->_{Time \leq 100}$ Train(0).Cross] ≥ 0.4

State-space explosion ✗

UPPAAL SMC



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

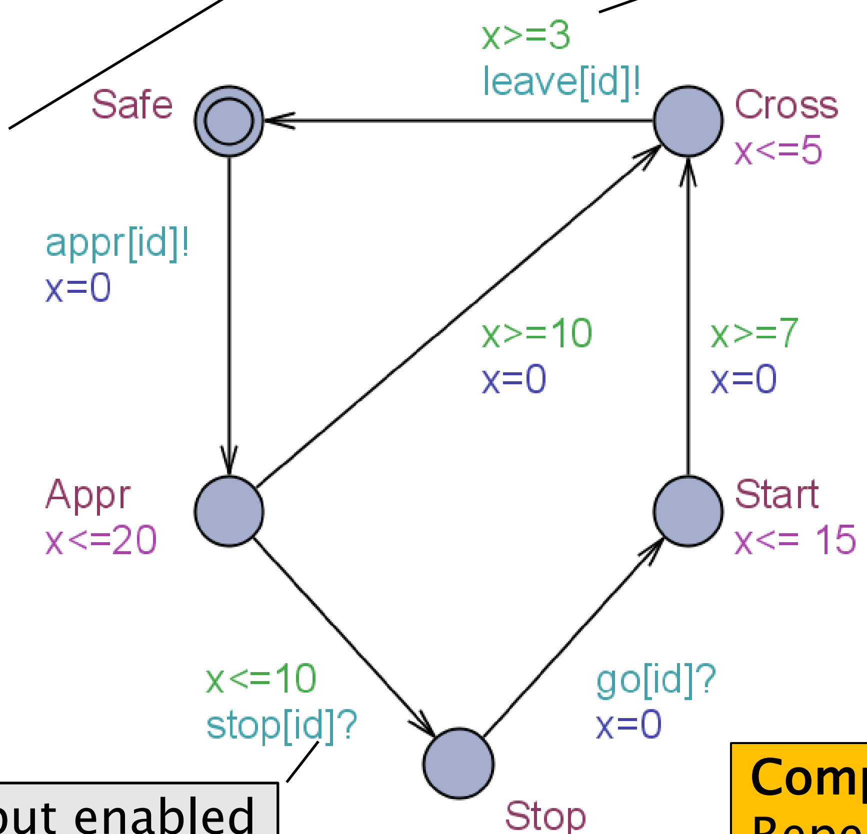
Overview

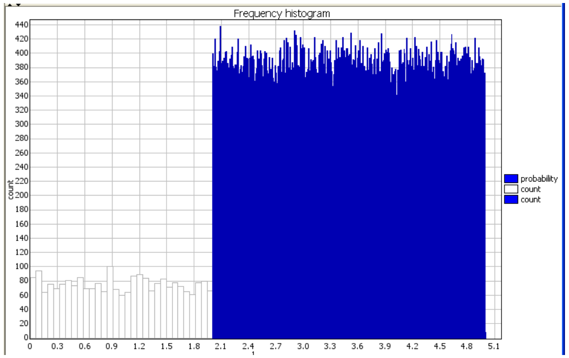
- Stochastic Semantics of Networks of Timed Automata
- Statistical Model Checking in UPPAAL
  - Estimation
  - Sequential Hypothesis Testing
  - Sequential Probability Comparison
  - Parameterized Probability Comparison
- SMC of Hybrid Automata
- Case Studies & Demo

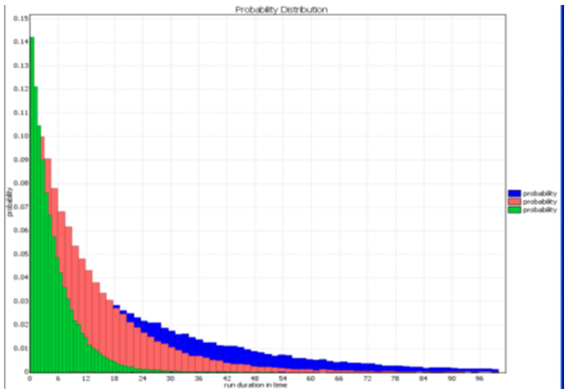
Stochastic Semantics of TA

Exponential Distribution

Uniform Distribution



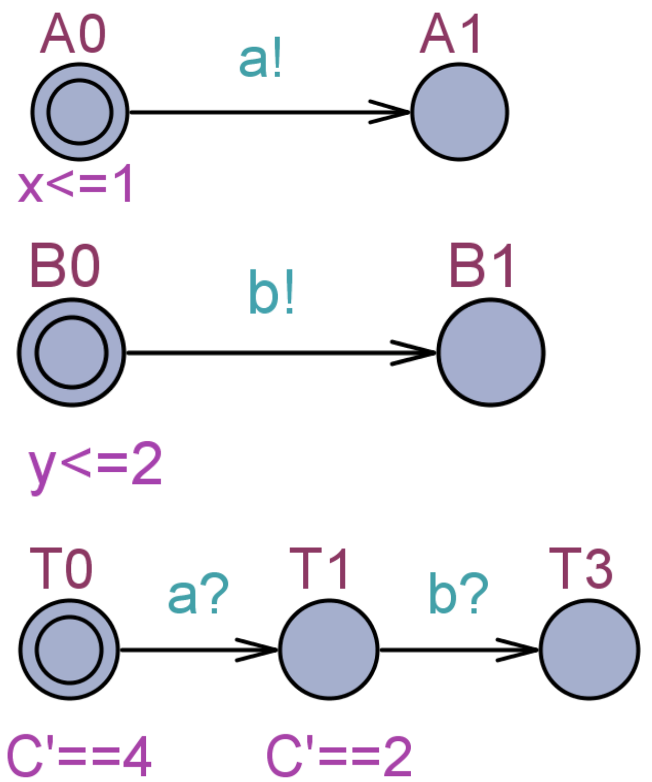


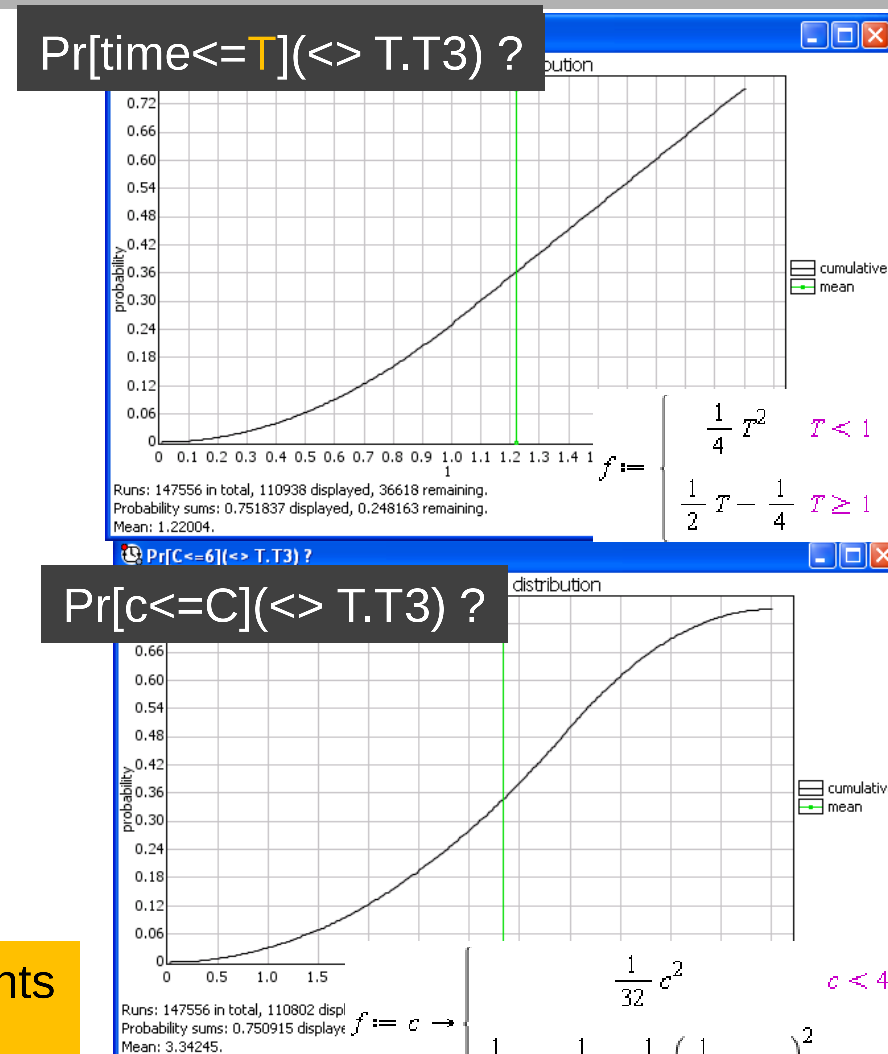


Input enabled

Composition =
Repeated races between components

Stochastic Semantics of Timed Automata





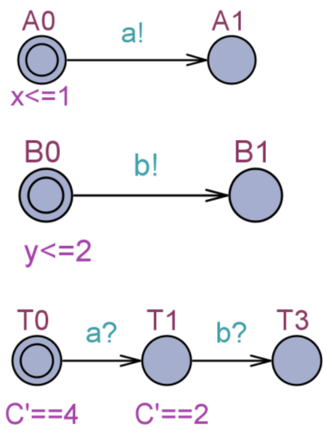
$$f := \begin{cases} \frac{1}{4}T^2 & T < 1 \\ \frac{1}{2}T - \frac{1}{4} & T \geq 1 \end{cases}$$

$$f := c \to \begin{cases} \frac{1}{32}c^2 & c < 4 \\ \frac{1}{4}c - \frac{1}{2} - \frac{1}{4}\left(\frac{1}{2}c - 2\right)^2 & c \geq 4 \end{cases}$$

Composition = Race between components for outputting

Stochastic Semantics of Timed Automata

$\mathcal{A}$



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 $t_1,\ldots,t_n \in$ **R**.

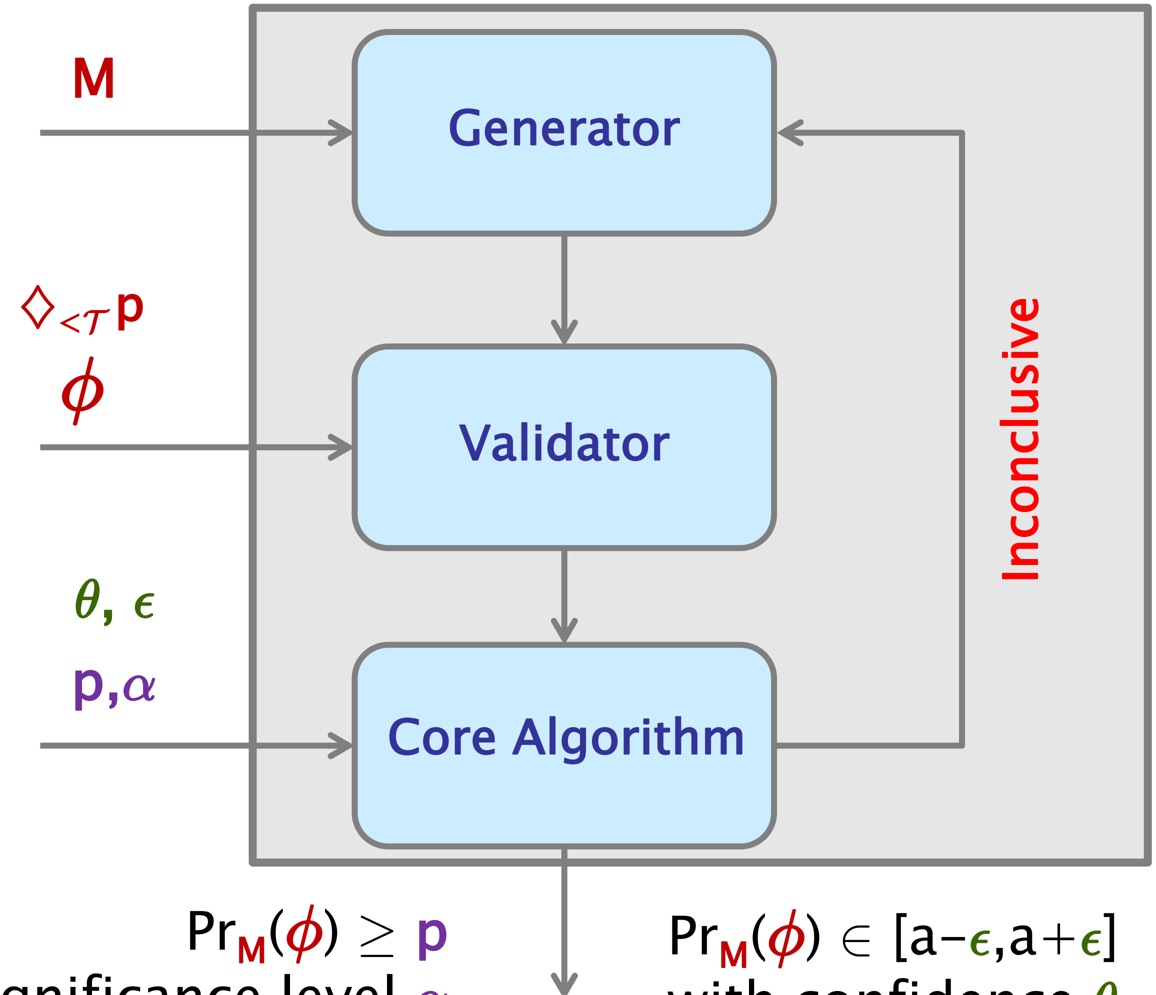
$$\mathbb{P}_{\mathcal{A}}\big(\pi(\mathbf{s},\, a_1 a_2 \ldots a_n)\big) =$$

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

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]

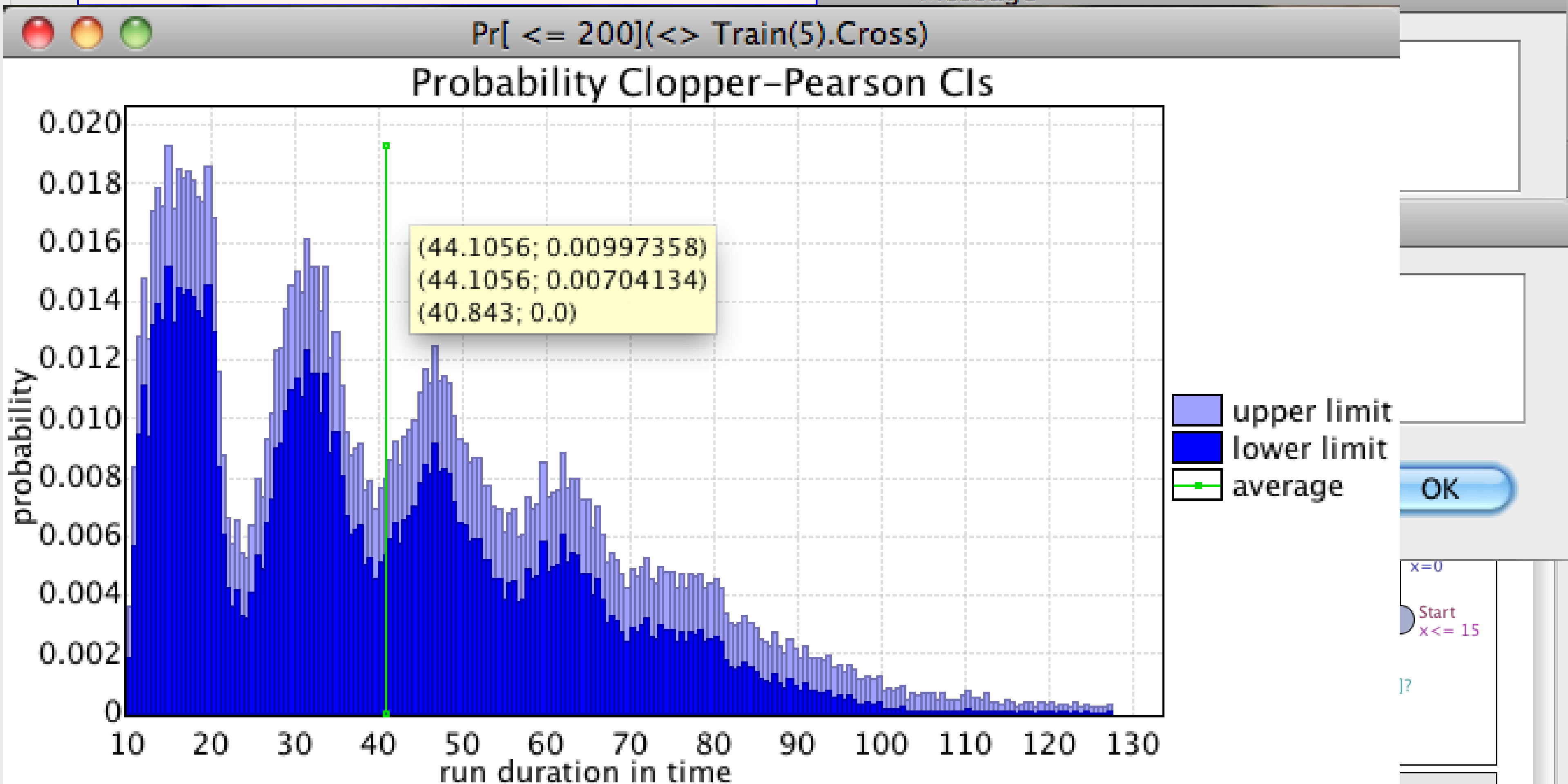


$Pr_M(\phi) \geq p$ at significance level α

$Pr_M(\phi) \in [a-\epsilon, a+\epsilon]$ with confidence θ

Queries in UPPAAL SMC

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

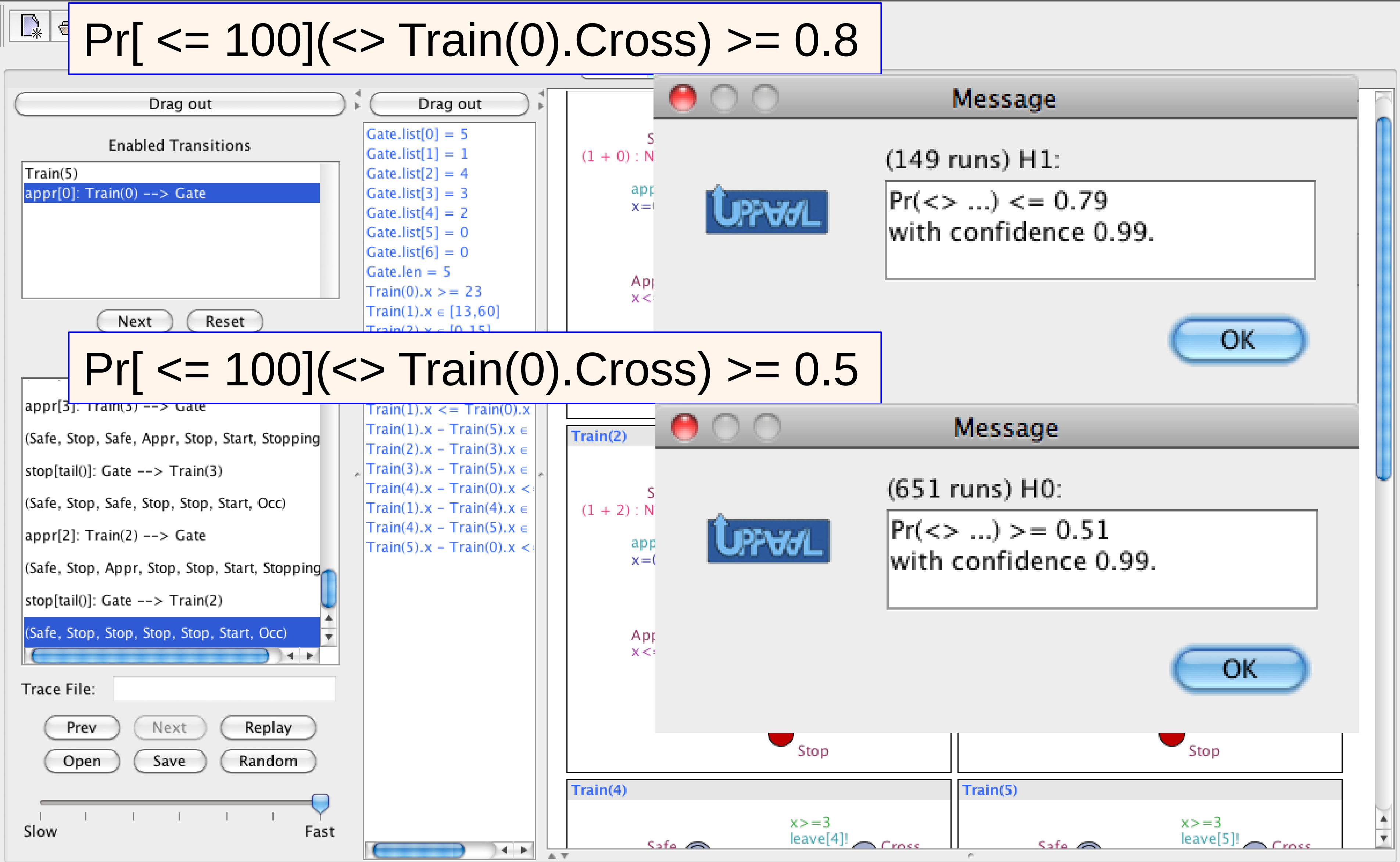


Parameters: α=0.01, ε=0.01, bucket width=0.587972, bucket count=200.
Runs: 26492 in total, 26492 displayed, 0 remaining.
Probability sums: 1 displayed, 0 remaining.
Average: 40.843.

Queries in UPPAAL SMC

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

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



Queries in UPPAAL SMC

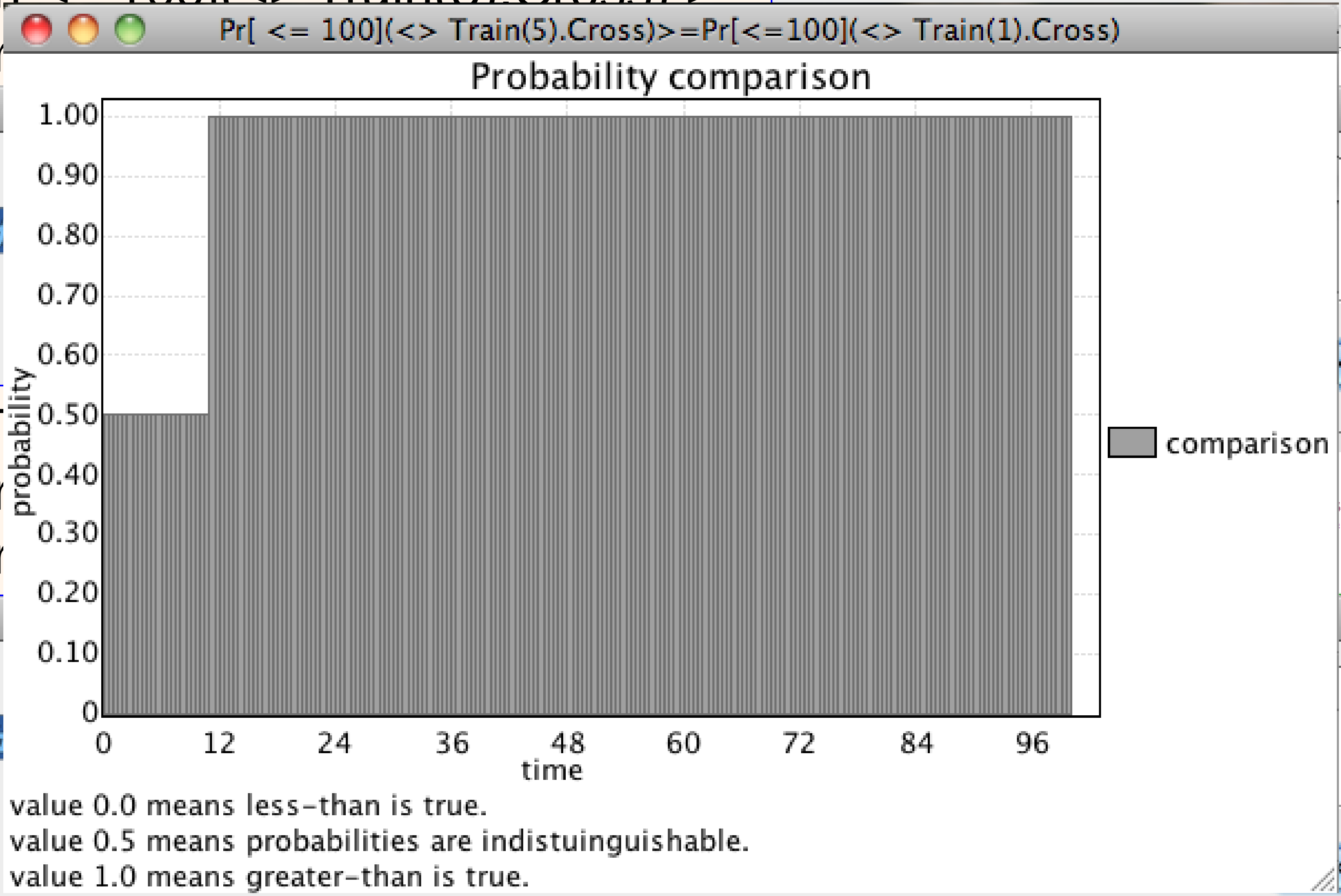
Pr[<= 100](<> Train(5).Cross) >=

Pr

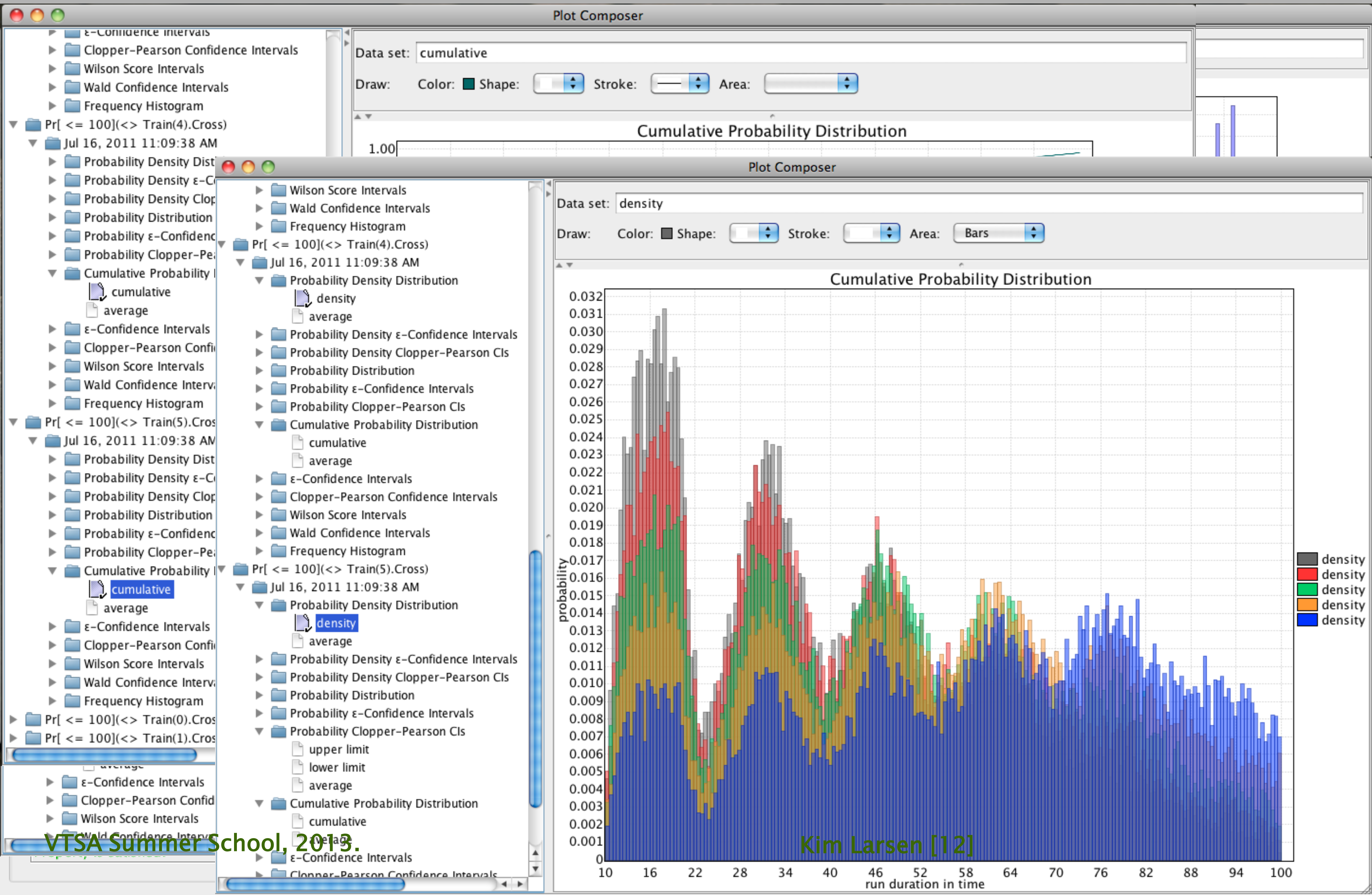
∀

Pr

Pr

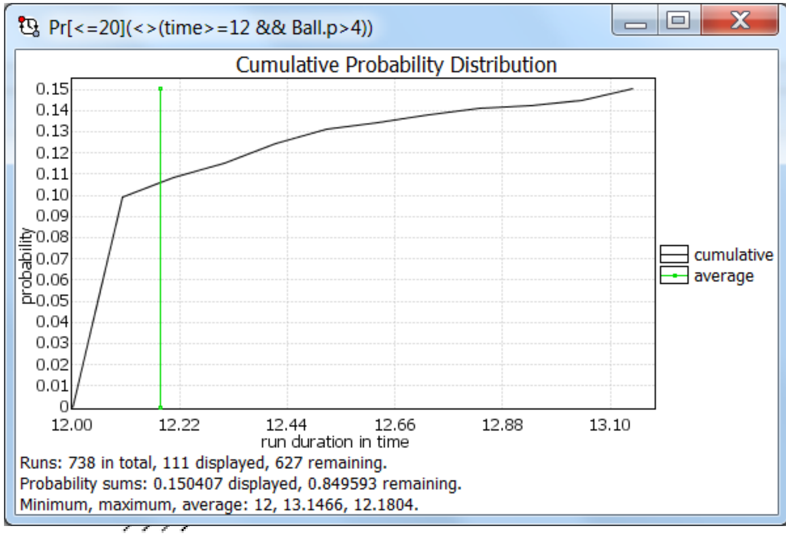


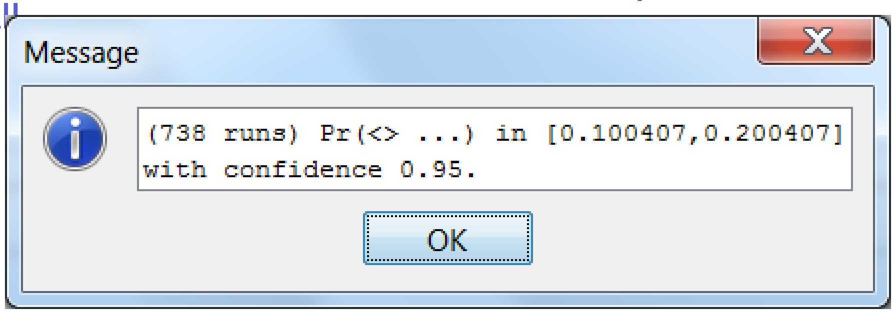
Analysis Tool: Plot Composer

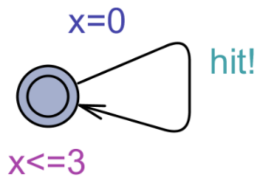


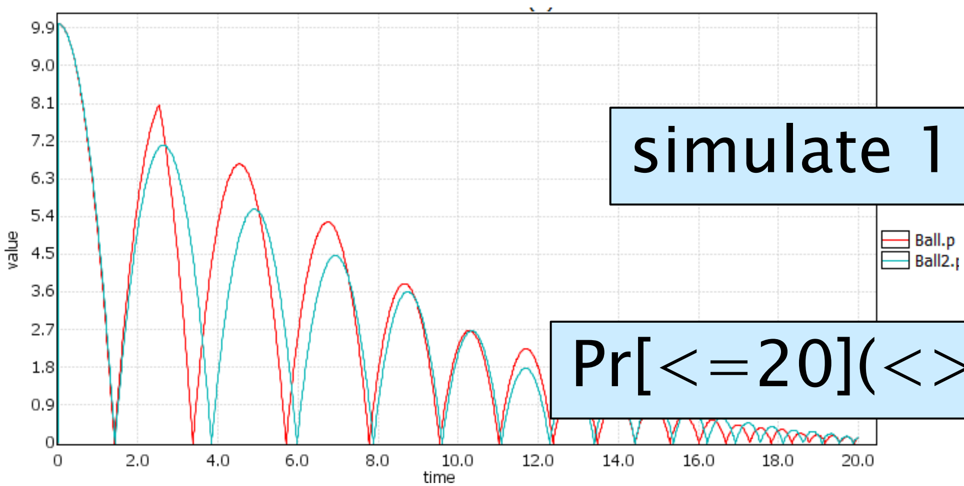
Demo

Stochastic Hybrid Systems









simulate 1 [<=20]{Ball1.p, Ball2.p}

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

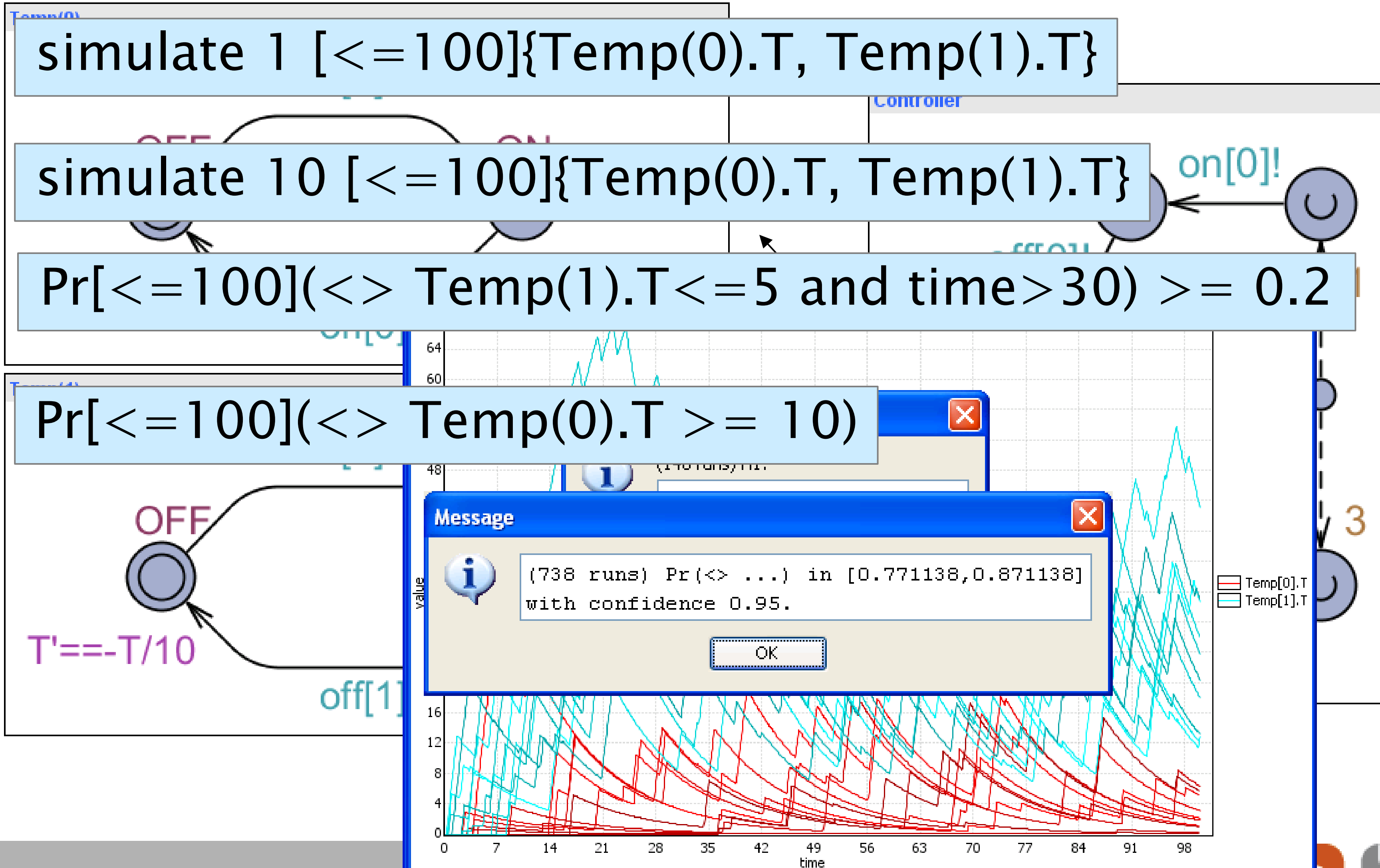
Stochastic Hybrid Systems

simulate 1 [<=100]{Temp(0).T, Temp(1).T}

simulate 10 [<=100]{Temp(0).T, Temp(1).T}

Pr[<=100](<> Temp(1).T<=5 and time>30) >= 0.2

Pr[<=100](<> Temp(0).T >= 10)



Stochastic Hybrid Systems

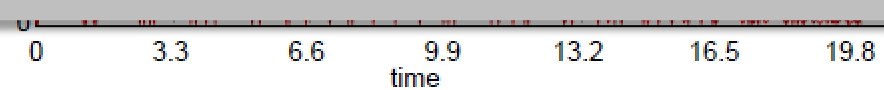
- A Bouncing Ball

UPPAAL SMC

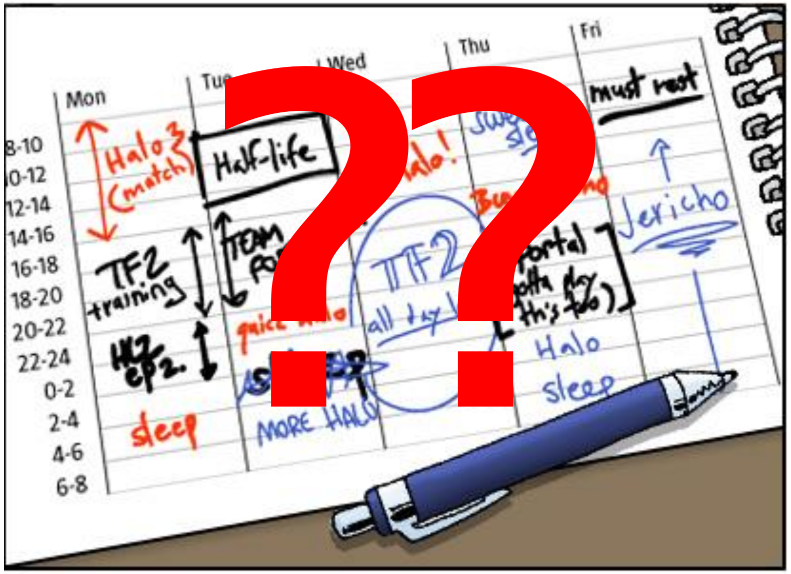
Uniform distributions (bounded delay)
Exponential distributions (unbounded delay)
Syntax for discrete probabilistic choice
Distribution on next state by use of `random`
Hybrid flow by use of ODEs
+ usual stuff (structured variables, user-defined types
  user-defined functions, ….)

Networks

Repeated races between components for outputting

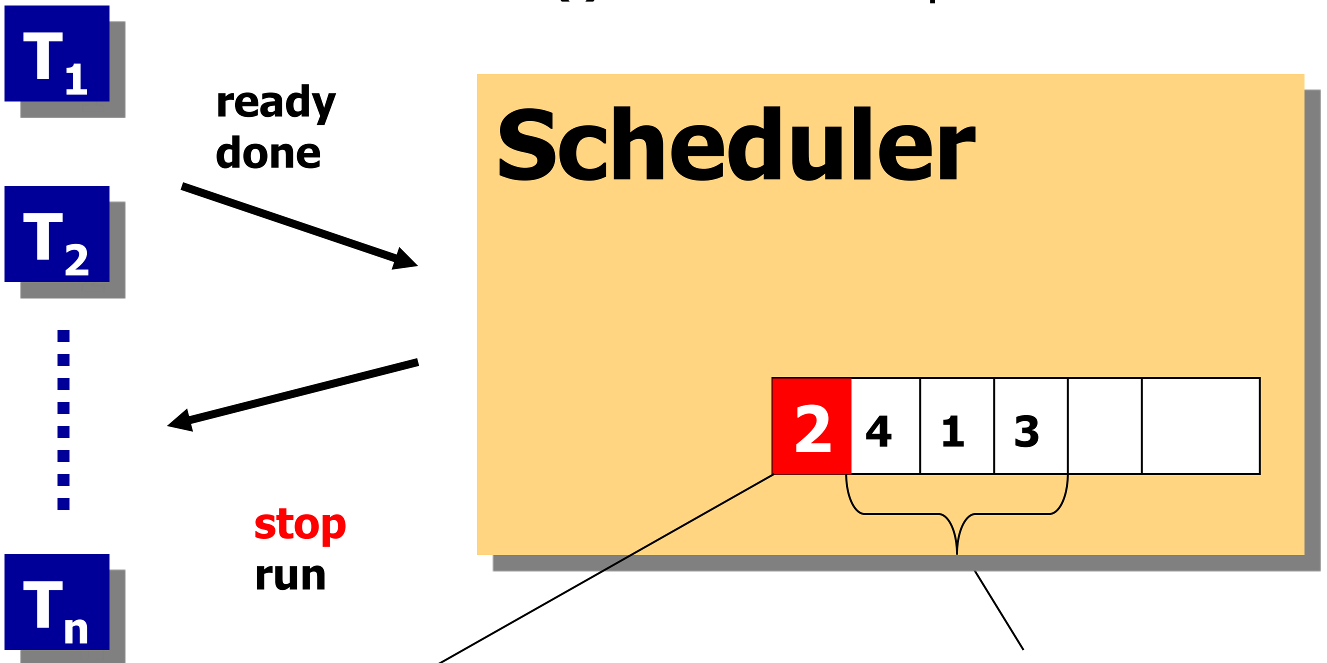


Schedulability
& Performance Analysis



Task Scheduling *utilization of CPU*

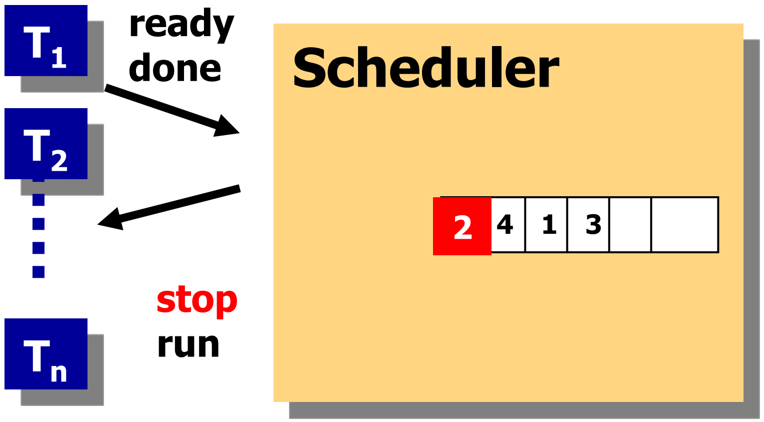
P(i), UNI[E(i), L(i)], .. : period or earliest/latest arrival or .. for T_i
C(i), UNI[BC(i),WC(i)] : execution time for T_i
D(i): deadline for T_i

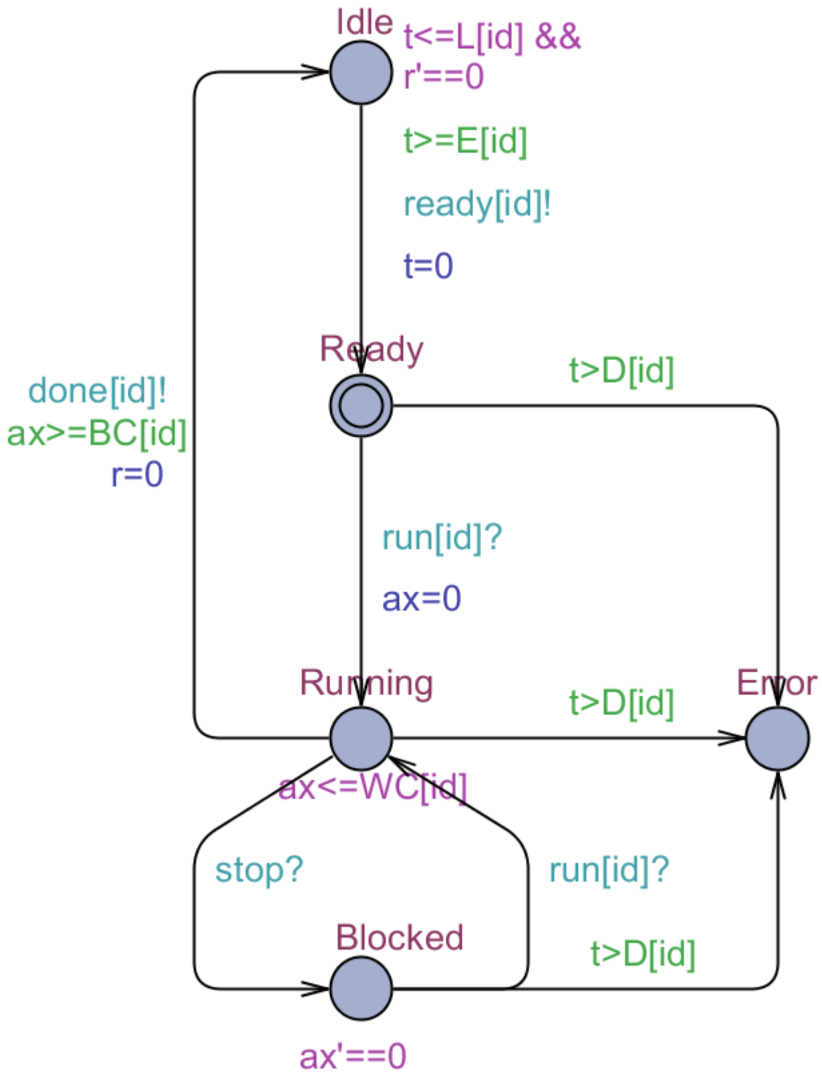


T_2 is running

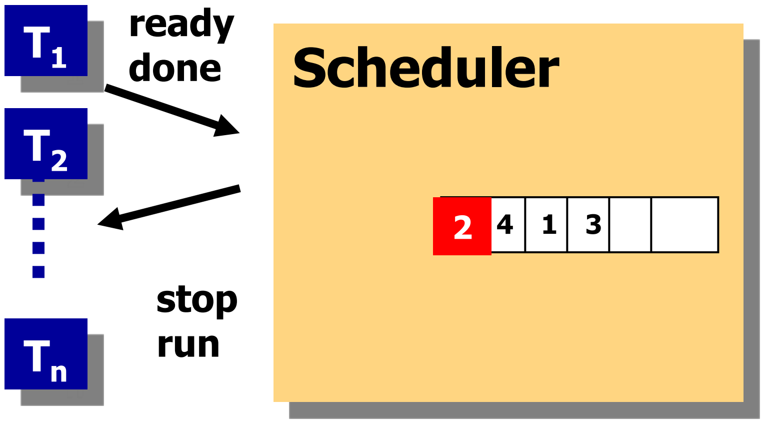
{ T_4 , T_1 , T_3 } ready ordered according to some given priority: (e.g. Fixed Priority, Earliest Deadline,..)

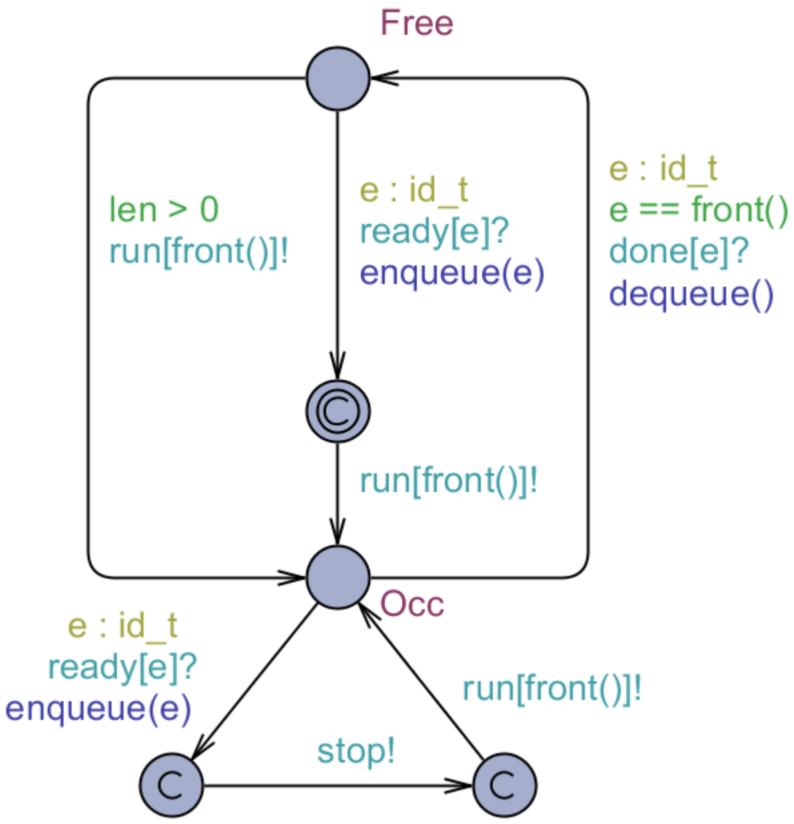
Modeling Task



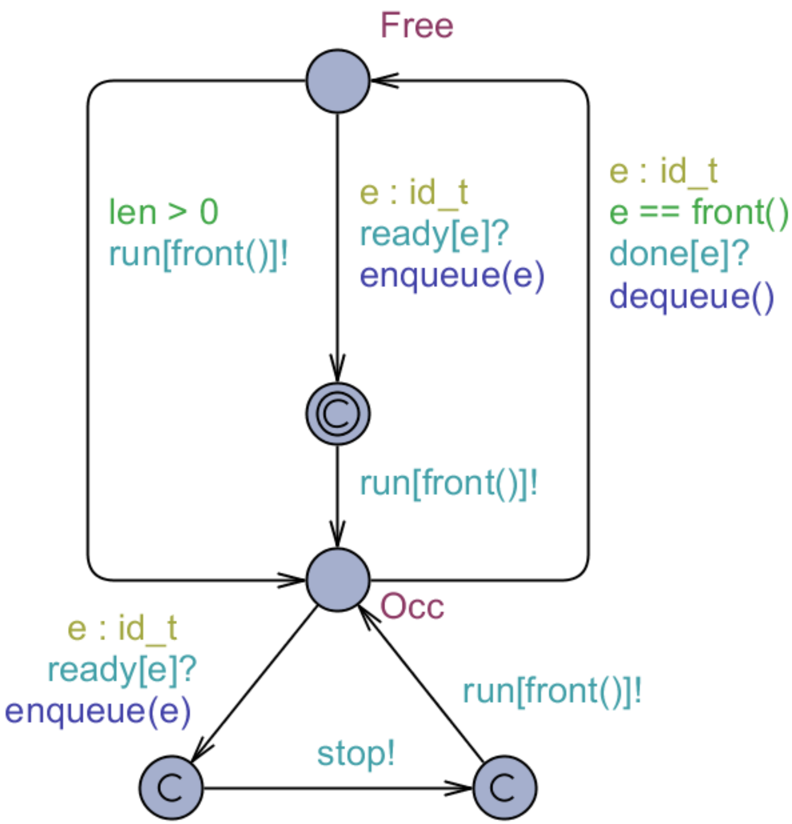


Modeling Scheduler





Modeling Queue



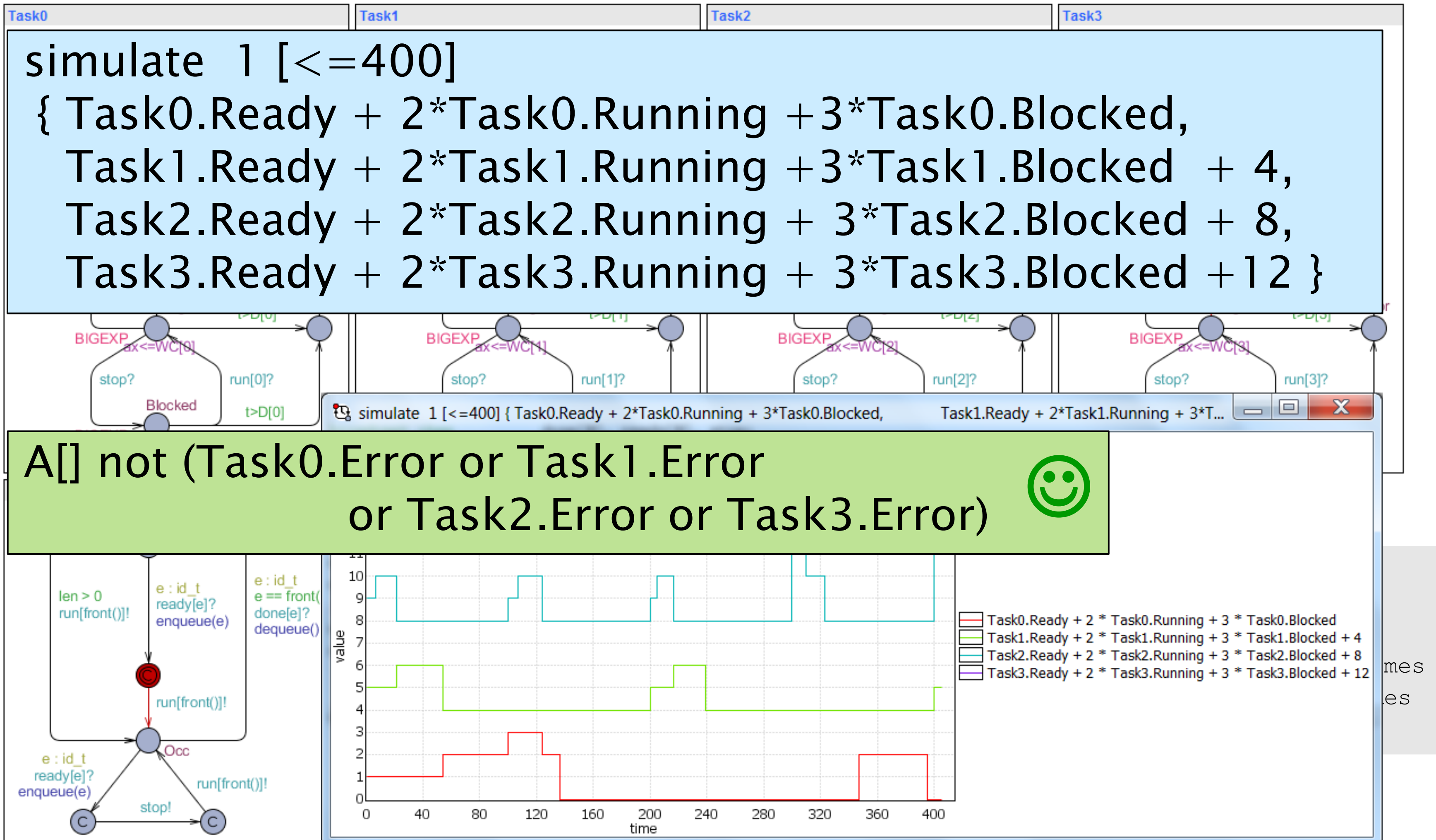

```
// Put an element at the end of the queue
void enqueue(id_t element)
{
int tmp=0;
list[len++] = element;
if (len>0)
{
        int i=len-1;
        while (i>1 && P[list[i]]>P[list[i-1]])
        {
                tmp = list[i-1];
                list[i-1] = list[i];
                list[i] = tmp;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

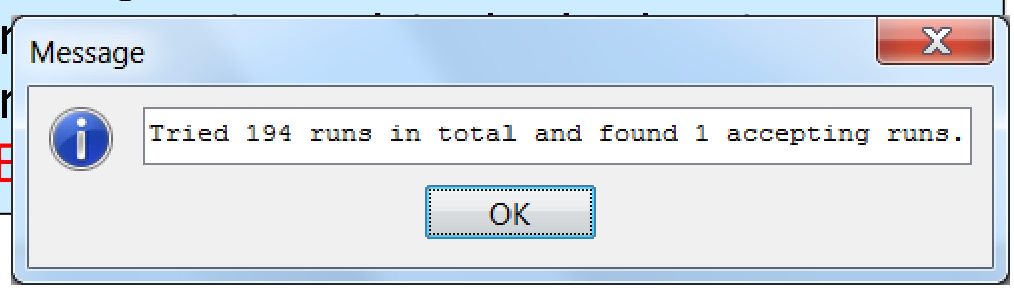
```
A[] not (Task0.Error or Task1.Error
          or Task2.Error or Task3.Error)
```

☺

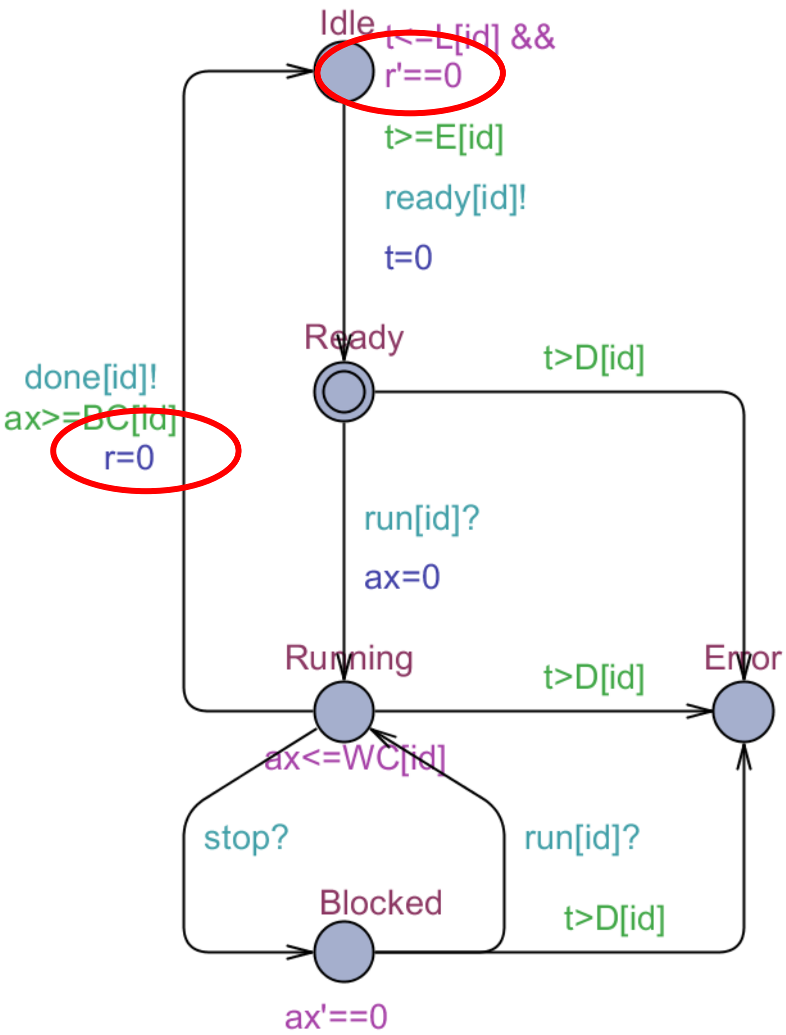


Schedulability Analysis

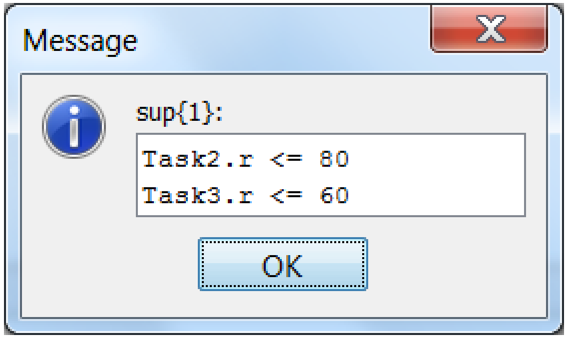
simulate 10000 [<=400]
{ Task0.Ready + 2*Task0.Running +3*Task0.Blocked,
Task1.Ready + 2*Task1.Running +3*Task1.Blocked + 4,
Task2.Ready + 2*Task2.Run
Task3.Ready + 2*Task3.Run
: 1 : (Task0.Error or Task1.E



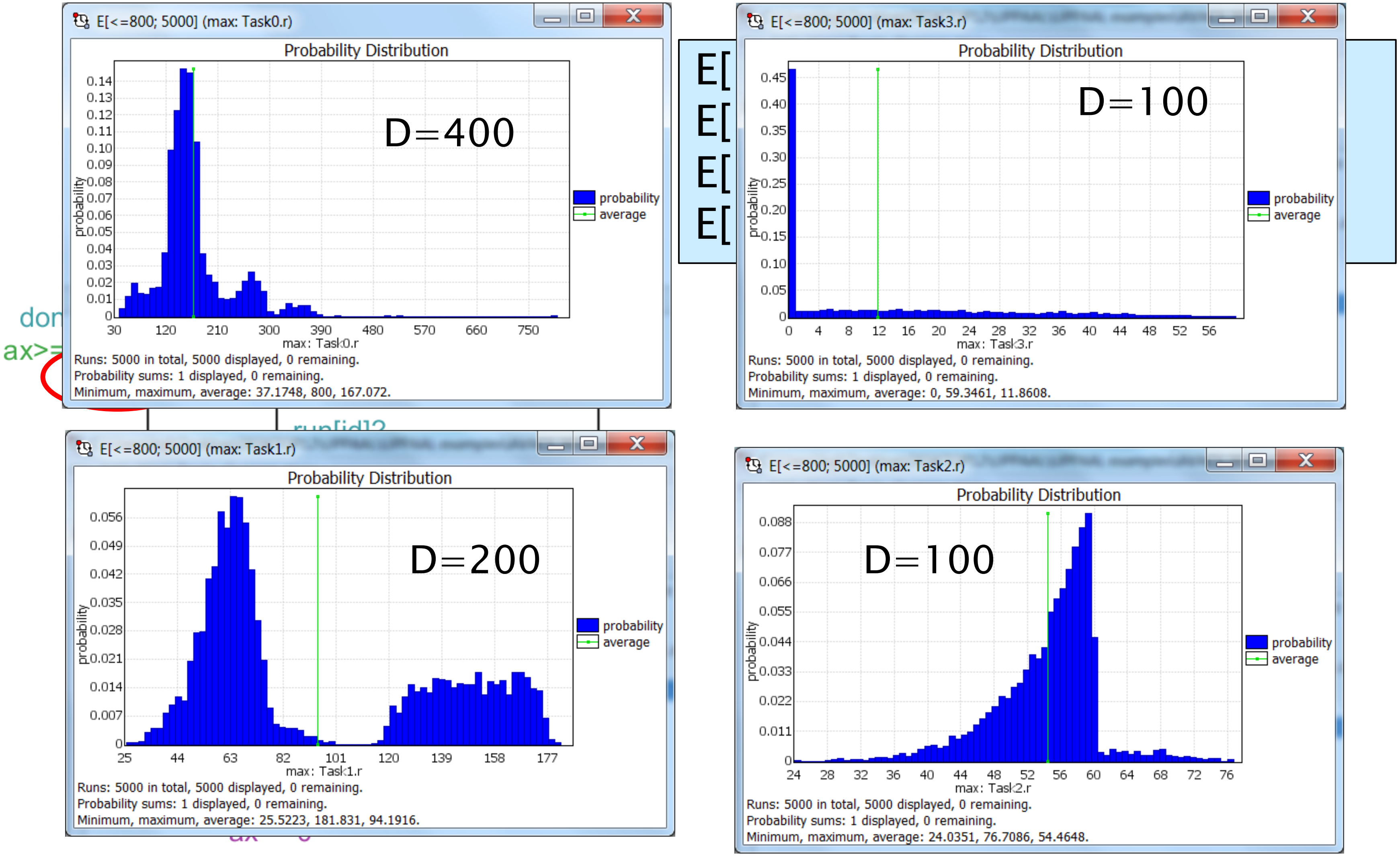
Performance Analysis



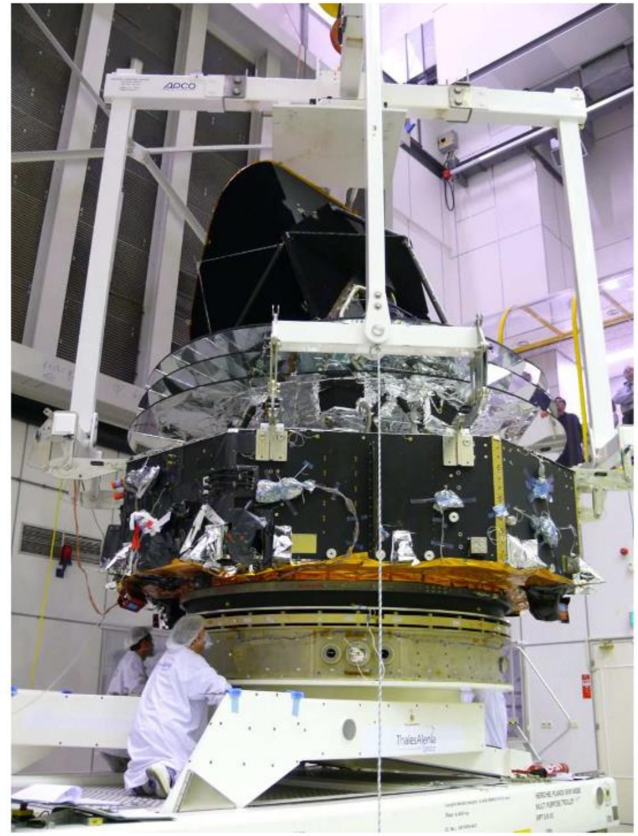
sup : Task2.r, Task3.r



Performance Analysis



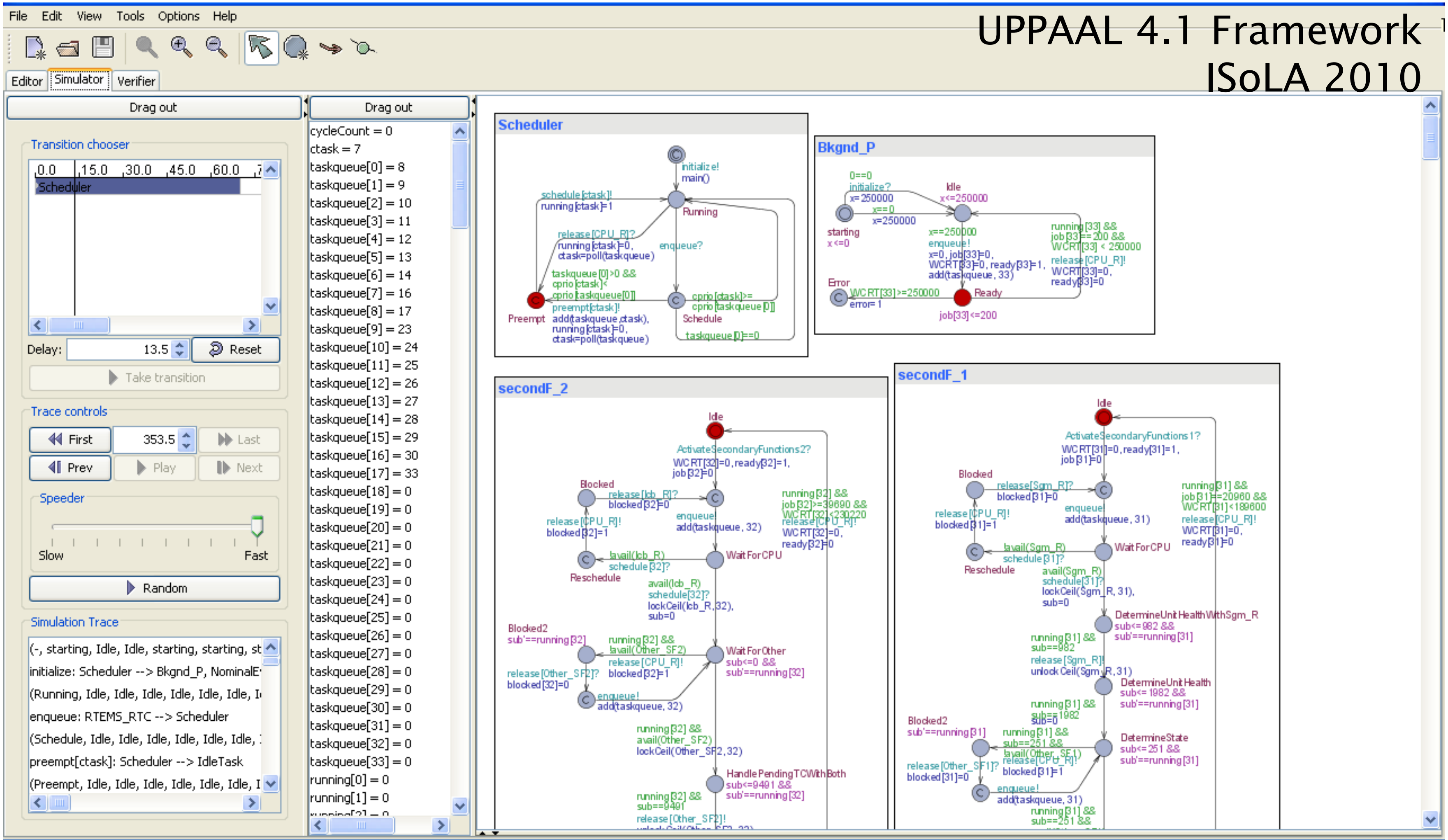
Herschel-Planck Scientific Mission at ESA



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

Modeling in UPPAAL

TERMA®



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*.

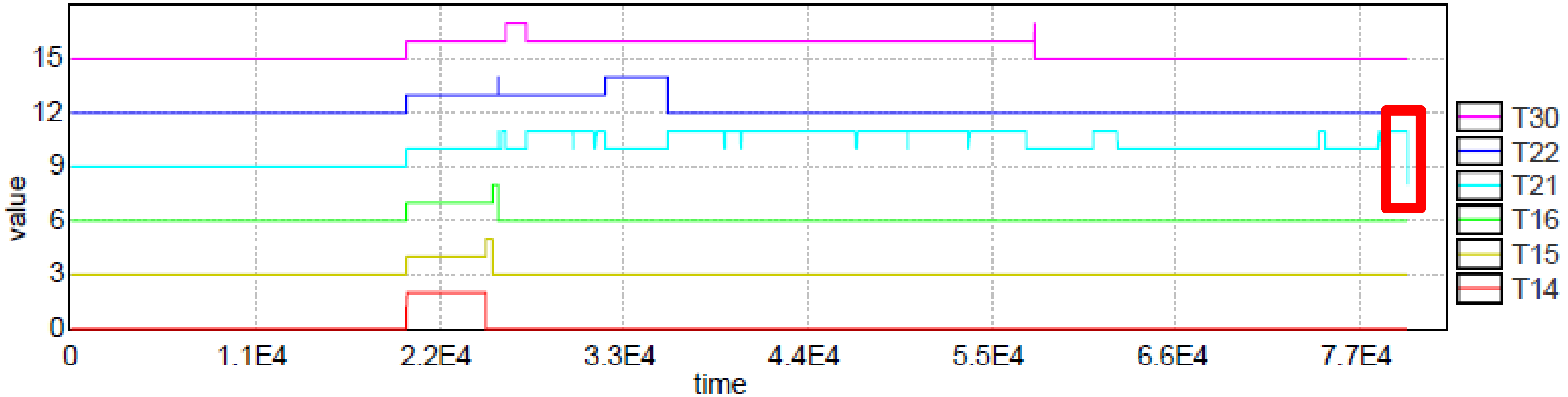
Statistical analysis:

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

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

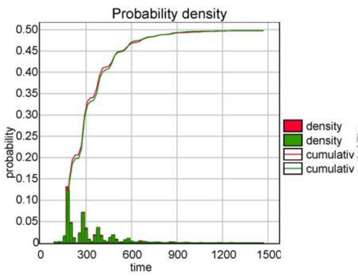
SMC Simulation to Find Error

Herschel deadline violation with $f = 50\%$:

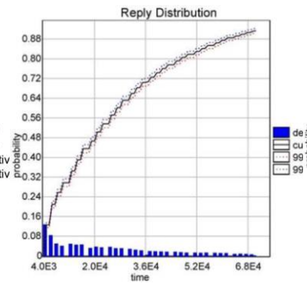


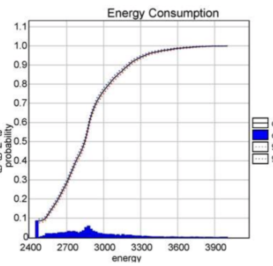

```
simulate 10000 [<=300] {
   (T(1).Ready+T(1).Computing+T(1).Release+runs[1]-2*T(1)
   (T(2).Ready+T(2).Computing+T(2).Release+runs[2]-2*T(1)
   (T(3).Ready+T(3).Computing+T(3).Release+runs[3]-2*T(1)
} : 1 : error
```

Other Case Studies

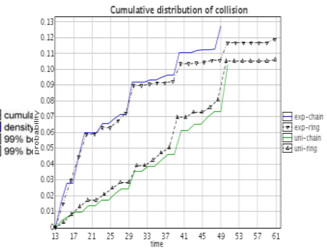


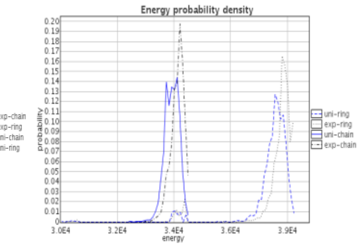
FIREWIRE



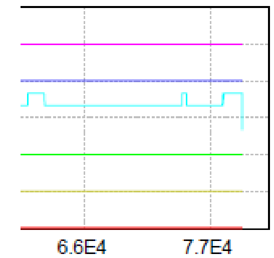


BLUETOOTH

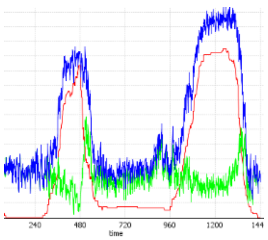




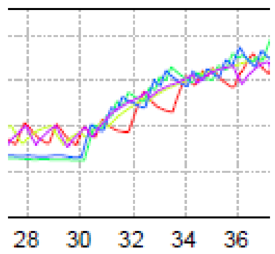
10 node LMAC



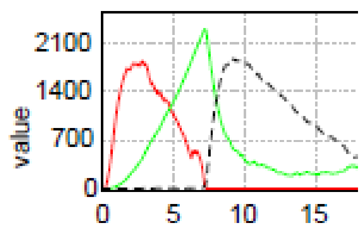
Schedulability Analysis for Mix Cr Sys



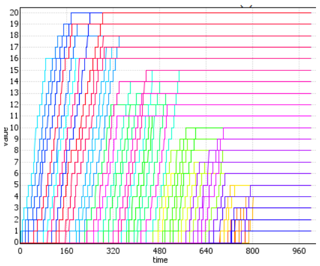
Smart Grid Demand / Response



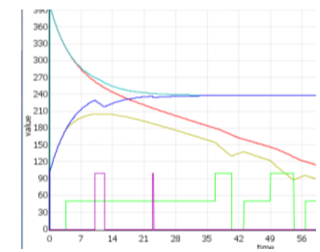
Energy Aware Buildings



Genetic Oscilator (HBS)



Passenger Seating in Aircraft



Battery Scheduling (SENSATION) Erik Wogensen

Formal & Informal Methods

- Model Checking vs Stat MC, Simulation
- Qualitative vs Quantitative (metrics)
- State Space Expl vs Confidence Expl
- Correctness (overap)
  vs Counterex (underap)
- Worst Case vs Expected Case
- Synthesis on abstract models
  vs Performance eval on refined models
- ....

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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)