Test and Verification

Of Real-Time Systems using UPPAAL

Brian Nielsen

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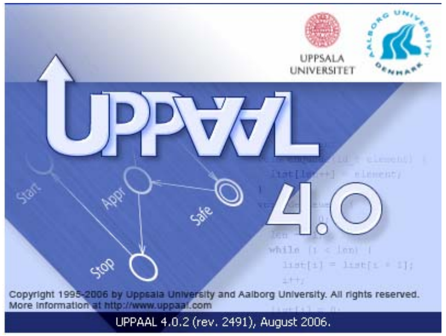

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UPPAAL 4.0.2 (rev. 2491), August 2006.

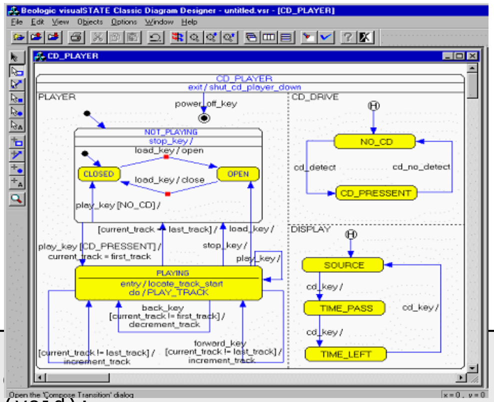
AALBORG UNIVERSITY DENMARK

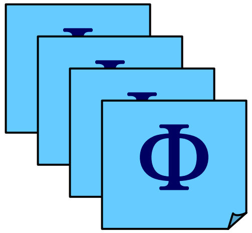
BRICS
Basic Research
in Computer Science

CISS
CENTER FOR INDLEJREDE SOFTWARE SYSTEMER

Verifikation og Test

Model





Spec

```
/* Wait for
void OS_Wait(void);

/* Operating system visualSTATE process. Mimics a OS process for a
 * visualSTATE system. In this implementation this is the mainloop
 * interfacing to the visualSTATE basic API. */
void OS_VS_Process(void);

/* Define completion code variable. */
unsigned char cc;

void HandleError(unsigned char ccArg)
{
  printf("Error code %c detected, exiting application.\n", ccArg);
  exit(ccArg);
}


/* In d-241 we only use the OS_Wait call. It is used to simulate a
 * system. It purpose is to generate events. How this is done is up to
 * you.
 */
void OS_Wait(void)
{
  /*  Ignore the parameters; just retrieve events from the keyboard and
   *  put them into the queue. When EVENT_UNDEFINED is read from the
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  SEM_EVENT_TYPE event;
  int num;
```

Kode

System

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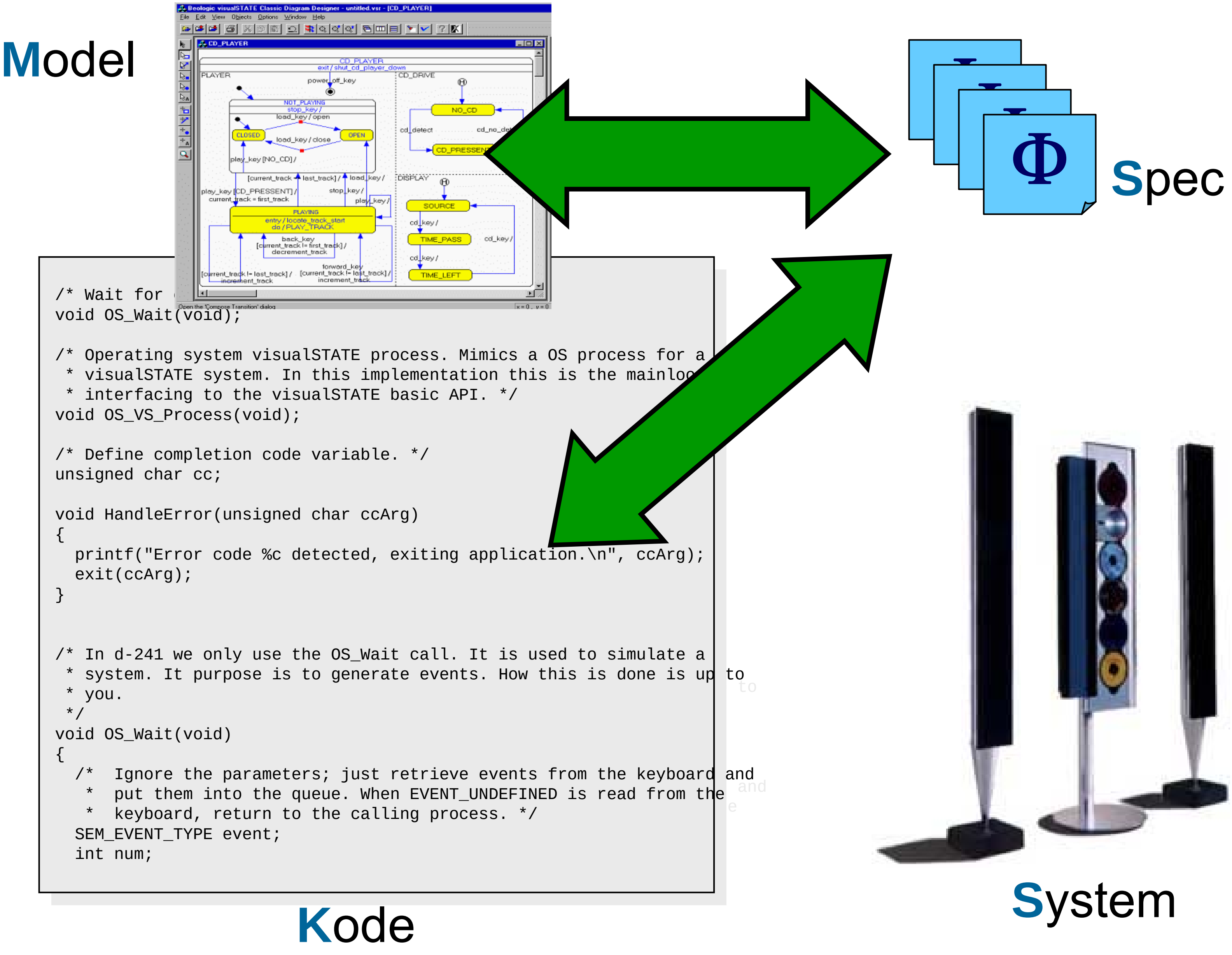
Verifikation og Test



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Verifikation og Test

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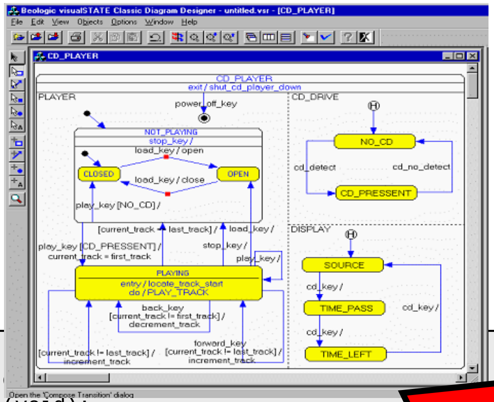

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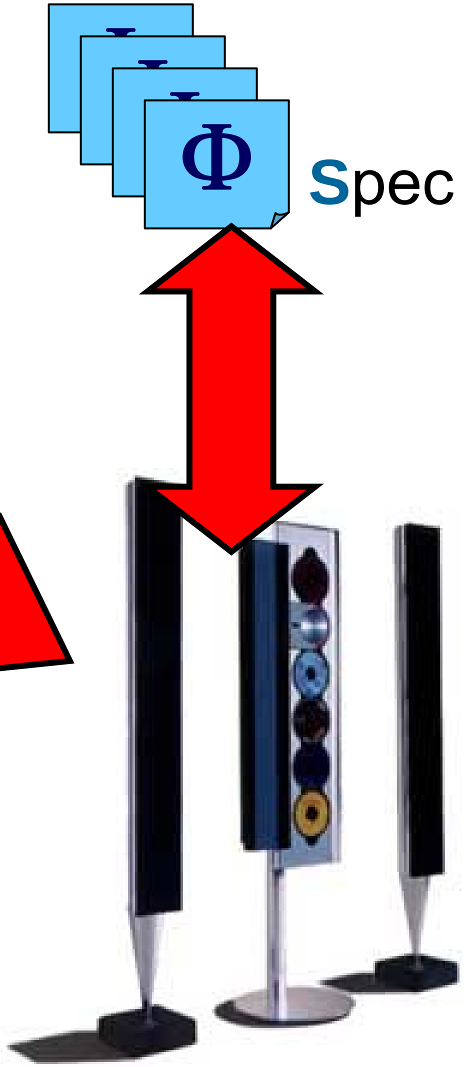

Spec

System

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Modelling Behaviour using State Machines

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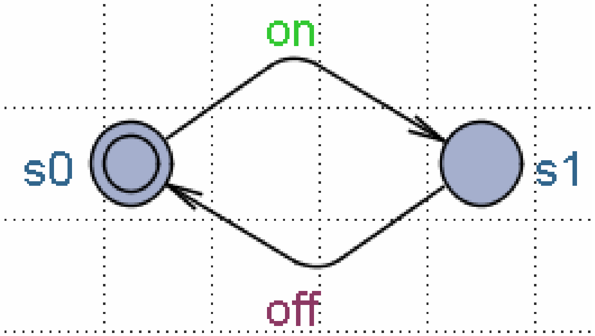
Modelling processes

- A process is the execution of a sequential program.
- modeled as a finite state machine (LTS)
  - transits from state to state
  - by executing a sequence of *atomic* actions.

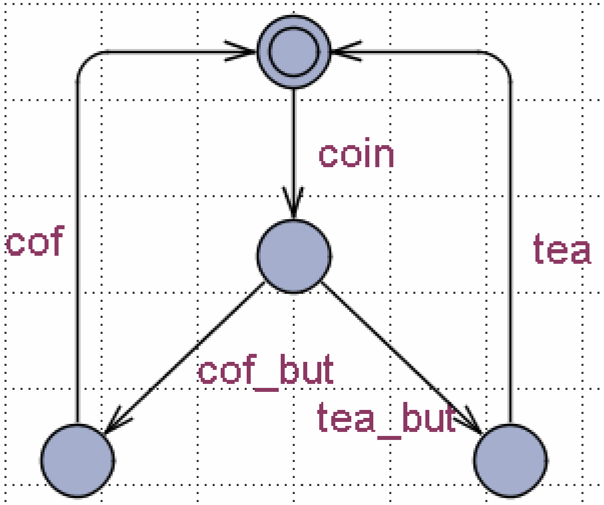
a light switch
LTS



on→off→on→off→on→off→ ……….

a sequence of actions or *trace*

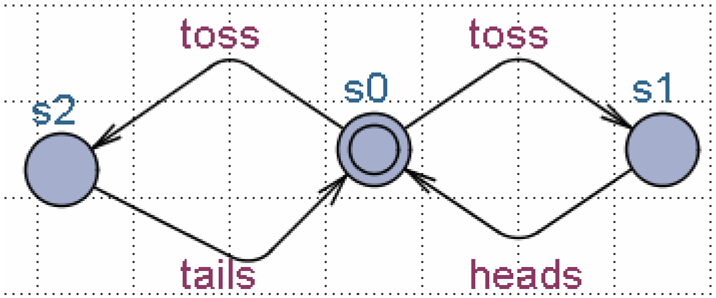
Modelling Choices



- Who or what makes the choice?
- Is there a difference between input and output actions?

Non-deterministic Choice

- Tossing a coin

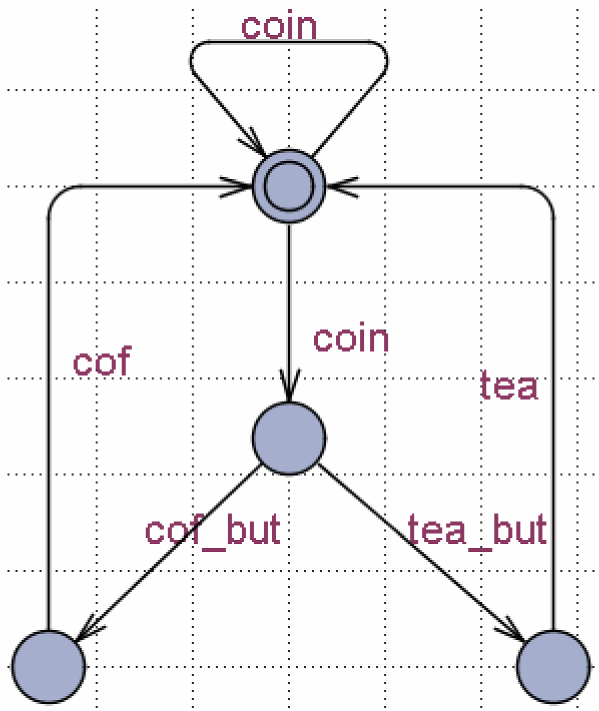


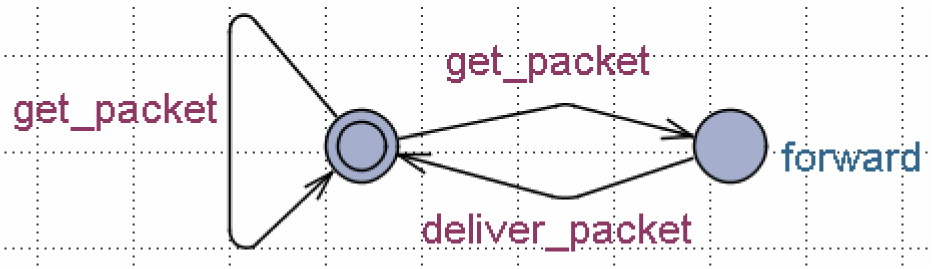
- Possible traces?
  - Both outcomes possible
  - Nothing said about relative frequency
  - If coin is fair, the outcome is 50/50

Non-Deterministic Choice -modelling failure

How do we model an unreliable communication channel which accepts **packets,** and if a failure occurs produces no output, otherwise **delivers** the packet to the receiver?

Use non-determinism...





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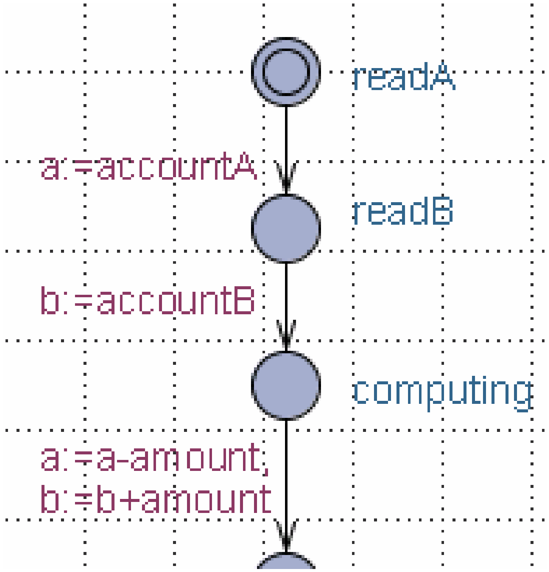
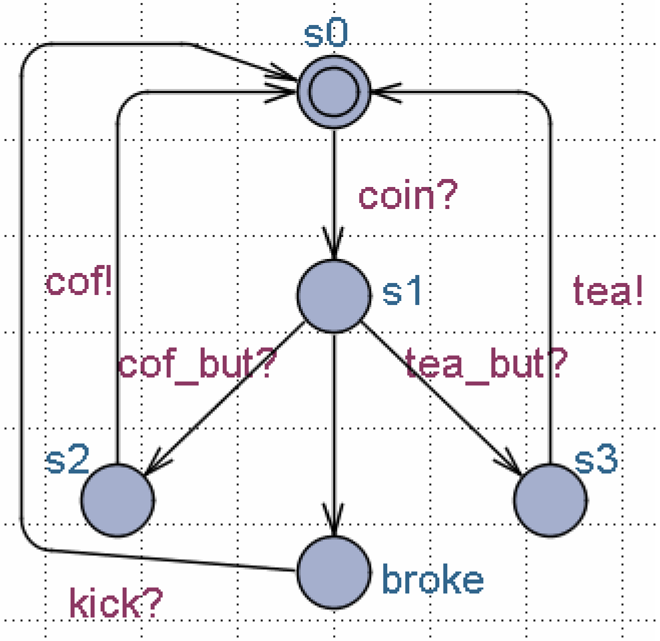
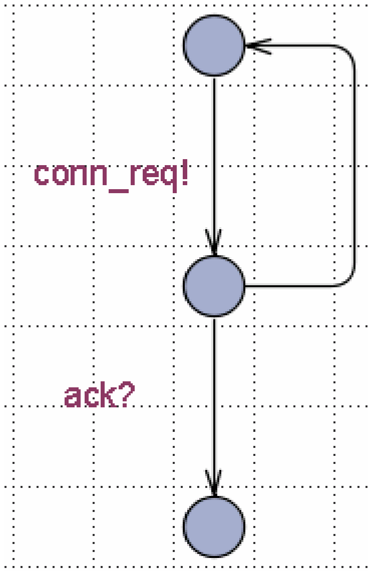
Internal-Actions

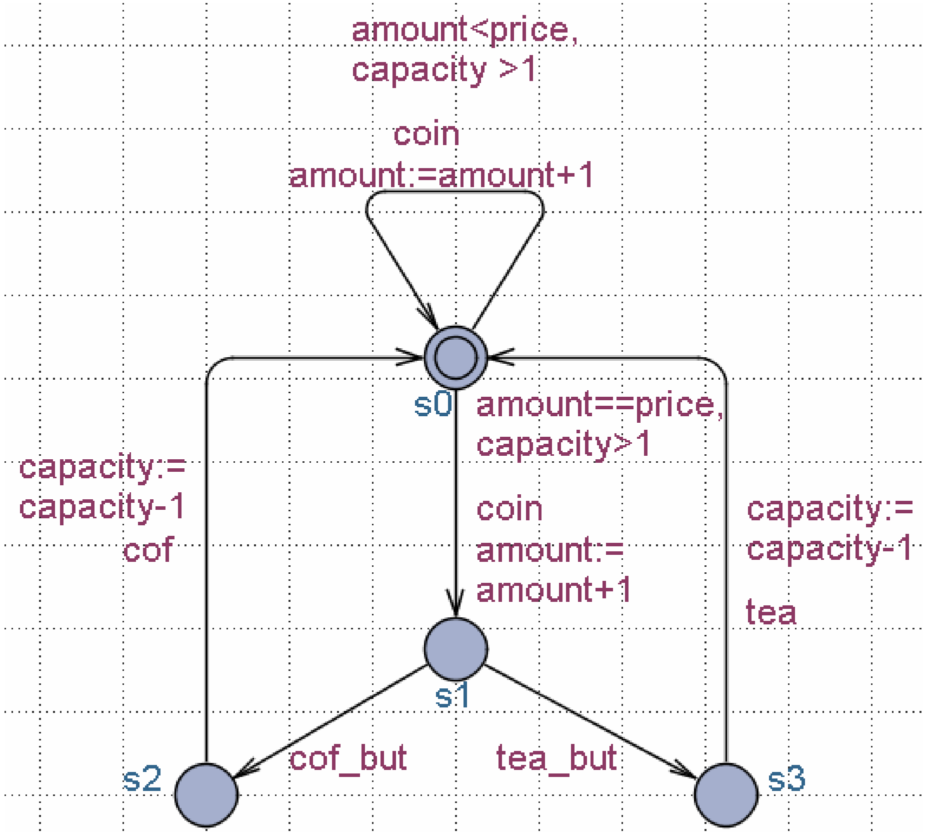
- Spontaneous actions
- Internal actions
- Tau-actions
- Internal transitions can be taken on the initiative of a single machine without communication with others







Extended FSM

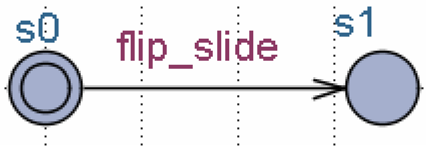


- EFSM = FSM + variables + enabling conditions + assignments
- Transition still atomic
- Can be translated into FSM if variables have bounded domain
- State: control location+variable states: (state,total,capacity)
- (s0,5,10)

SS

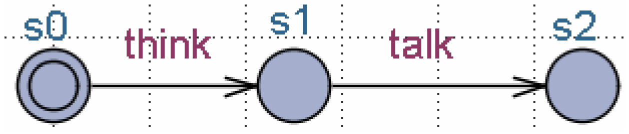
Parallel Composition: interleaving

Flipper



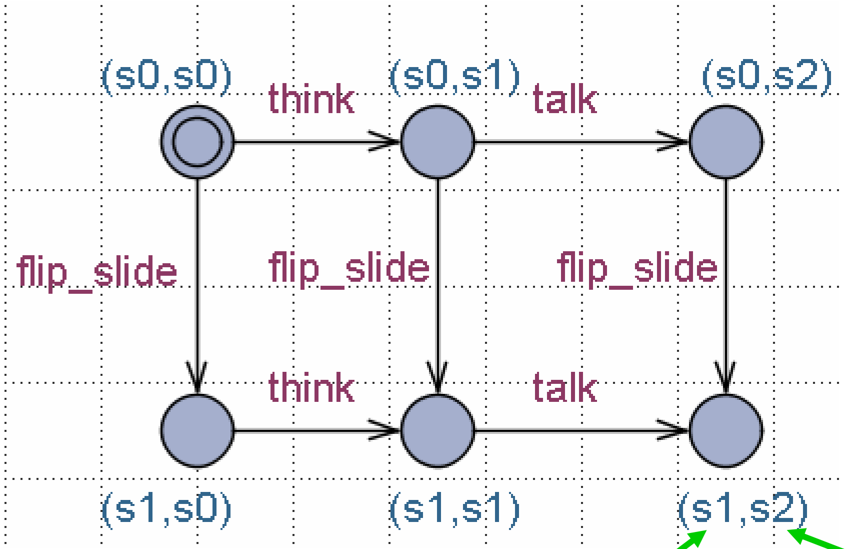
2 states

Speaker



3 states

Lecturer =
Speaker || Flipper



2*3 states

from Flipper

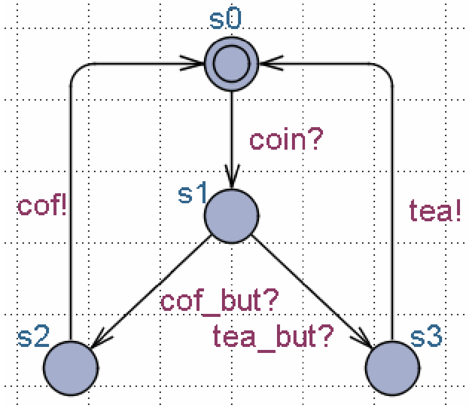
from Speaker

Process Interaction

- ! = Output, ? = Input
- Handshake communication
- Two-way

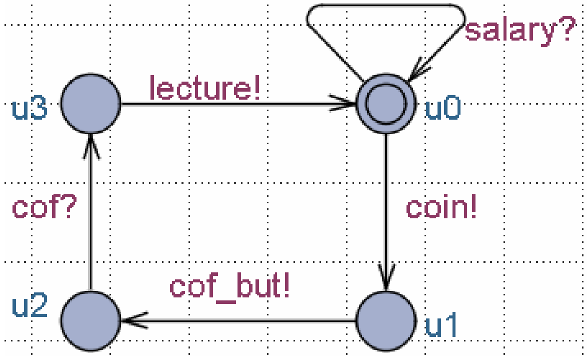
University=
Coffee Machine || Lecturer
•LTS?
•How many states?
•Traces ?

Coffee Machine

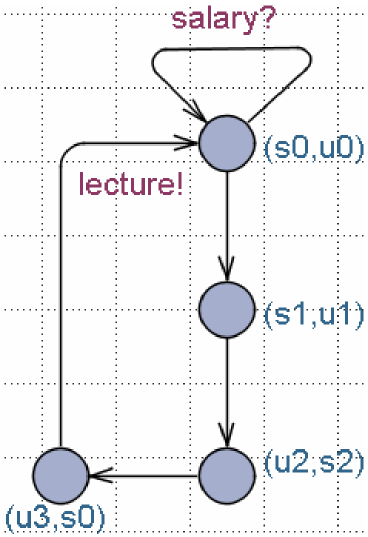


4 states

Lecturer



4 states



synchronization results in internal actions

4 states:Interaction constrain overall behavior

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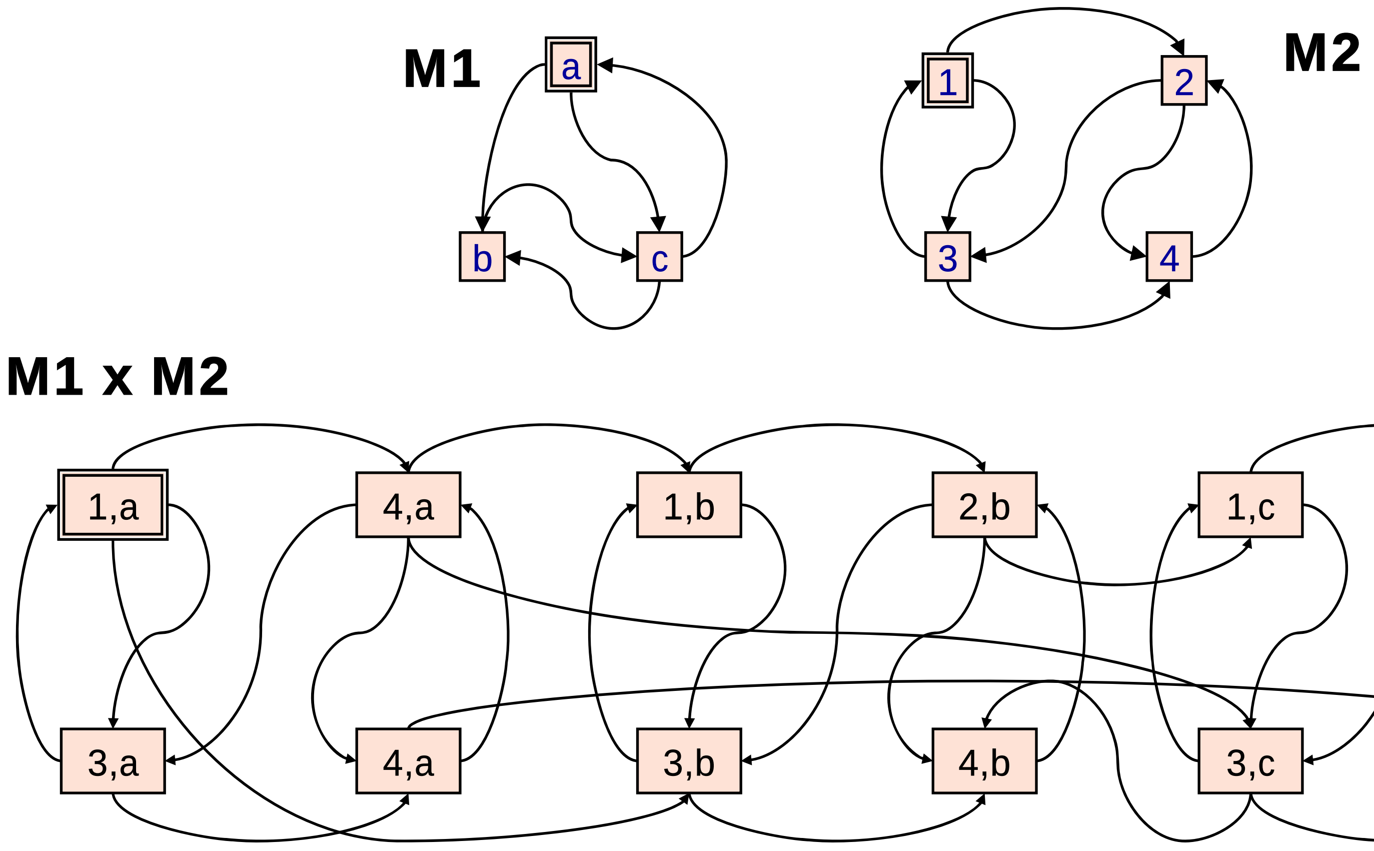
Composition



All combinations=
exponential in no of machines

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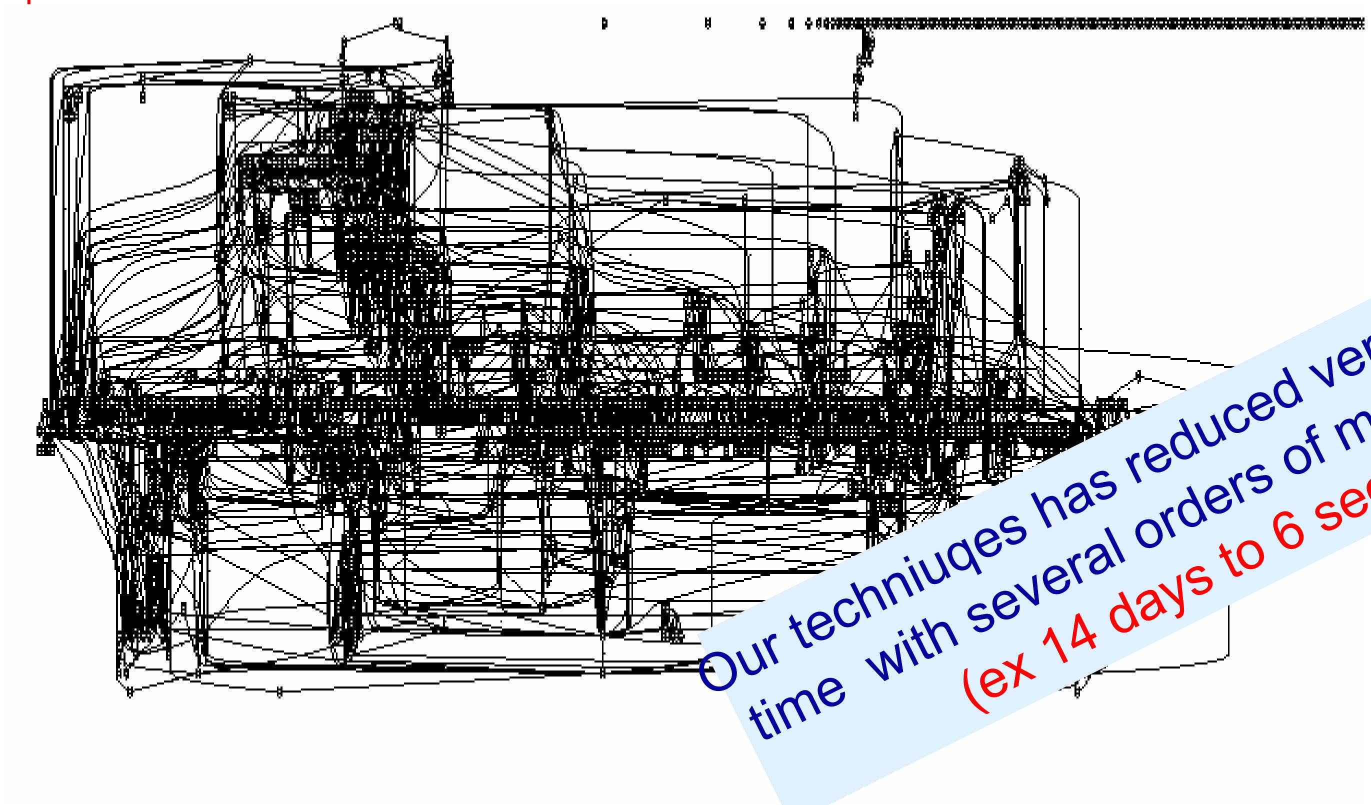
Train Simulator

VVS
visualSTATE

1421 machines
11102 transitions
2981 inputs
2667 outputs
3204 local states
Declare state sp.: 10^476

BUGS ?



Our techniuqes has reduced verification time with several orders of magnitude (ex 14 days to 6 sec)

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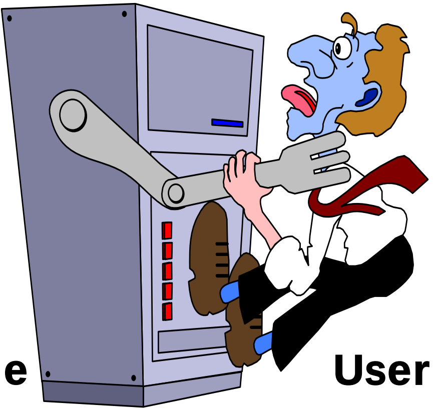
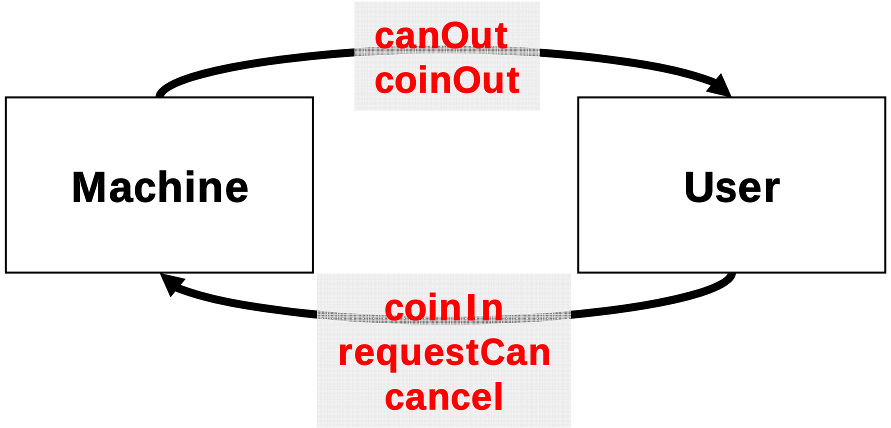
Modelling Exercise

The Vending Machine





Machine

User

canOut
coinOut

coinIn
requestCan
cancel

- Simulate model w
  Random User
- Model Fair User
- Model Non-Thirsty User
- Deadlocks ?

- Cans requested will be delivered ?
- Cancellations are obeyed ?

- What happens if multiple users?

Assumption: 1 can = 1 coin!

Exercise

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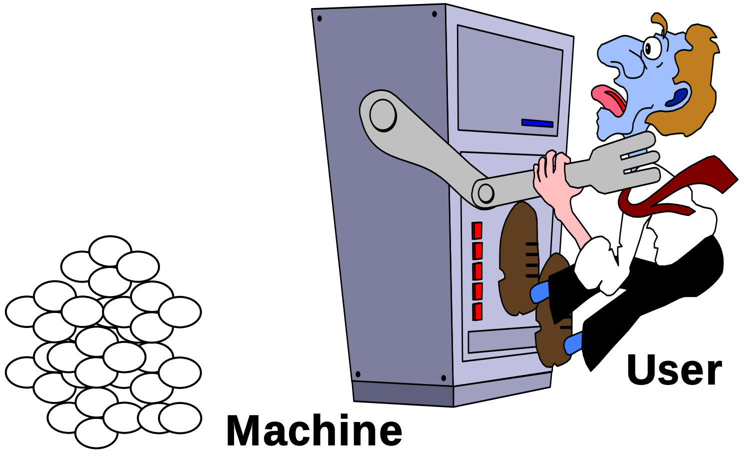
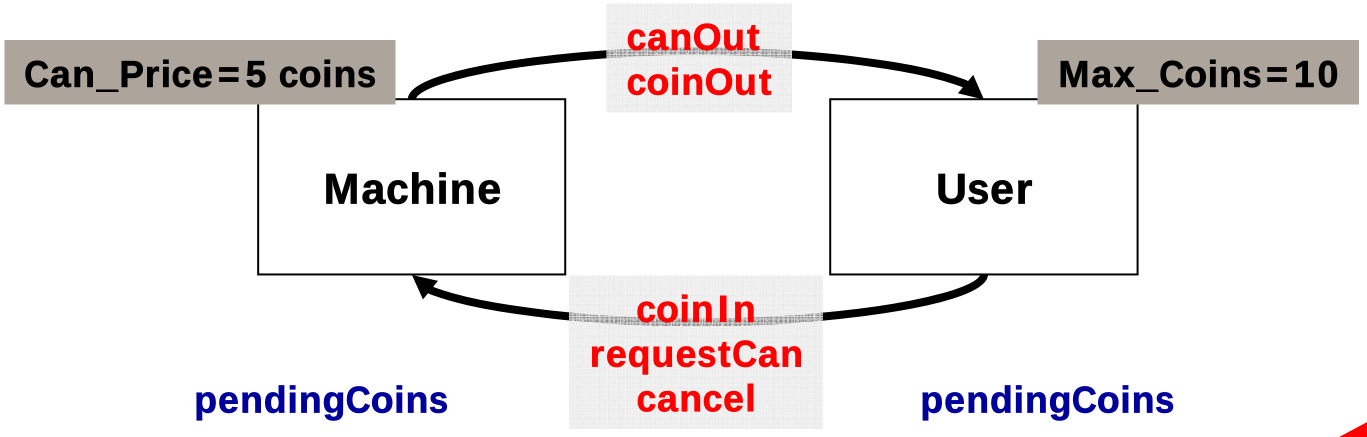
Modelling Exercise

The Vending Machine



- Extend model of Machine and FairUser
- Do extensive simulation



Can_Price=5 coins

canOut
coinOut

Max_Coins=10

Machine

User

coinIn
requestCan
cancel

pendingCoins

pendingCoins

Exercise

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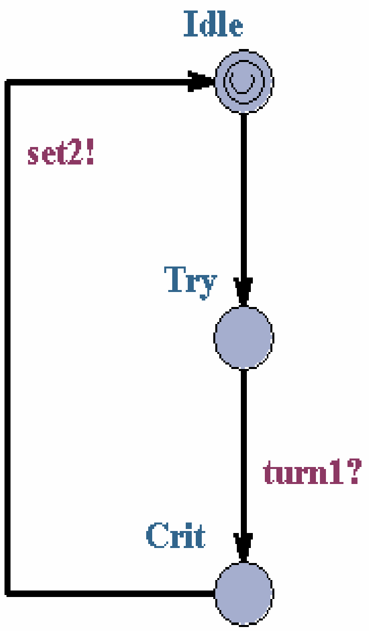
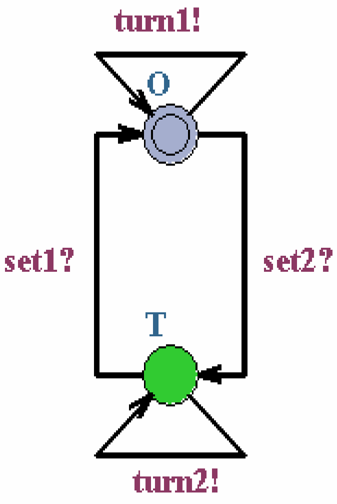
Verification = Model Checking

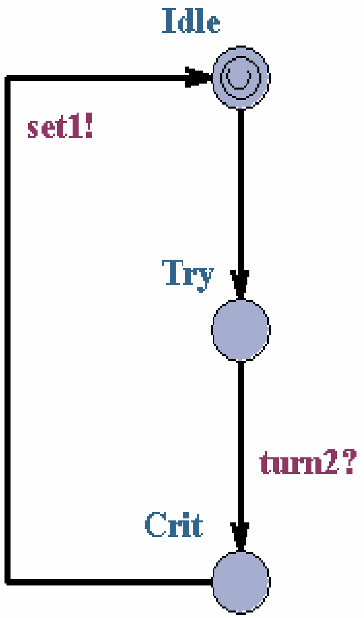
- Reachability
- Generic properties

Mutual Exclusion

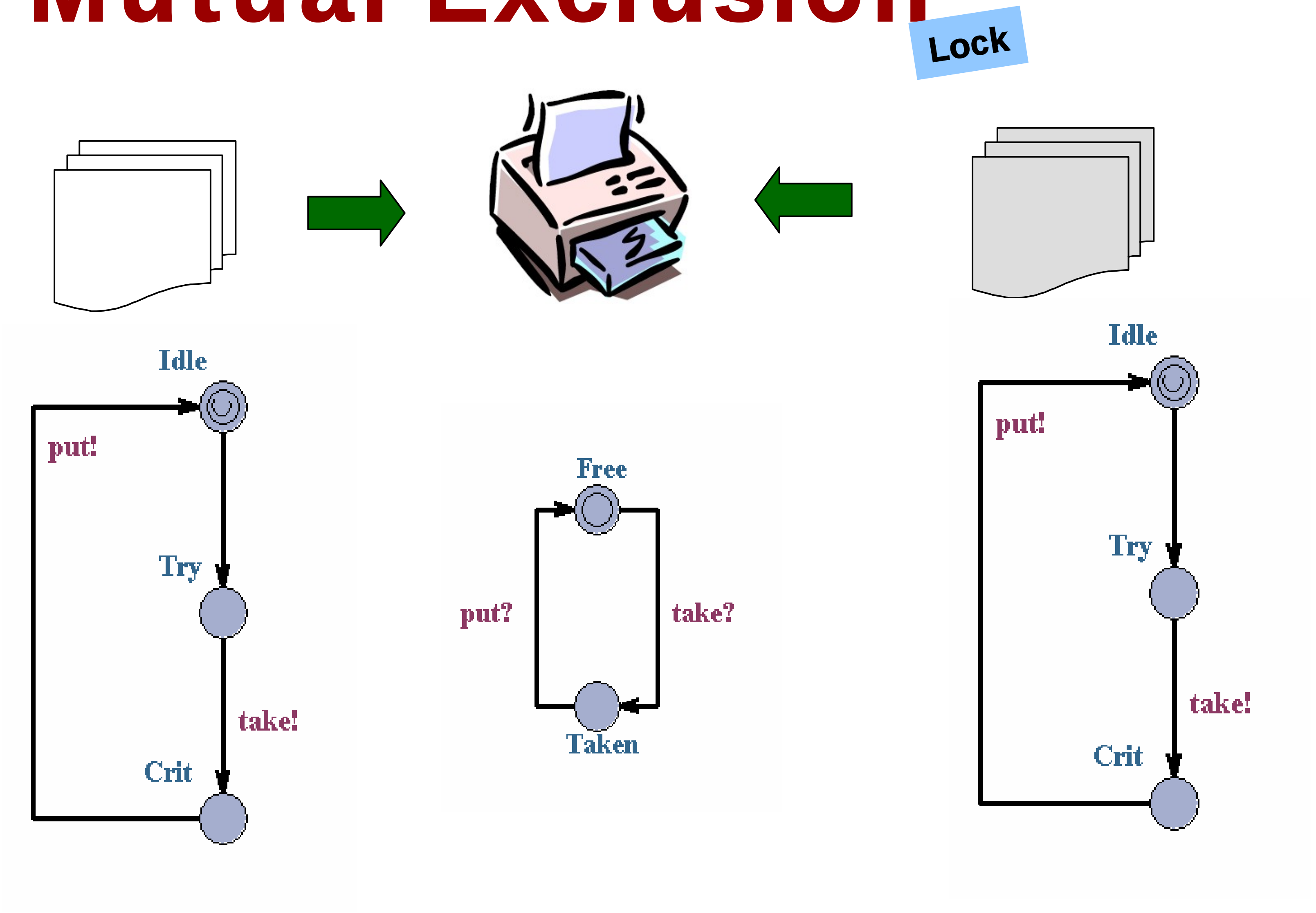
Taking turns



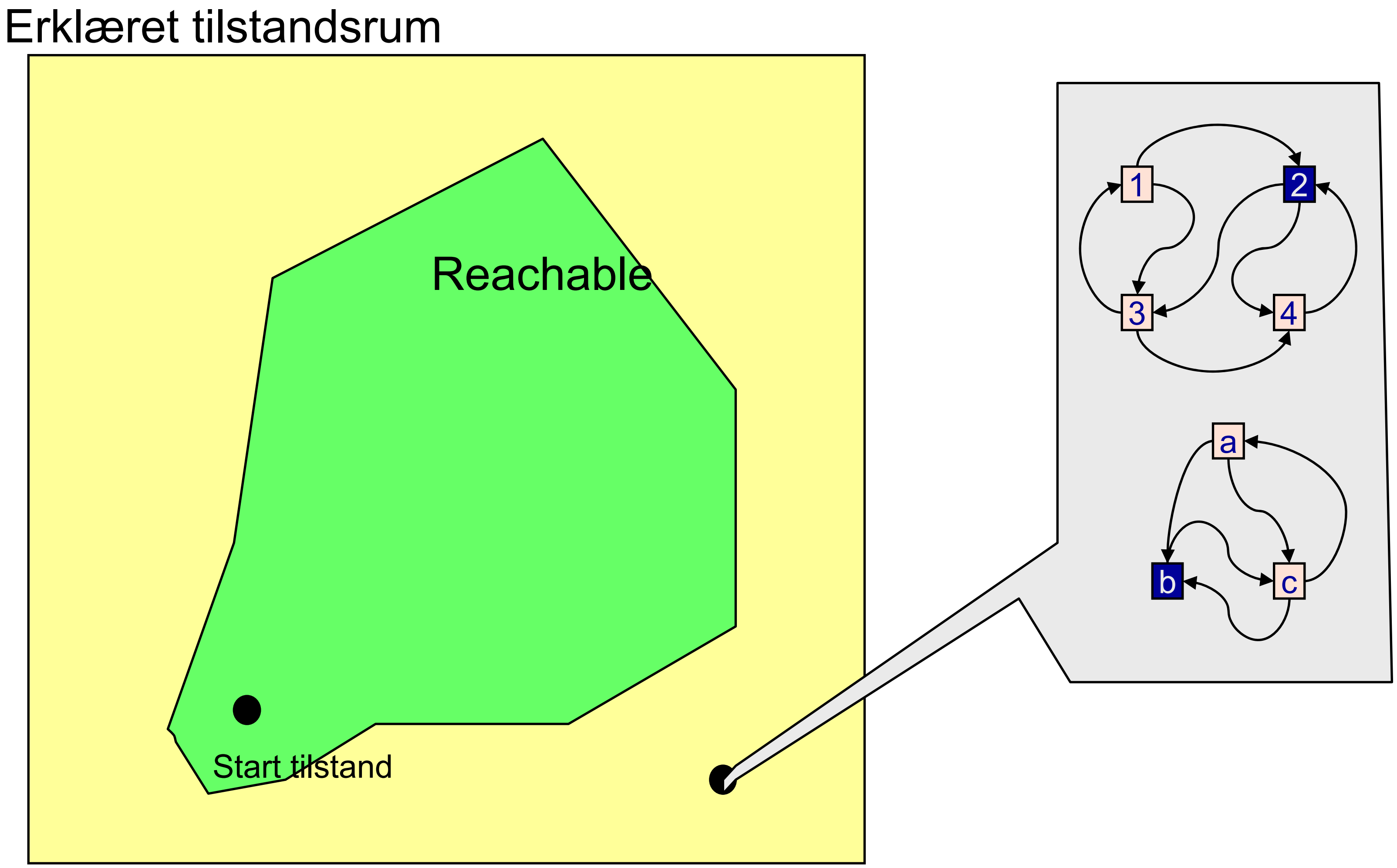




Mutual Exclusion



Udforskning af Tilstandsrum



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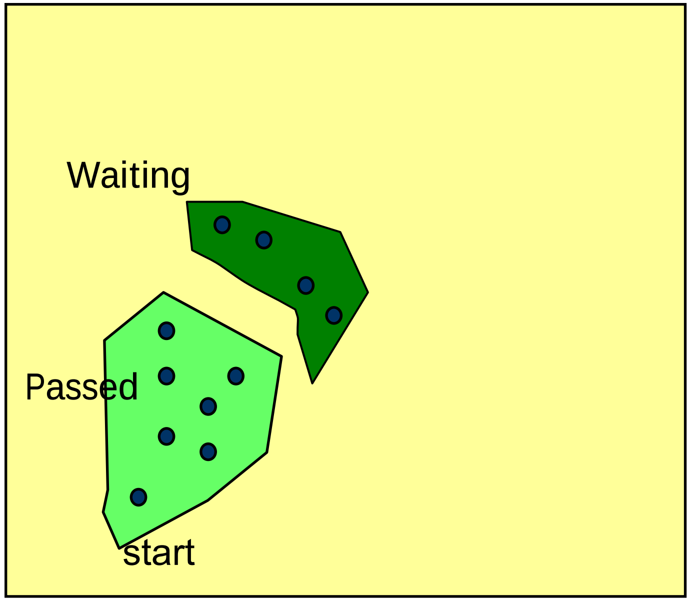
Udforskning af tilstandrum

Forward Reachability Analysis

Erklæret tilstandsrum



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Waiting:={$s_0$}
While(Waiting!=Ø)
   {
   select s∈ Waiting
   Waiting:=Waiting\{s}
   if s∉Passed
      whenever (s → t) then
         Waiting:=Waiting ∪ {t}
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Udforskning af tilstandrum

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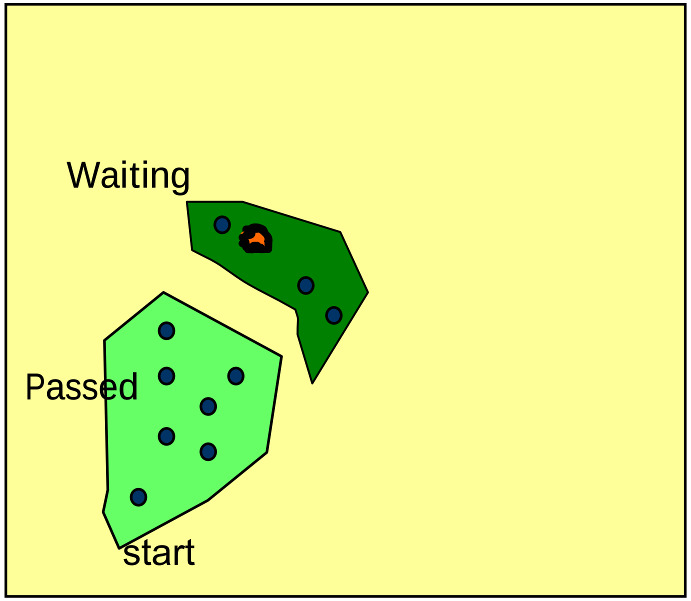

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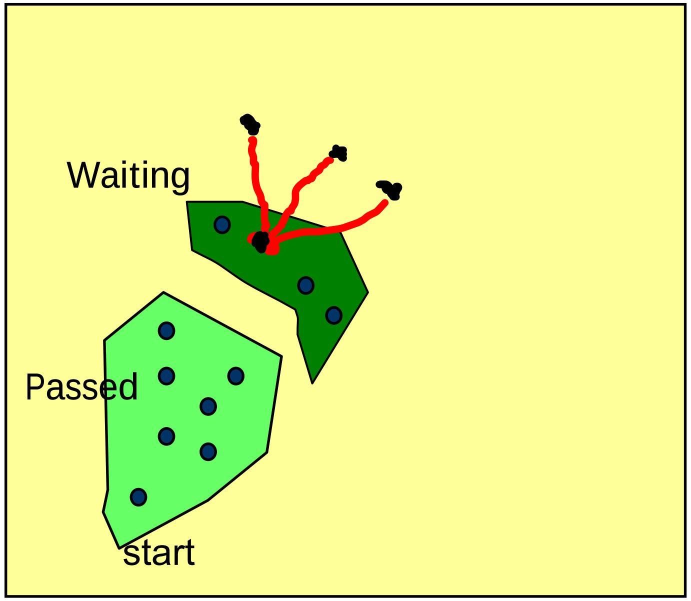

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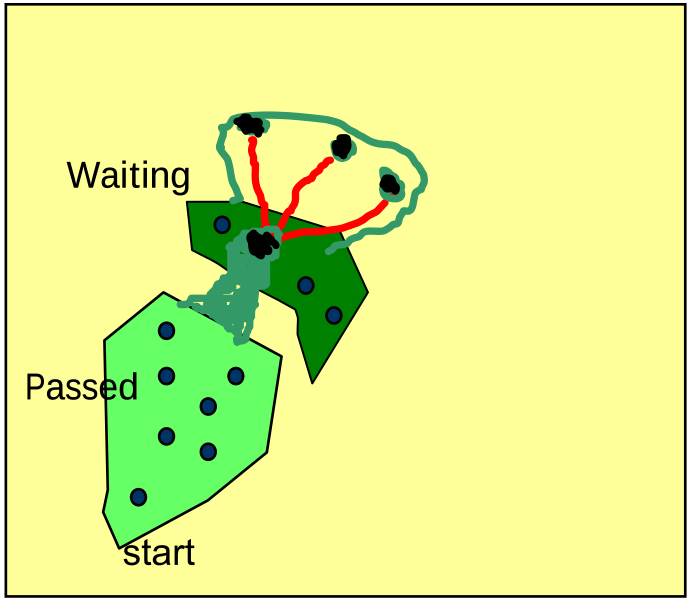

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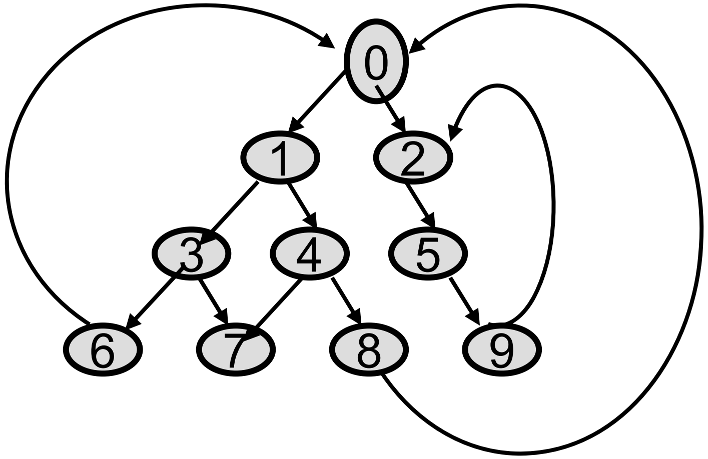

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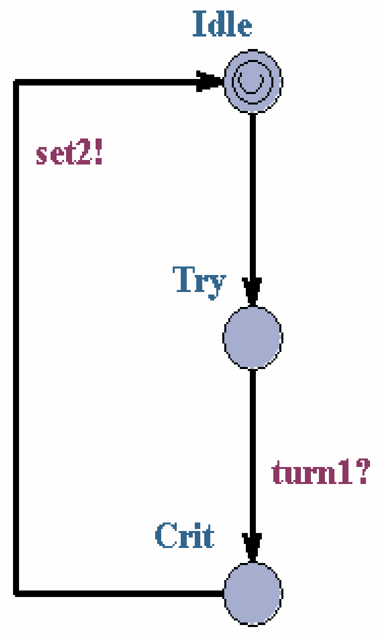
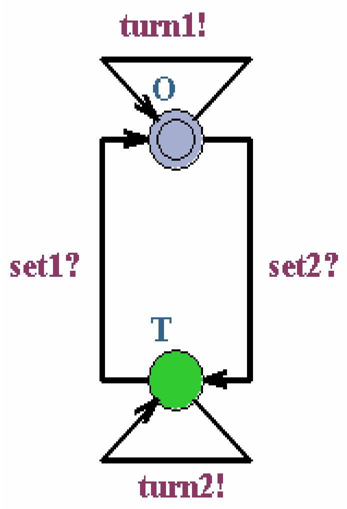
```

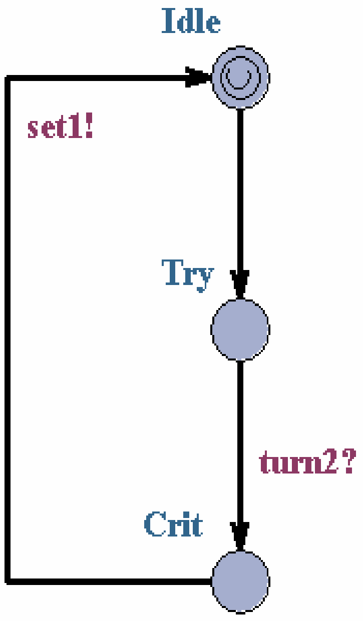
Depth-first search: organize Waiting as a **Stack**
Order: 0 1 3 6 7 4 8 2 5 9

Breadth-first search: organize Waiting as a **Queue**
Order: 0 1 2 3 4 5 6 7 8 9

Gensidig Udelukkelse



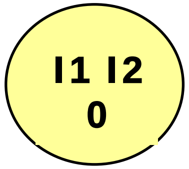


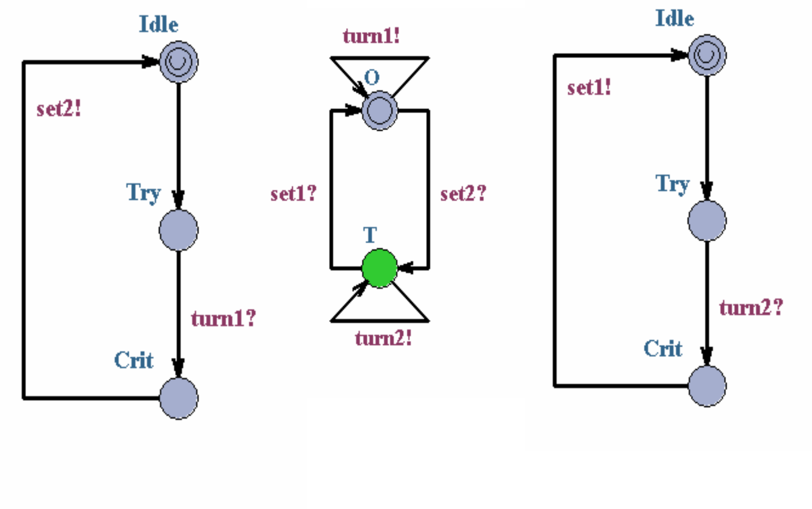


Turn

Gensidig udelukkelse

Forward Reachability





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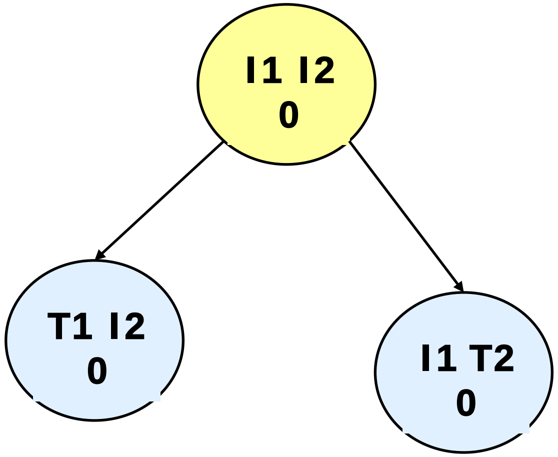

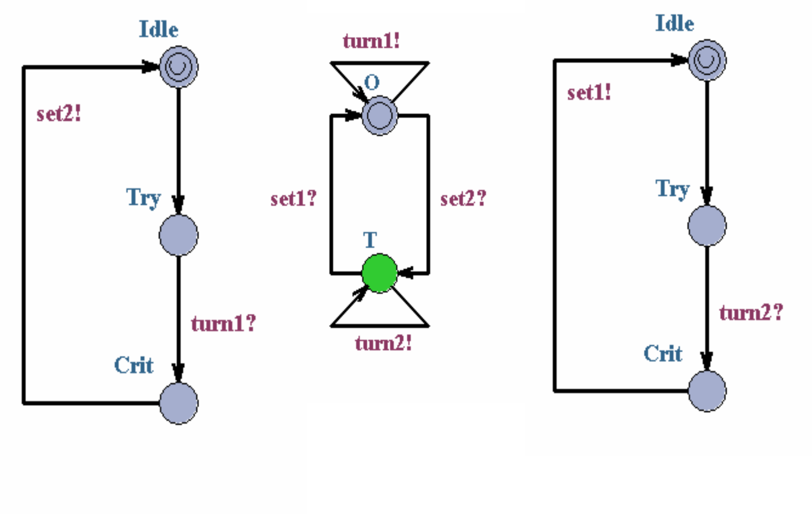

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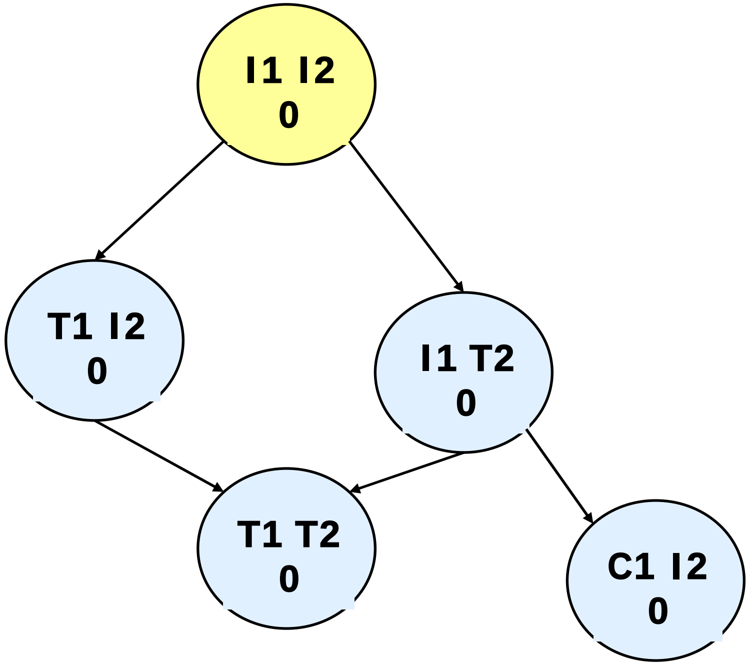


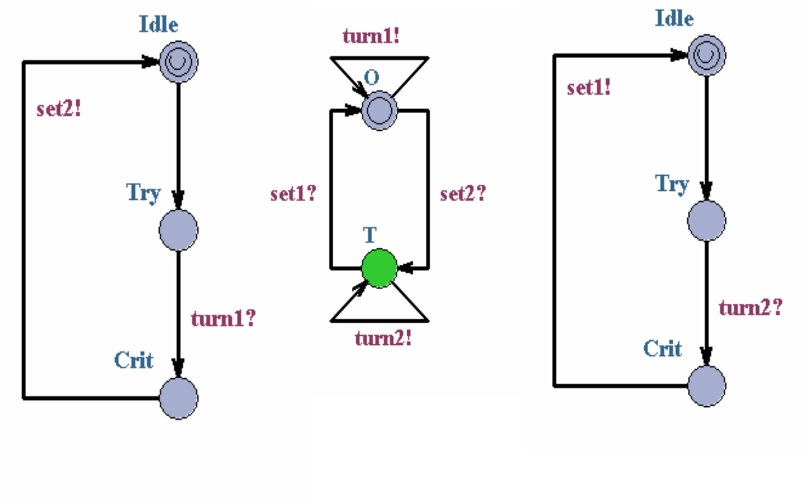
I1 I2
0

T1 I2
0

I1 T2
0

T1 T2
0

C1 I2
0



Turn

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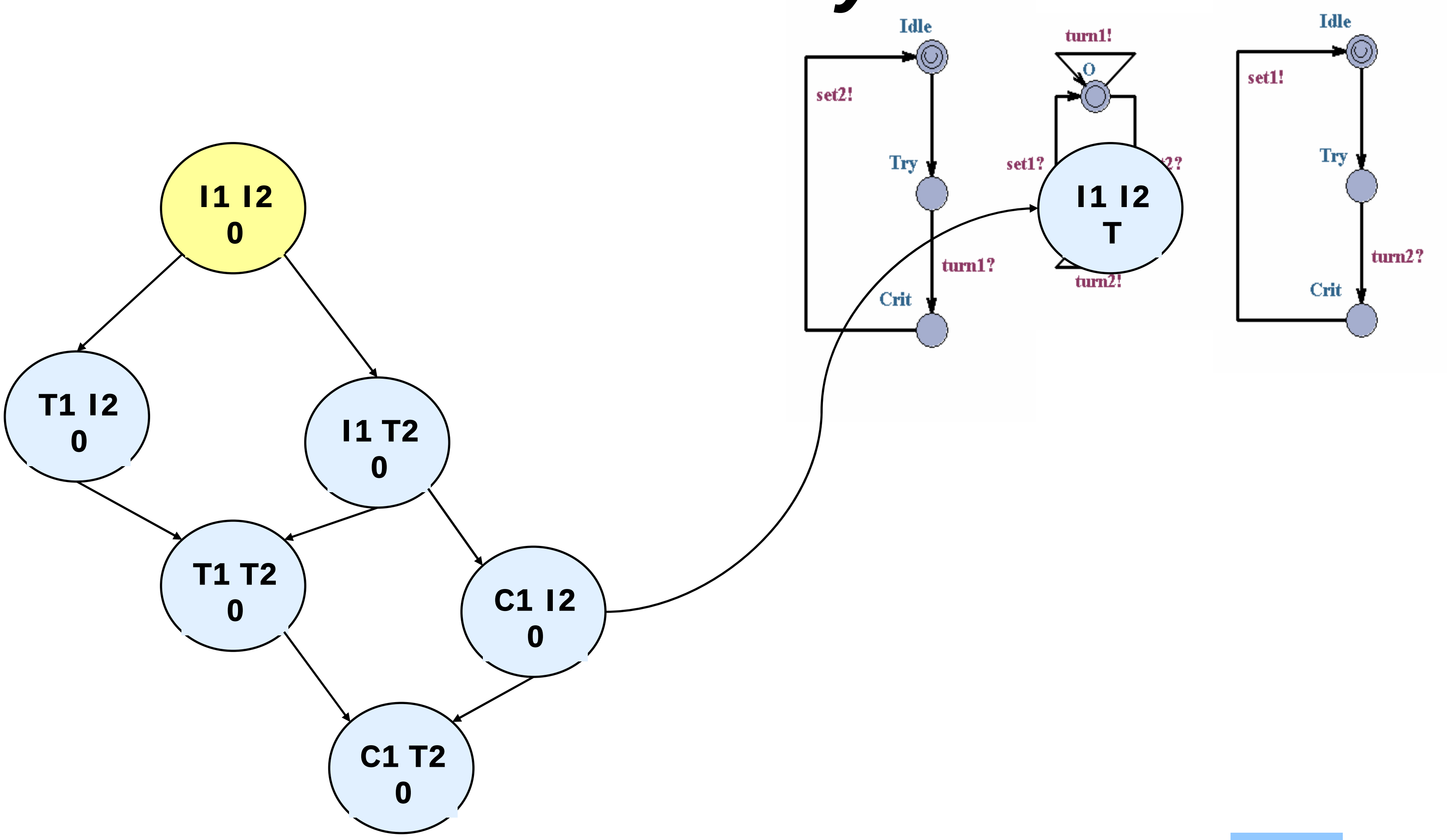

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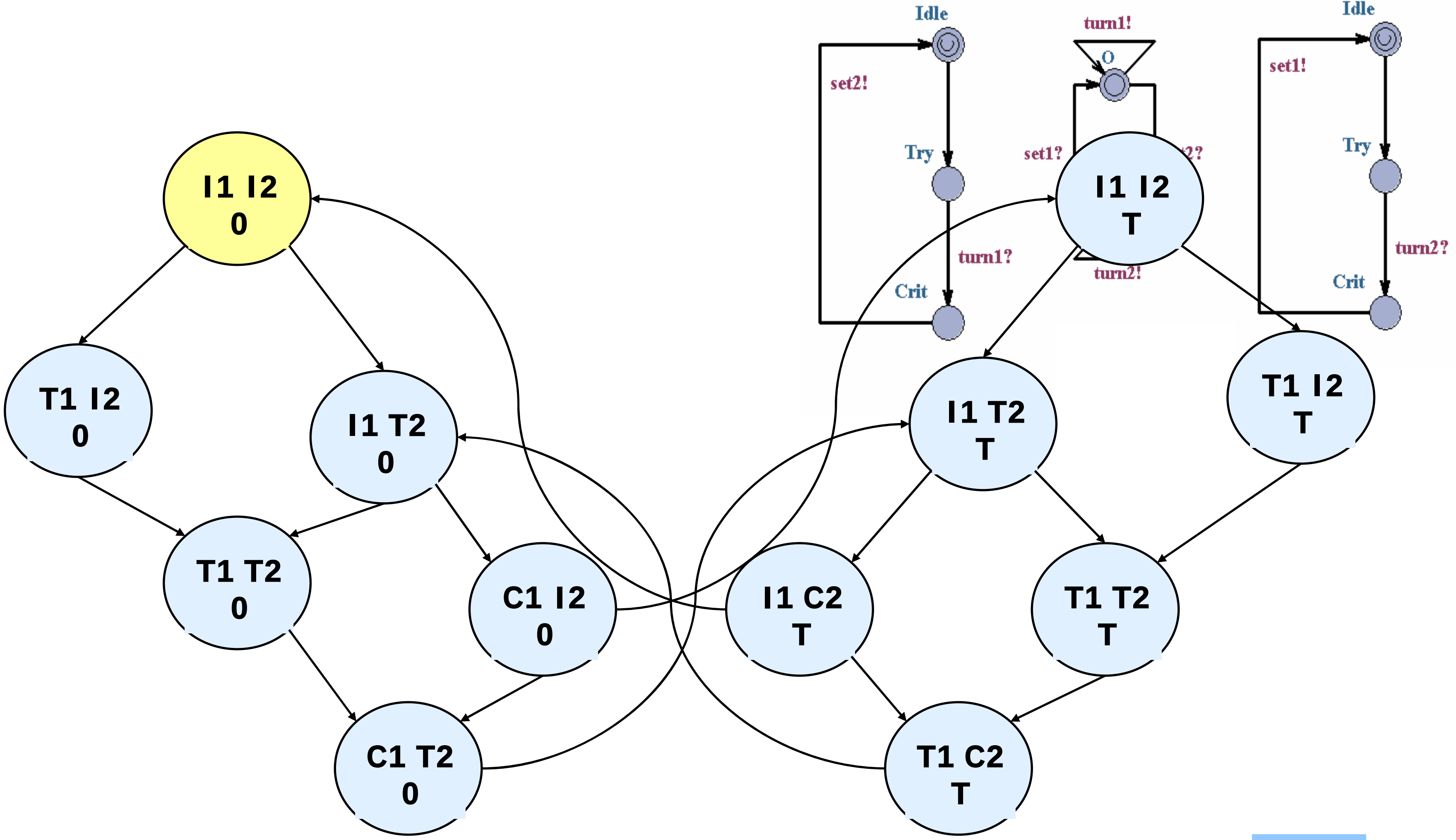

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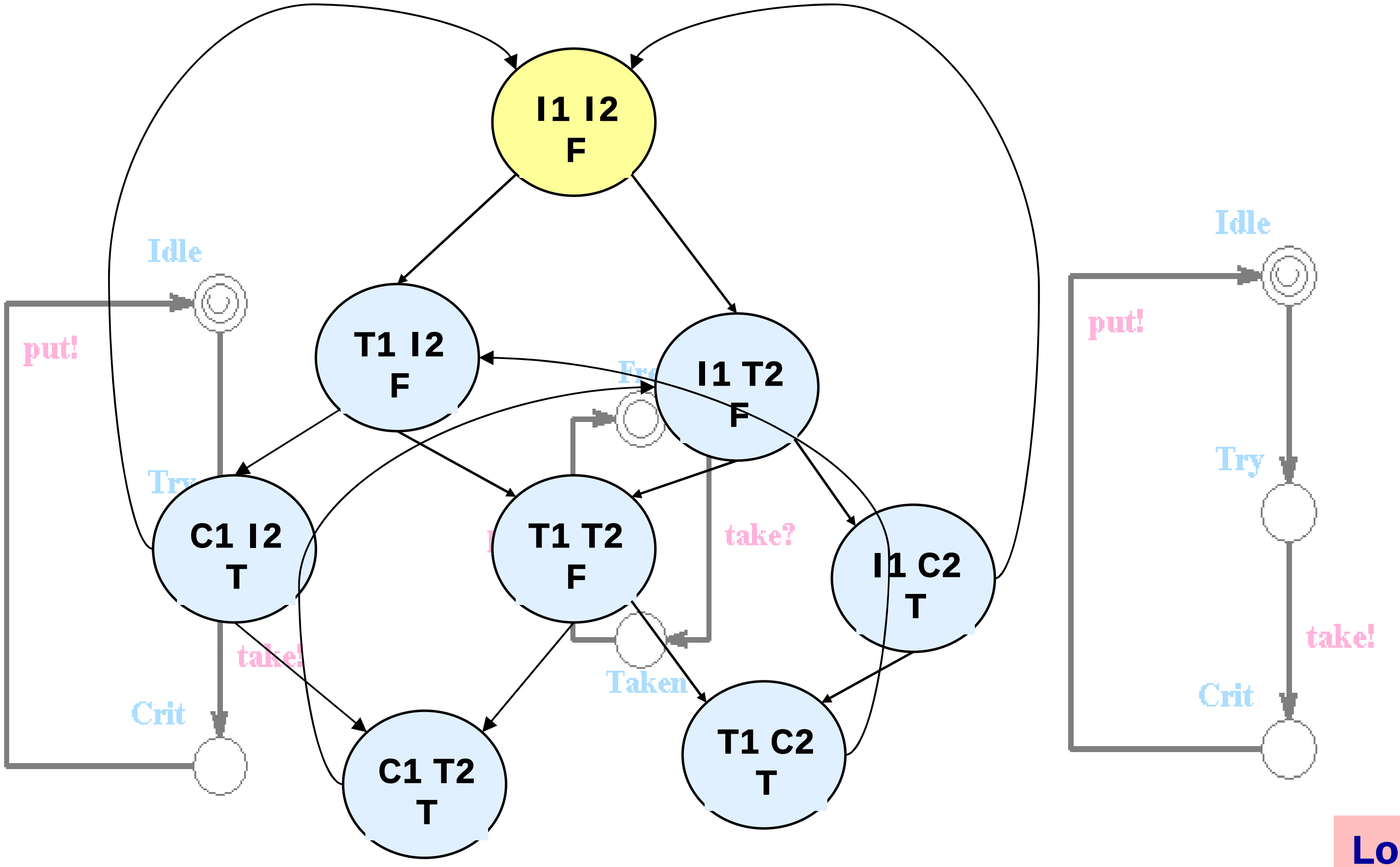


Lock

Generiske egenskaber

- Non-determinisme
- Tilstande der ikke aktiveres
- Transitioner der ikke bruges
- Input der ikke processeres
- Output der ikke genereres
- Lokal deadlock
- System deadlock

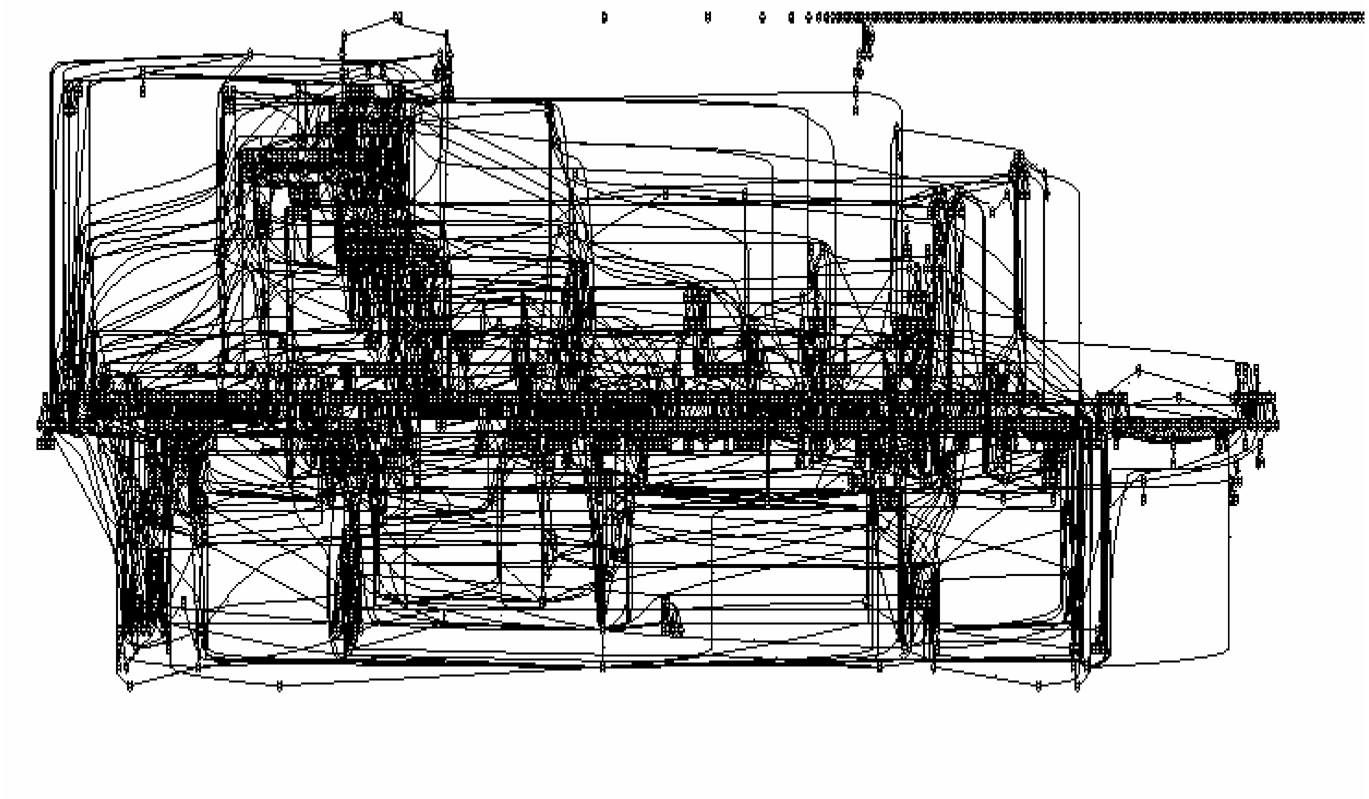
Kan alle reduceres til REACHABILITY

Train Simulator

VVS
visualSTATE

1421 machines
11102 transitions
2981 inputs
2667 outputs
3204 local states
Declare state sp.: 10^476

BUGS ?



CISS

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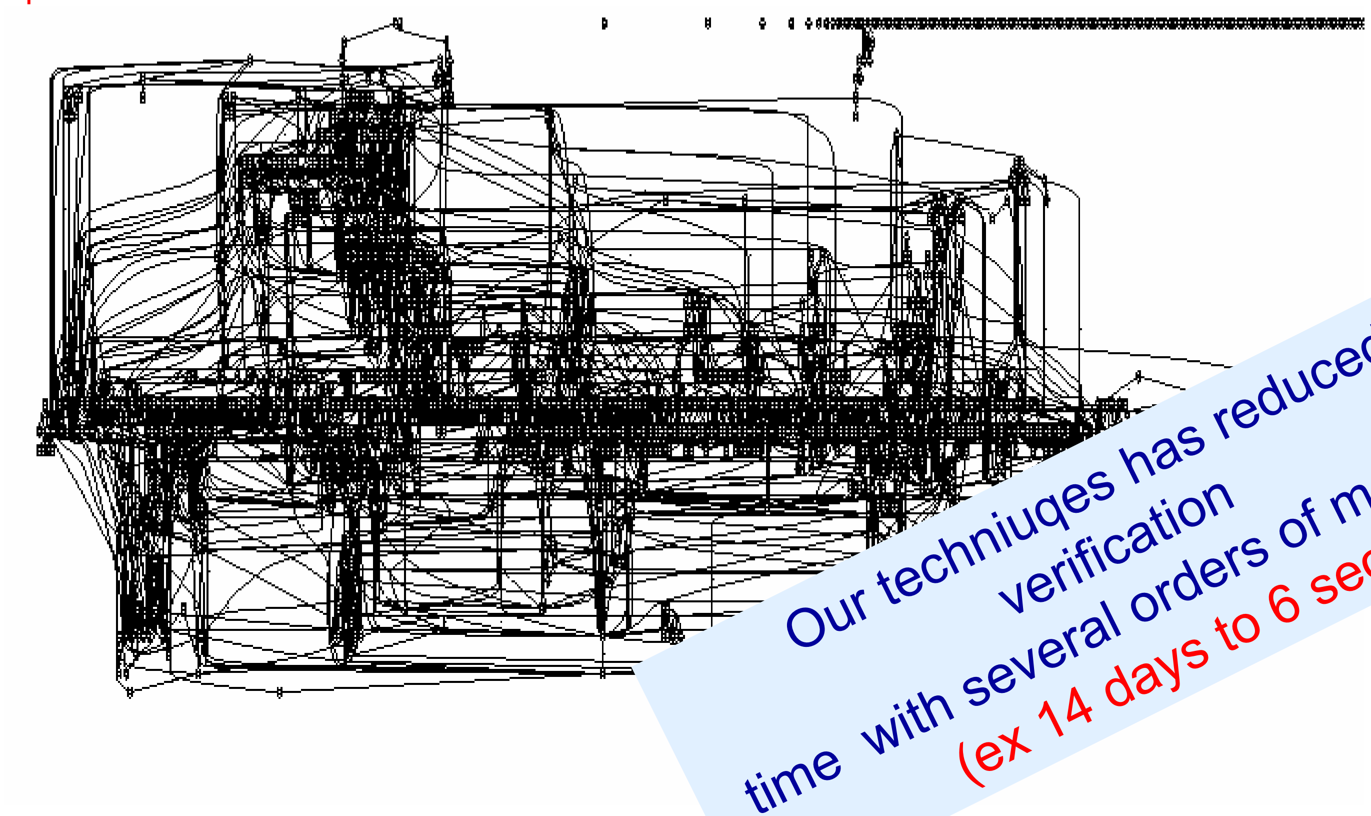
Declare state sp.: 10^476

BUGS ?



Our techniuqes has reduced verification time with several orders of magnitude
(ex 14 days to 6 sec)

Adding Time

FSM

↓

Timed Automata

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More information at http://www.uppaal.com

UPPAAL 4.0.2 (rev. 2491), August 2006.

AALBORG UNIVERSITY DENMARK

BRICS
Basic Research
in Computer Science

CISS
CENTER FOR INDLEJREDE SOFTWARE SYSTEMER

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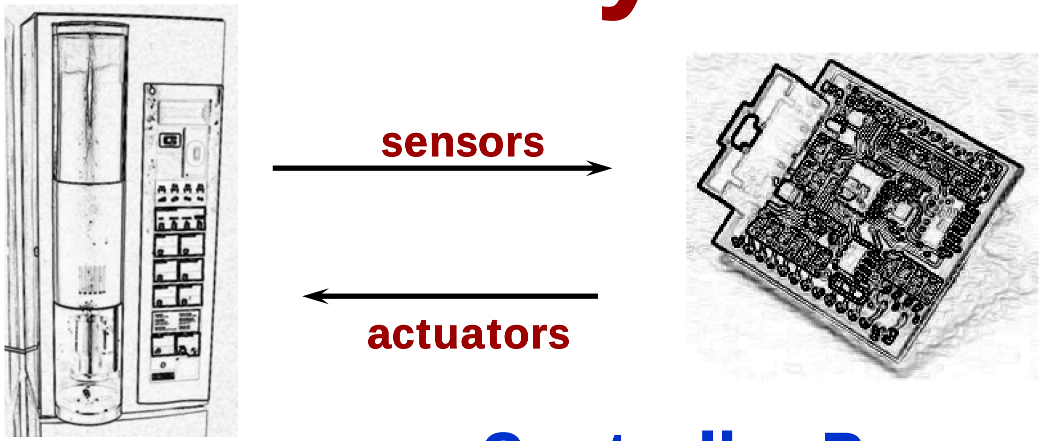
Real Time Systems



sensors

actuators

Plant

Continuous

Controller Program

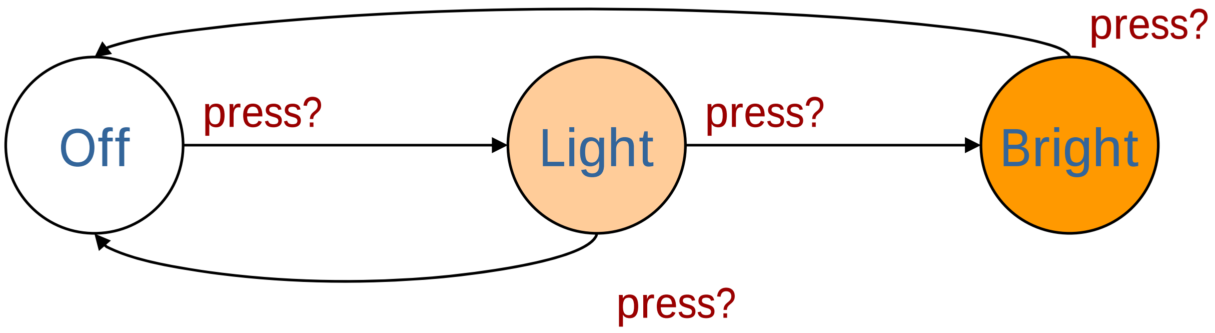
Discrete

Eg.: Realtime Protocols
Pump Control
Air Bags
Robots
Cruise Control
ABS
CD Players
Production Lines

Real Time System

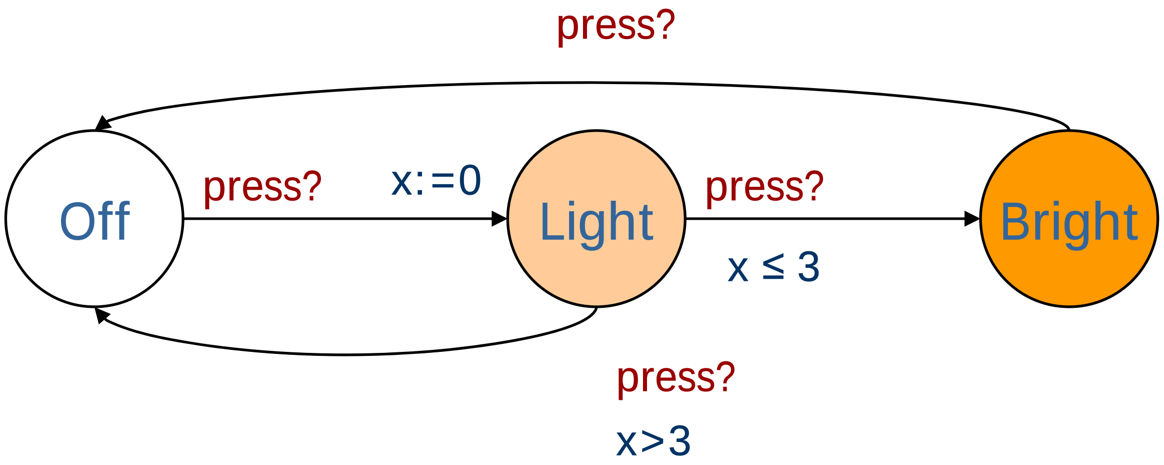
A system where correctness not only depends on the logical order of events but also on their **timing**!!

Dumb Light Control



WANT: if press is issued twice quickly then the light will get brighter; otherwise the light is turned off.

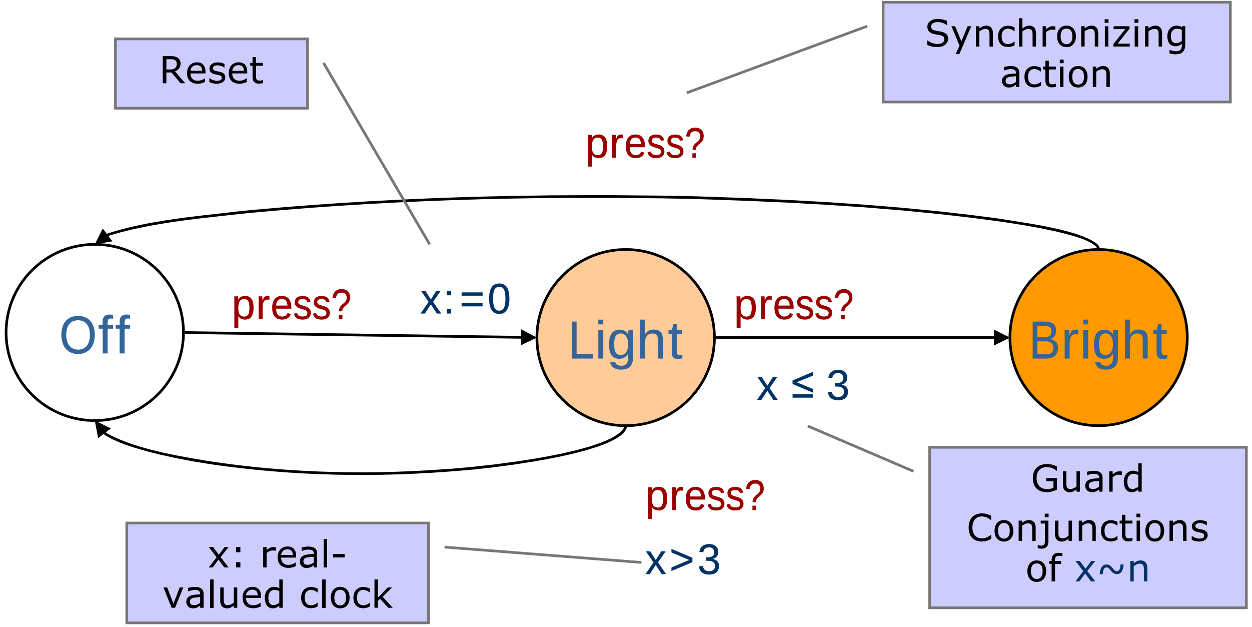
Dumb Light Control *Alur & Dill 1990*



Solution: Add real-valued clock **x**

Timed Automata

Alur & Dill 1990



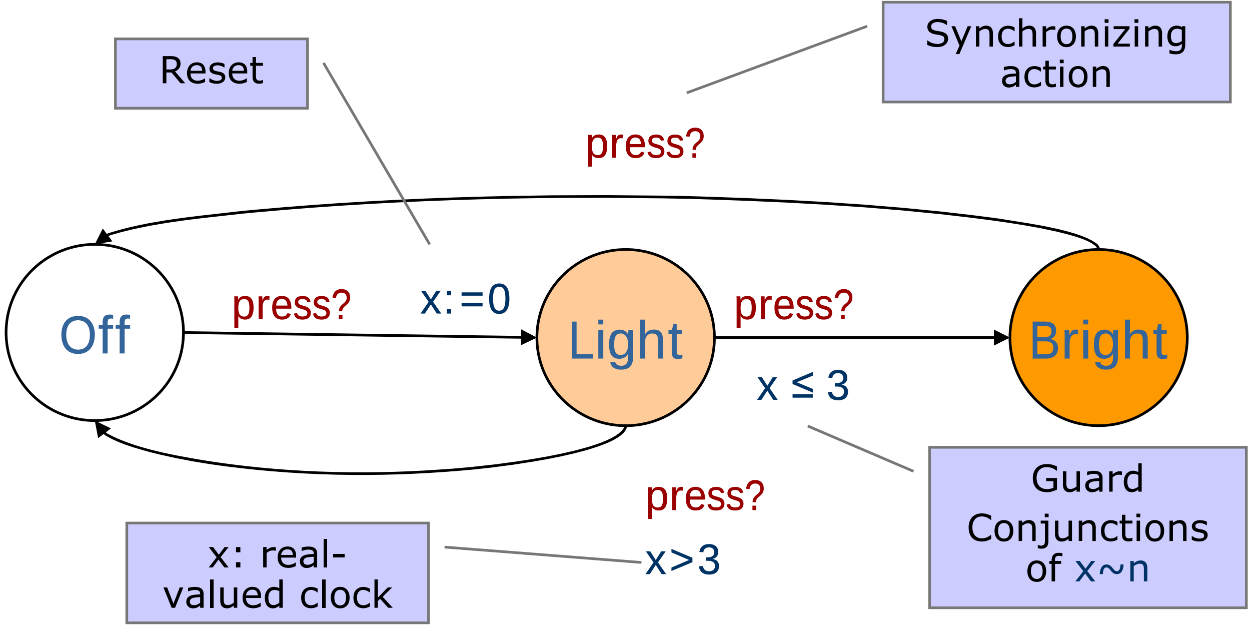
States:

(location , x=v) where v ∈ **R**

Transitions:

(Off , x=0)

Timed Automata *Alur & Dill 1990*



States:

(location , x=v) where v ∈ **R**

Transitions:

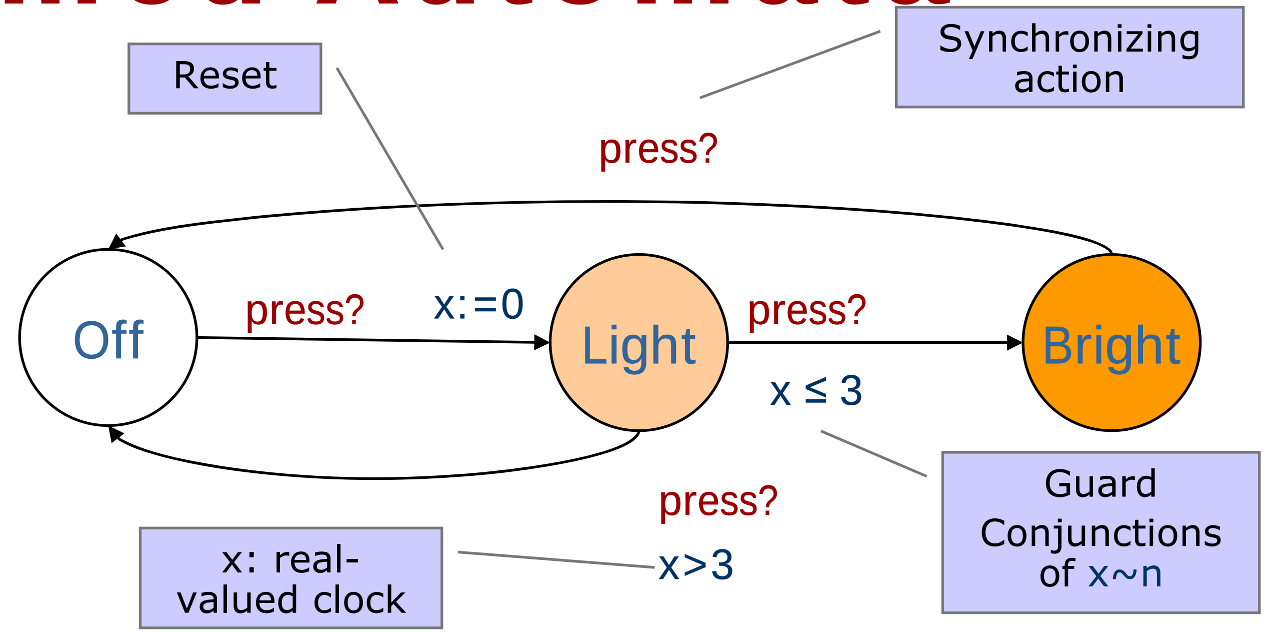
(Off , x=0)

delay 4.32 → (Off , x=4.32)

CISS

Timed Automata

Alur & Dill 1990



States:

(location , x=v) where v ∈ **R**

Transitions:

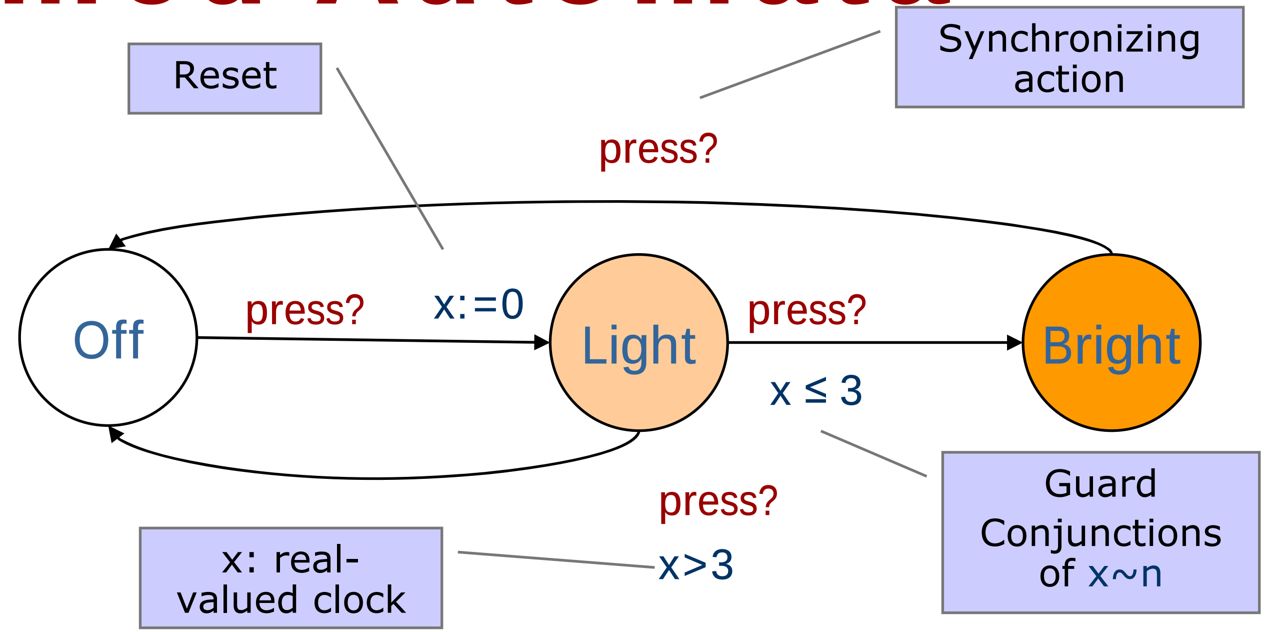
(Off , x=0)

delay 4.32 → (Off , x=4.32)

press? → (Light , x=0)

Timed Automata

Alur & Dill 1990



Reset

Synchronizing action

Guard
Conjunctions of x~n

x: real-valued clock

States:

(location , x=v) where v $\in$ **R**

Transitions:

(Off , x=0)

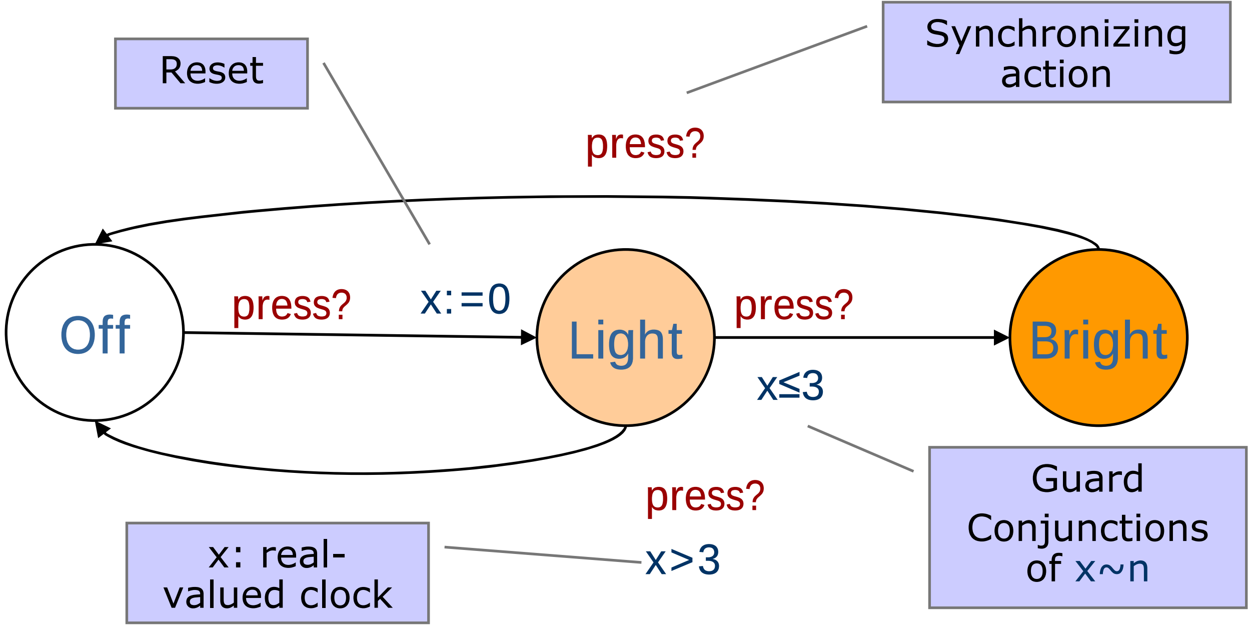
delay 4.32 → (Off , x=4.32)

press? → (Light , x=0)

delay 2.51 → (Light , x=2.51)

Timed Automata

Alur & Dill 1990



Reset

Synchronizing action

Guard Conjunctions of x~n

x: real-valued clock

States:

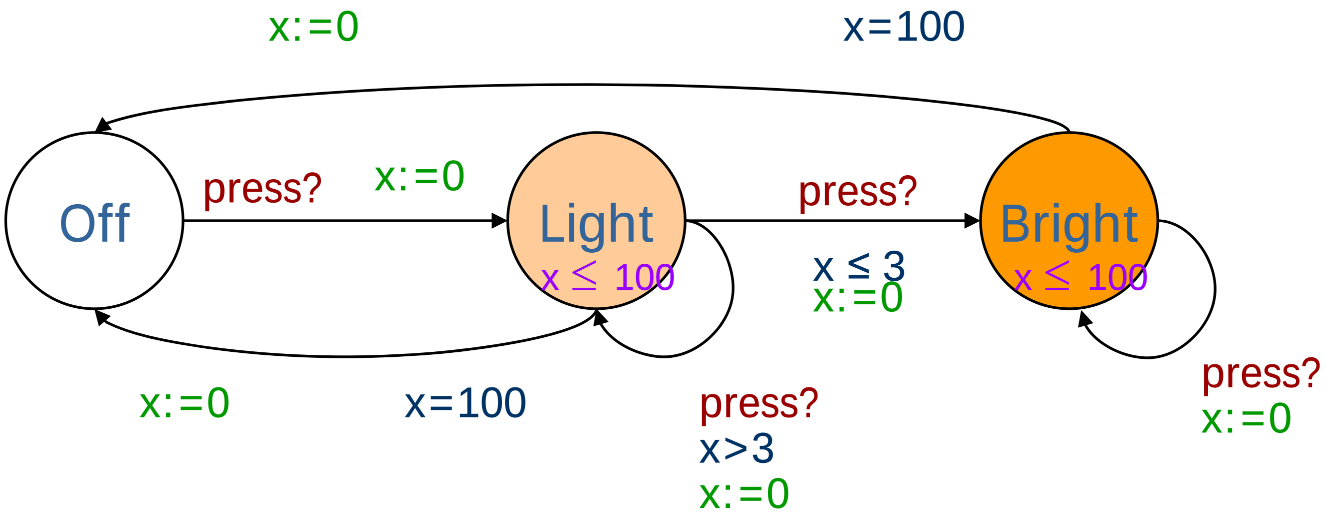
(location , x=v) where v ∈ **R**

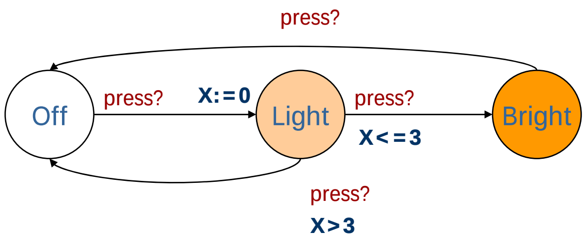
Transitions:

(Off , x=0)
delay 4.32 → (Off , x=4.32)
press? → (Light , x=0)
delay 2.51 → (Light , x=2.51)
press? → (Bright , x=2.51)

Intelligent Light Control

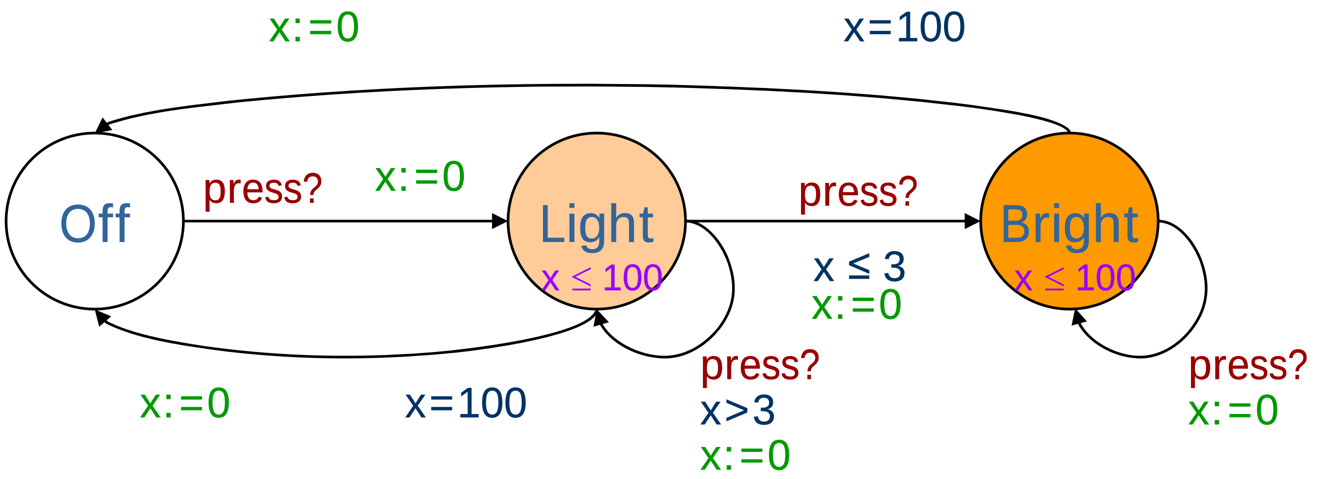
Using Invariants





Intelligent Light Control

Using Invariants



Transitions:

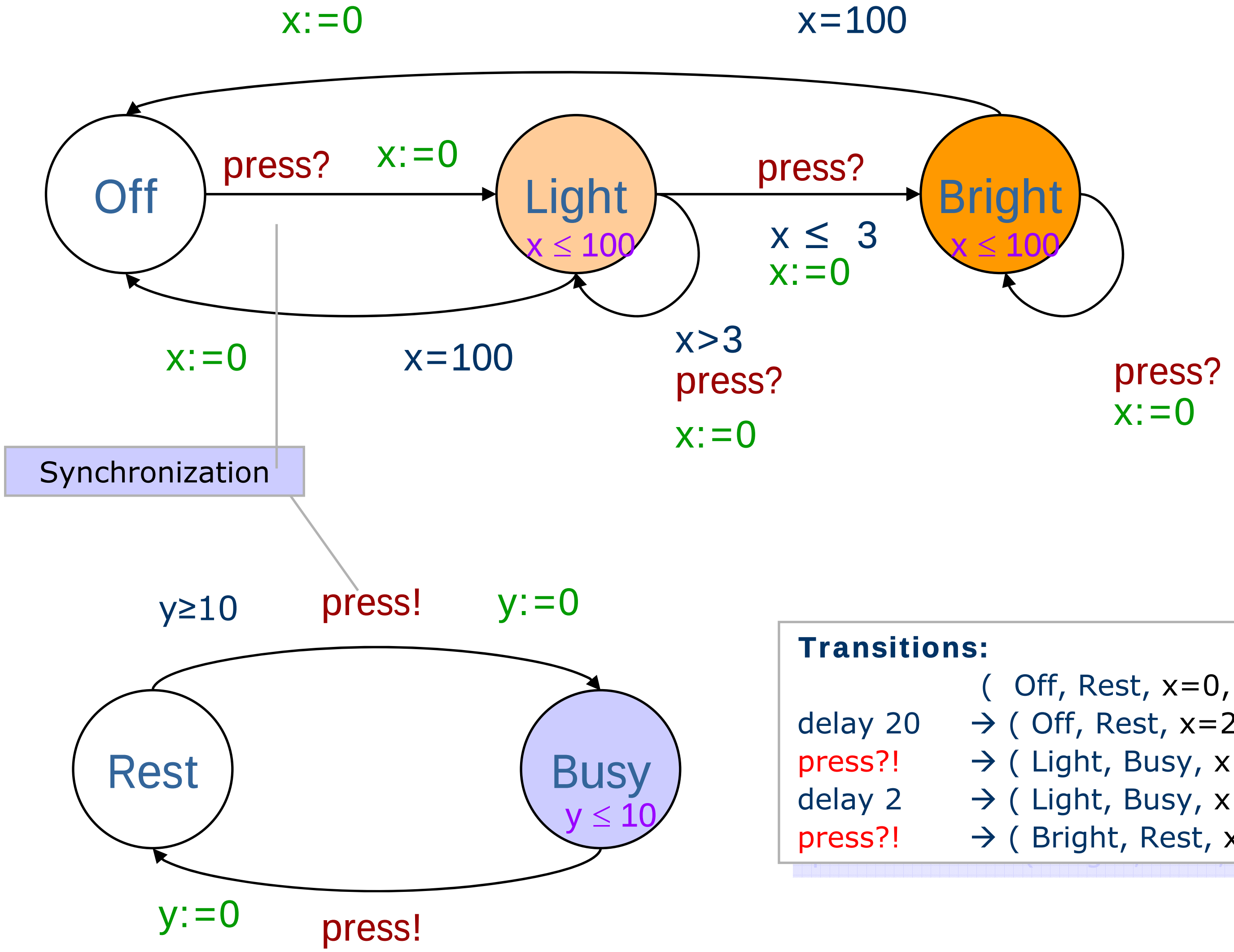
	(Off , x=0)
delay 4.32	→ (Off , x=4.32)
press?	→ (Light , x=0)
delay 4.51	→ (Light , x=4.51)
press?	→ (Light , x=0)
delay 100	→ (Light , x=100)
τ	→ (Off , x=0)

Note:
(Light , x=0) delay 103 → X

Invariants ensures progress

CISS

Light Controller || User



Transitions:

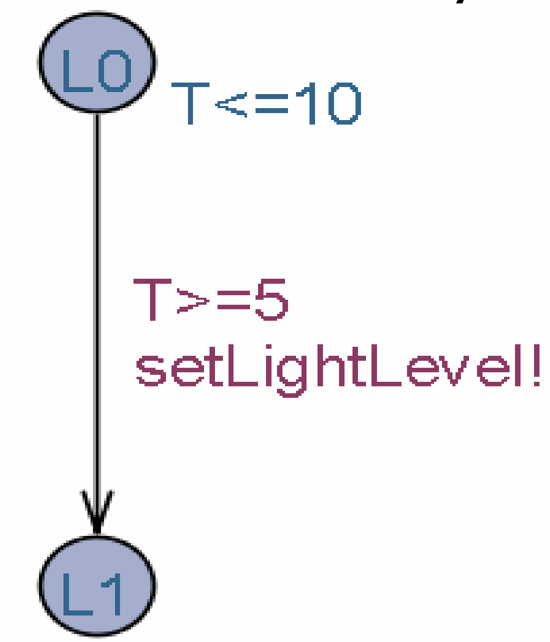
	(Off, Rest, x=0, y=0)
delay 20	→ (Off, Rest, x=20, y=20)
press?!	→ (Light, Busy, x=0, y=0)
delay 2	→ (Light, Busy, x=2, y=2)
press?!	→ (Bright, Rest, x=0, y=0)

CISS

Timing Uncertainty

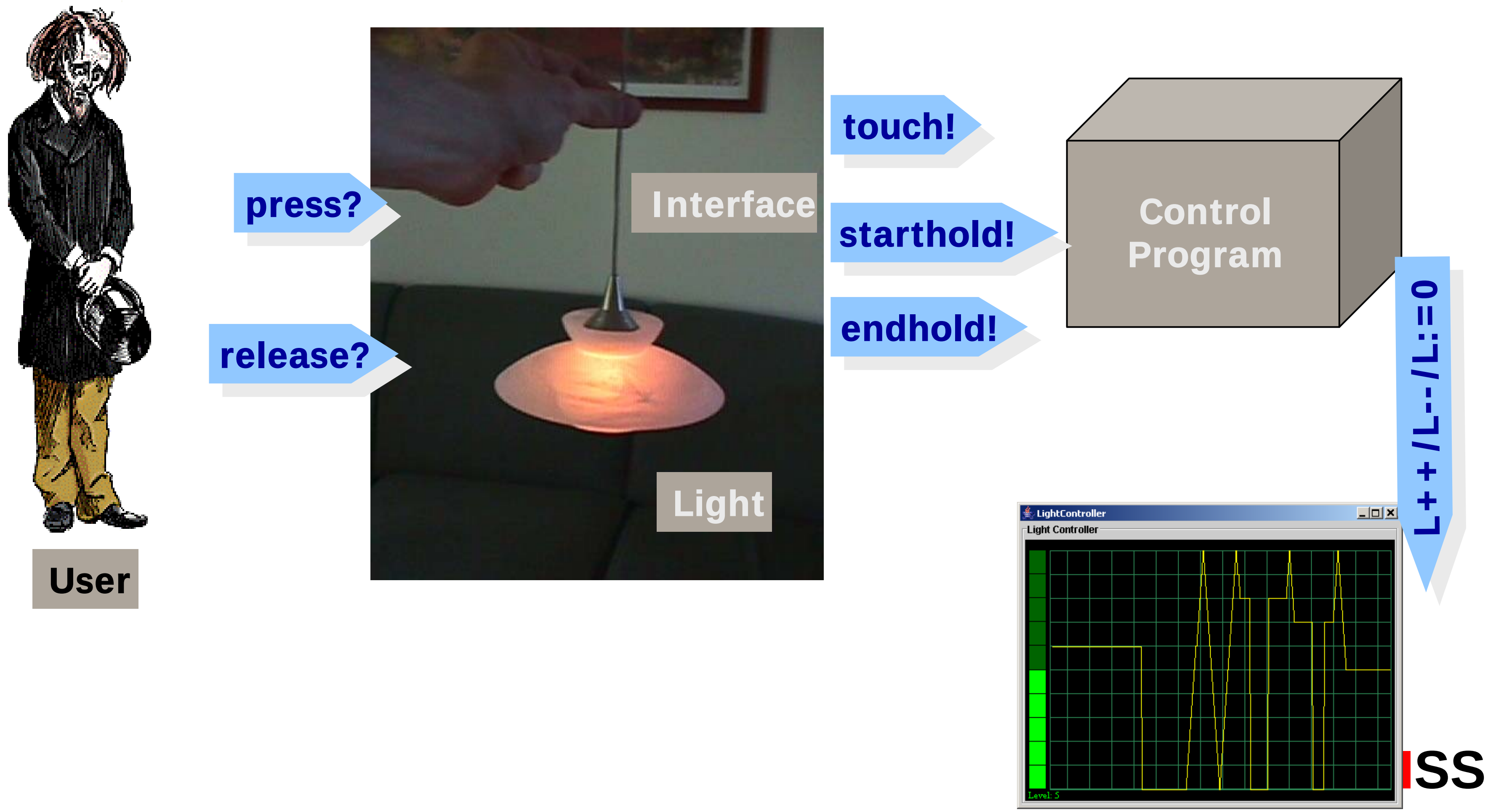
- Unpredictable or variable
  - response time,
  - computation time
  - transmission time etc:

- Initially T=0



LightLevel must be adjusted
between 5 and 10

Light Control Interface



User

press?

release?

Interface

Light

touch!

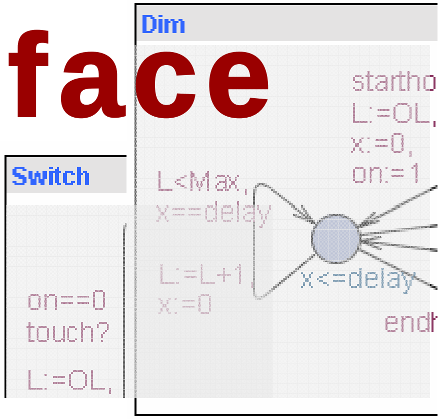
starthold!

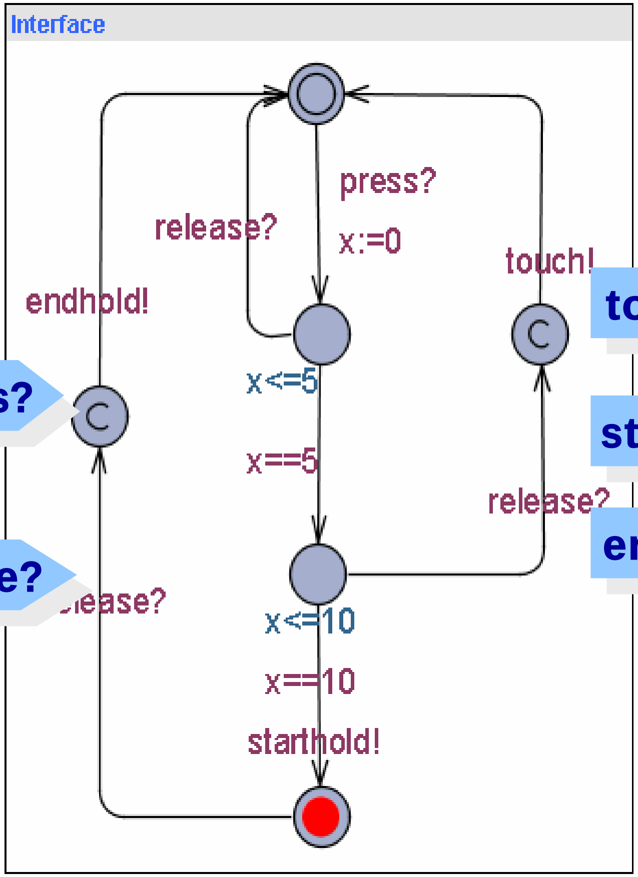
endhold!

Control Program

L++/L--/L:=0

Light Control Interface





User

press?

release?

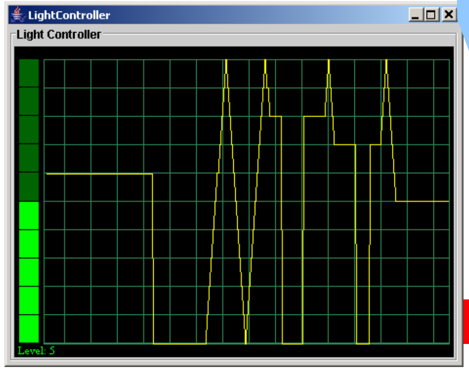
touch!

starthold!

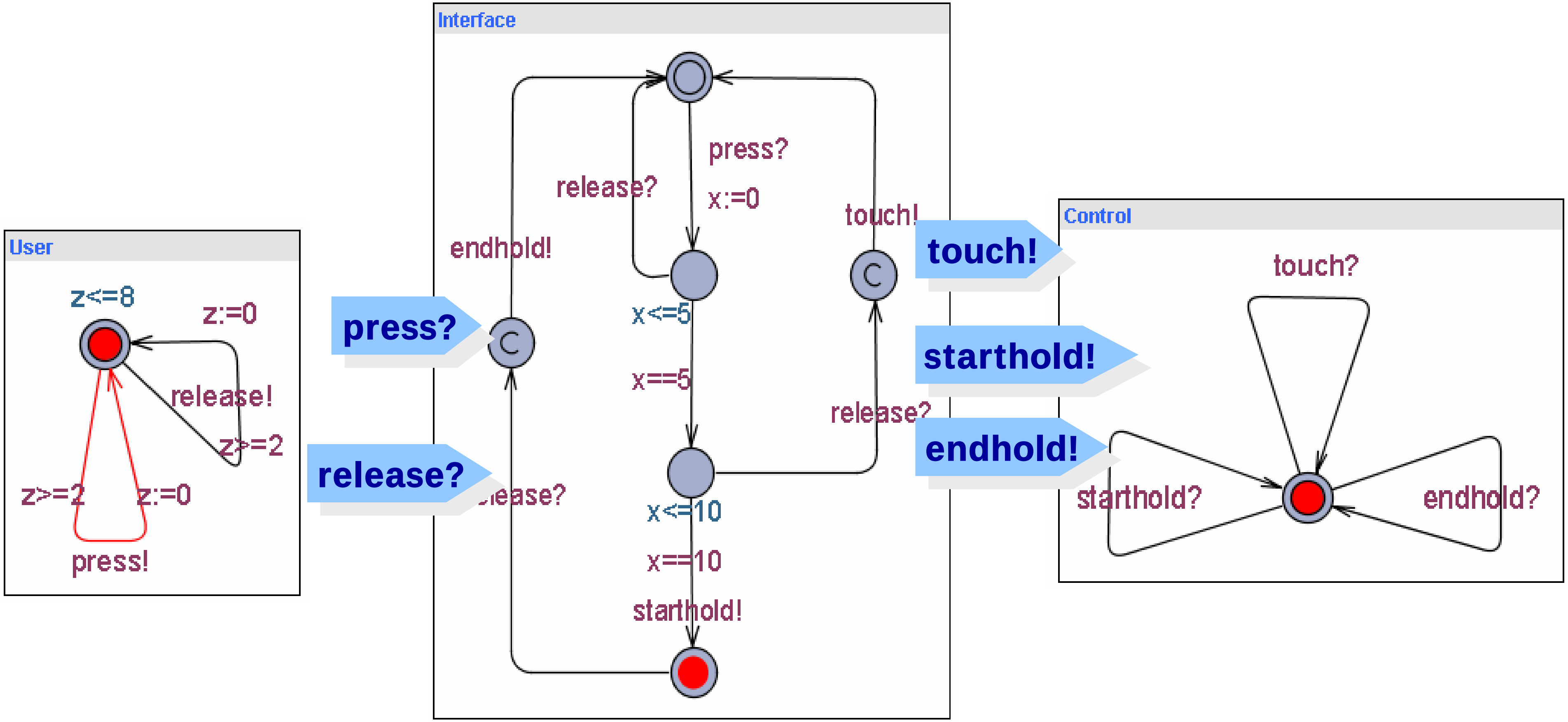
endhold!

Control Program

L++/L--/L:=0



Light Control Network



Broad-casts

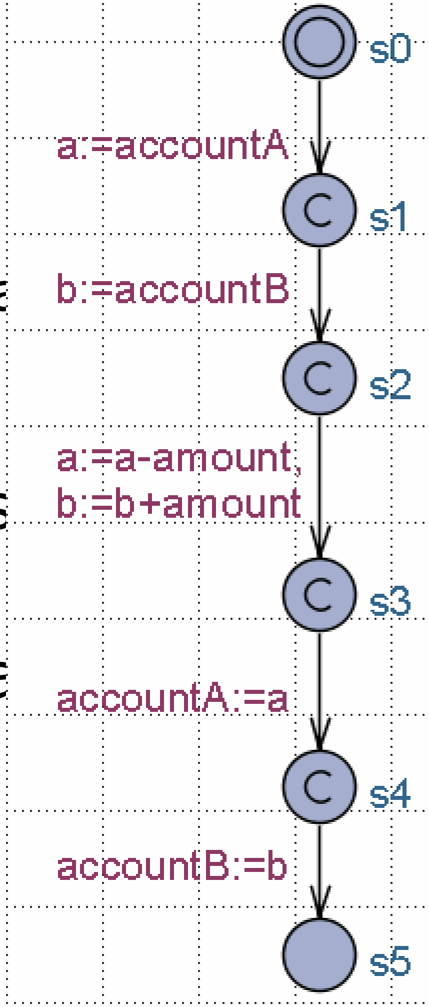
- chan coin, cof, cofBut;
- broadcast chan join;
  - sending: output join!
  - every automaton that listens to join moves
  - ie. every automaton with enabled “join?” transition moves in one step
  - may be zero!

Comitted Locations

- Locations marked **C**
  - ***No delay*** in committed location.
  - Next transition must involve automata in ***committed location.***

- Handy to model atomic sequences
- The use of committed locations <u>reduces</u> the number of states in a model, <u>and</u> allows for more space and time efficient analysis.

- S0 to s5 executed atomically



CISS

Urgent Channels and Locations

- Locations marked **U**
  - ***No delay*** in committed location.
  - Interleaving permitted
- Channels declared "**`urgent chan`**"
  - Time doesn't elapse when a synchronization is possible on a pair of urgent channels
  - Interleaving allowed

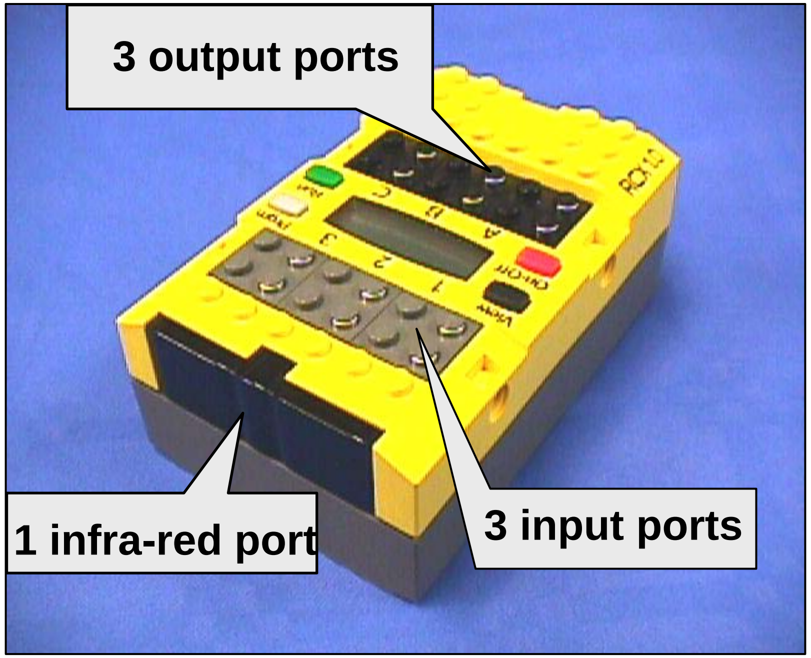
Other Uppaal features

- Bounded domain
  - Int [1..4] a;
- C-like data-structures and user defined functions in declaration section
  - structs, arrays, and typedef
- **`select a:T`** construct
- `Forall`, `exists` in expr
- Scalar sets (for giving unique ID’s)
- Process and channel **priorities**
- Value passing (emulation)

BRICK SORTING

LEGO Mindstorms/RCX

- Sensors: temperature, light, rotation, pressure.
- Actuators: motors, lamps,
- Virtual machine:
  - 10 tasks, 4 timers, 16 integers.



- Several Programming Languages:
  - NotQuiteC, Mindstorm, Robotics, legOS, etc.

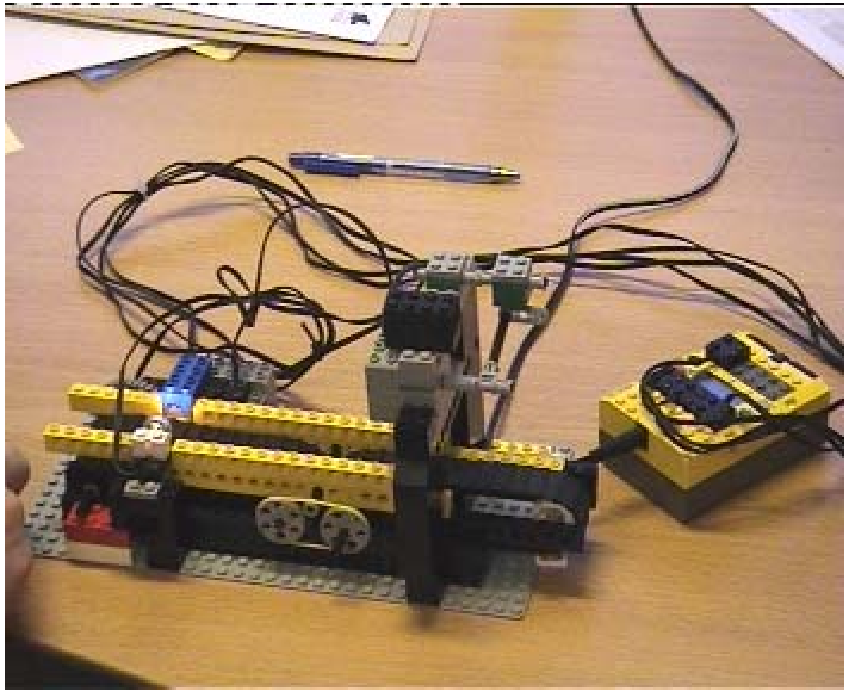
A Real Timed System

The Plant

Conveyor Belt

&

Bricks



Controller Program

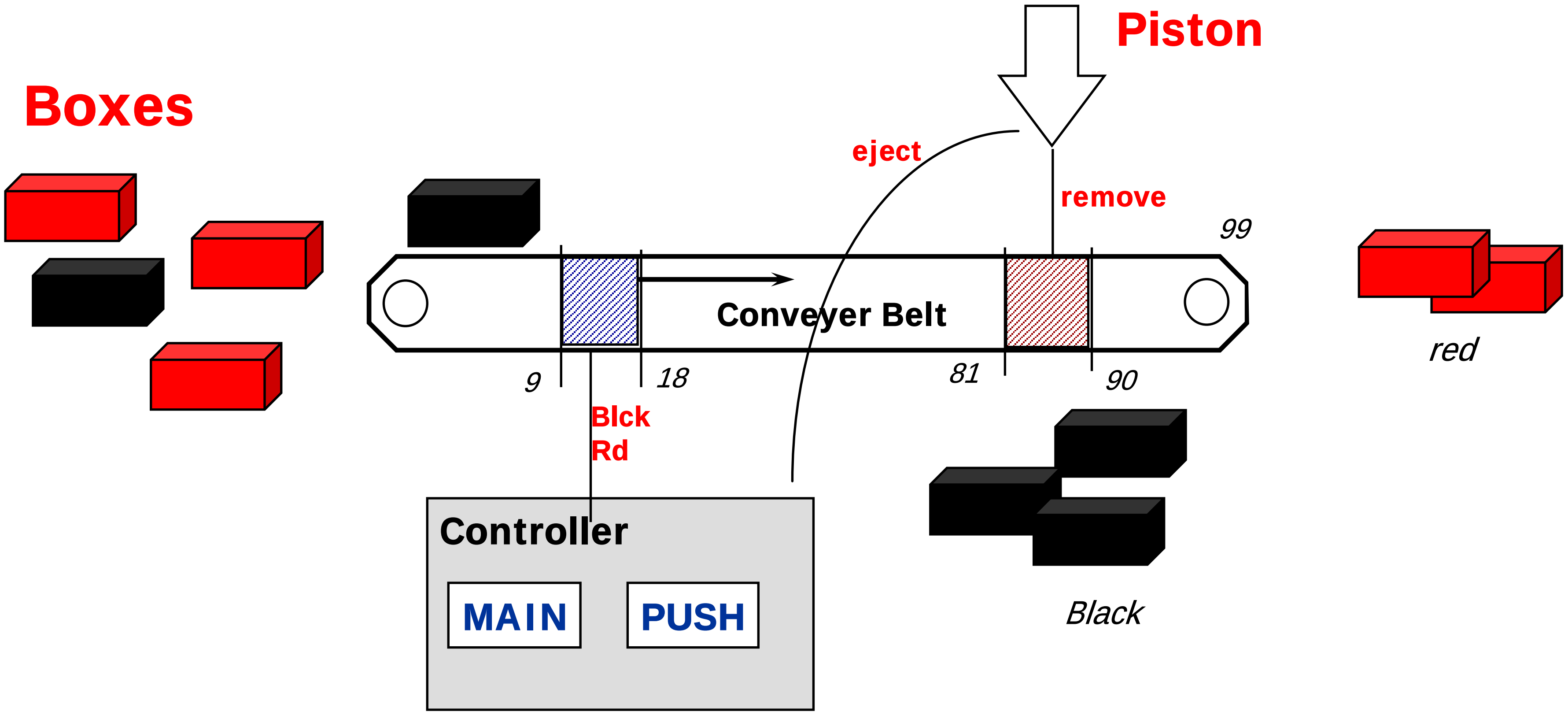
LEGO MINDSTORM

What is suppose to happen?

First UPPAAL model

Sorting of Lego Boxes

Ken Tindell



Exercise: Design **Controller** so that only black boxes are being pushed out

NQC programs

```
int active;
int DELAY;
int LIGHT_LEVEL;
```

```
task MAIN{
 DELAY=75;
 LIGHT_LEVEL=35;
 active=0;
 Sensor(IN_1, IN_LIGHT);
 Fwd(OUT_A,1);
 Display(1);

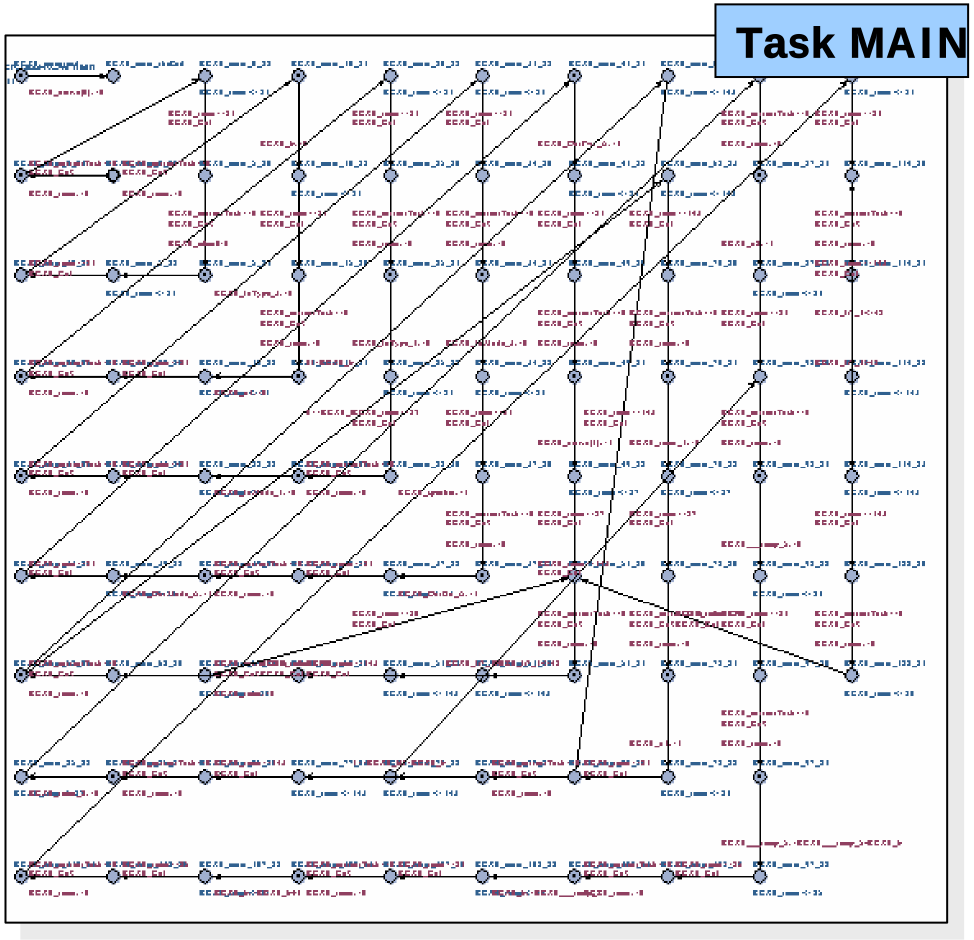
 start PUSH;

 while(true){
   wait(IN_1<=LIGHT_LEVEL);
   ClearTimer(1);
   active=1;
   PlaySound(1);
   wait(IN_1>LIGHT_LEVEL);
  }
}
```

```
task PUSH{
  while(true){
    wait(Timer(1)>DELAY && active==1);
    active=0;
    Rev(OUT_C,1);
    Sleep(8);
    Fwd(OUT_C,1);
    Sleep(12);
    Off(OUT_C);
  }
}
```

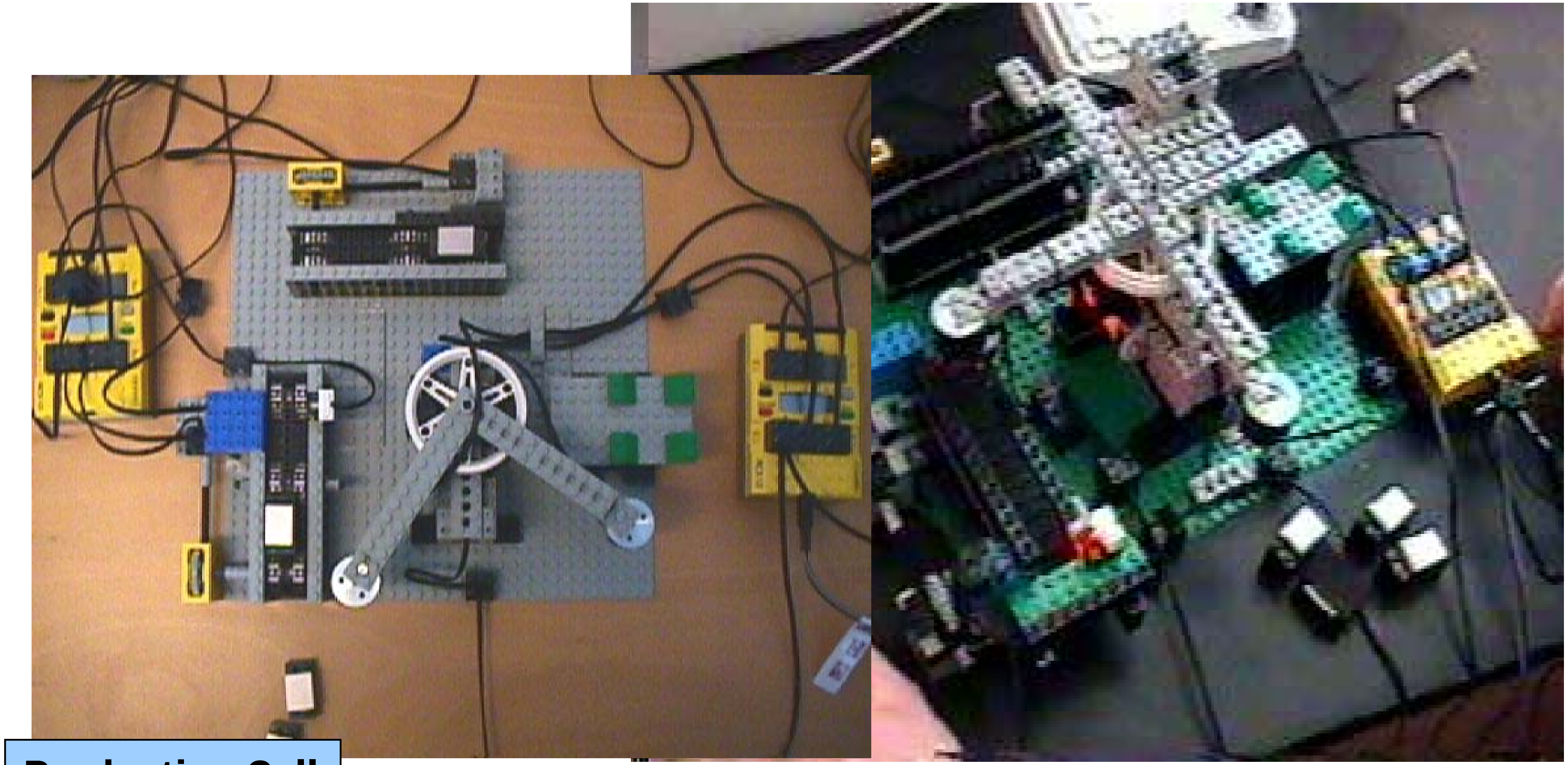
From RCX to UPPAAL

- Model includes Round-Robin Scheduler.
- Compilation of RCX tasks into TA models.
- Presented at ECRTS 2000



The Production Cell

Course at DTU, Copenhagen



Production Cell