An Introduction to Reactive and Real-time System Modelling

(slides by Brian Nielsen)

Agenda

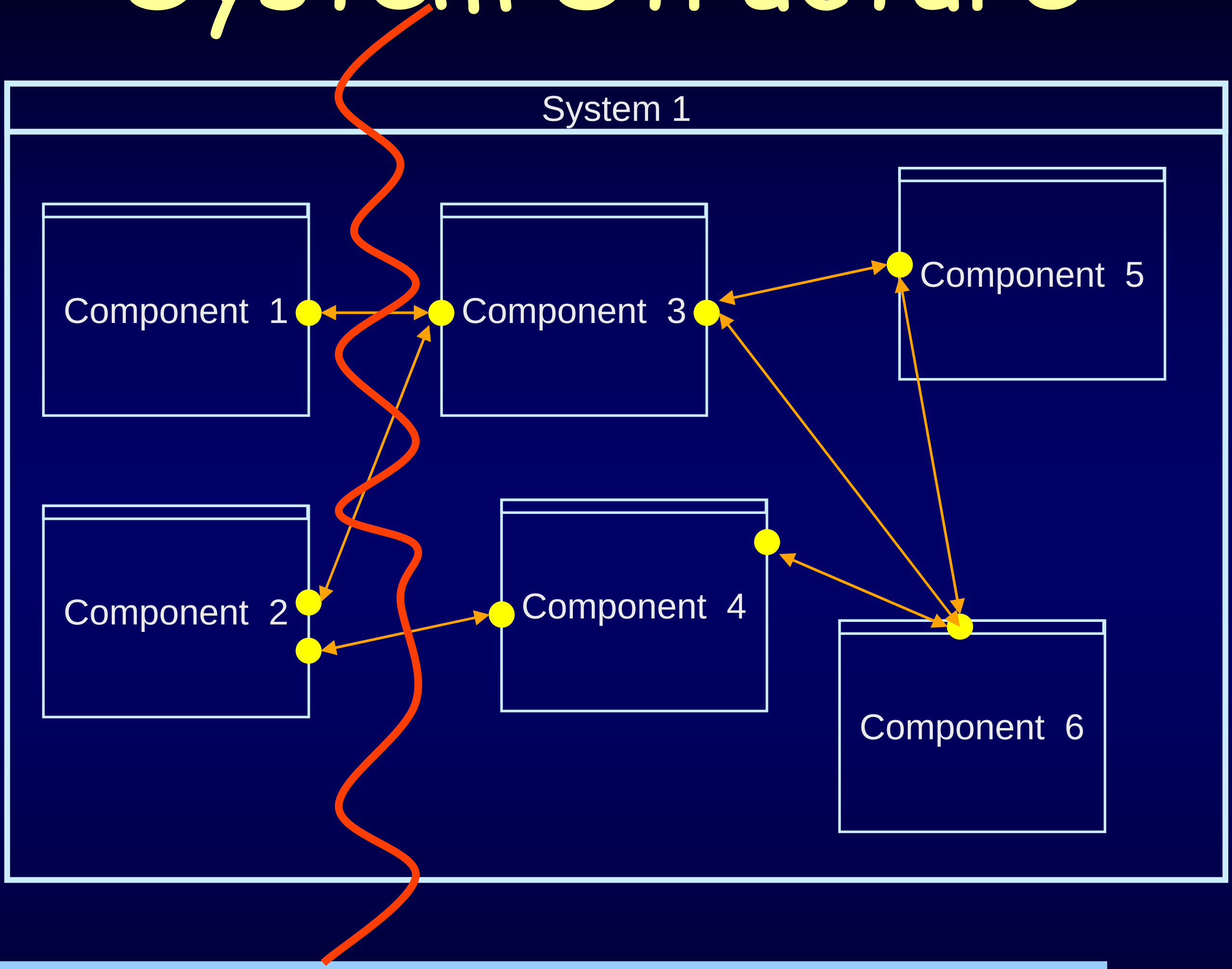
- Finite state machine (FSM)
- High-level FSM languages
- Modelling untimed systems using Uppaal

- Timed automaton (TA)
- Modelling timed systems using Uppaal

- Verification using Uppaal

Finite State Machine (FSM)

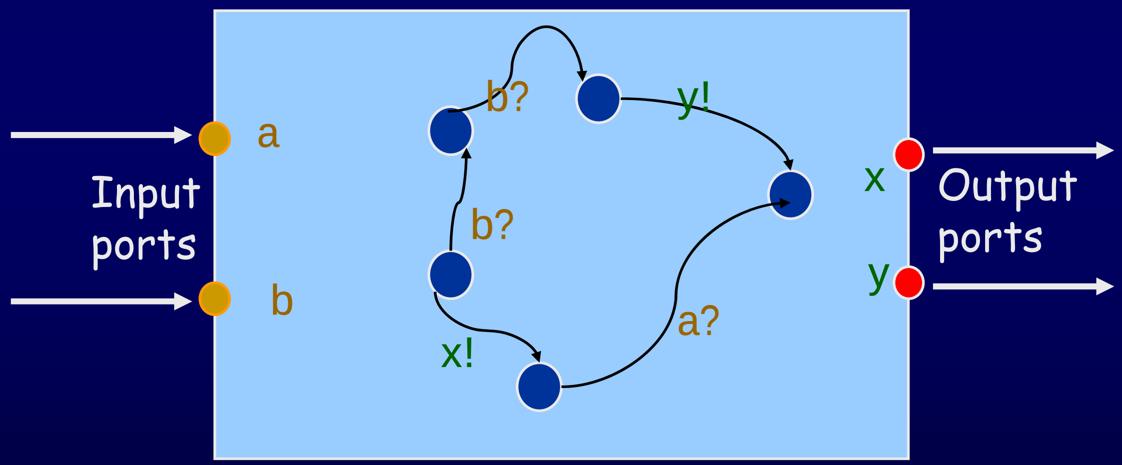
System Structure



- How do we model components?
- How do components interact?
- How do we specify environment assumptions?
- How do we ensure correct behaviour?

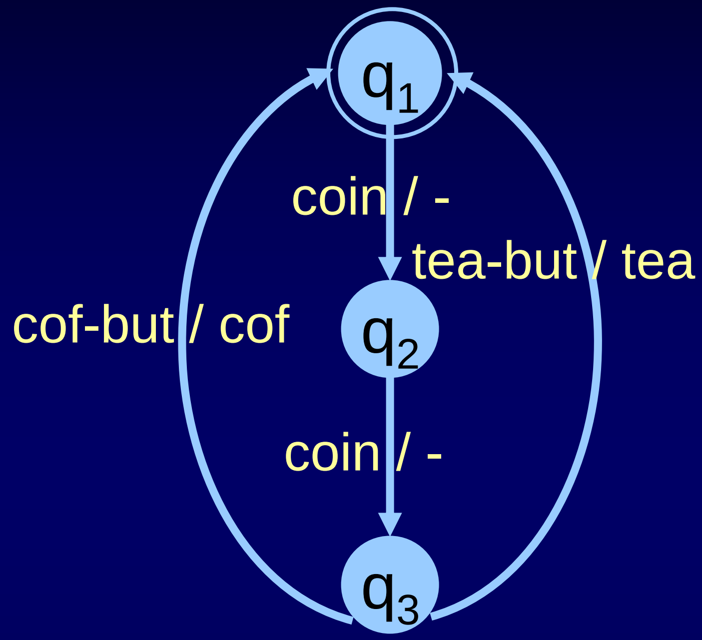
Component Behavior

Unified Model: State Machine



Control states

Finite State Machine (Mealy machine)



condition		effect	
current state	input	output	next state
q_1	coin	-	q_2
q_2	coin	-	q_3
q_3	cof-but	cof	q_1
q_3	tea-but	tea	q_1

Inputs = {cof-but, tea-but, coin}
Outputs = {cof,tea}
States: $\{q_1,q_2,q_3\}$
Initial state = q_1
Transitions= {
$(q_1$, coin, -, $q_2)$,
$(q_2$, coin, -, $q_3)$,
$(q_3$, cof-but, cof, $q_1)$,
$(q_3$, tea-but, tea, $q_1)$
}

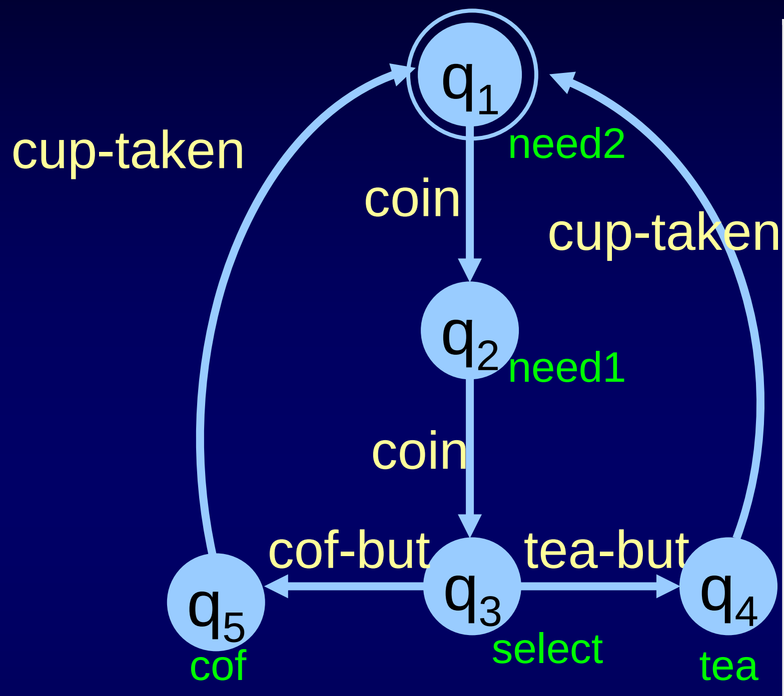
In Mealy machine the **output** depends on the **current state** as well as the **input**

Sample run:

$$q_1 \xrightarrow{\text{coin/ -}} q_2 \xrightarrow{\text{coin/-}} q_3 \xrightarrow{\text{cof-but / cof}} q_1 \xrightarrow{\text{coin/ -}}$$

$$q_2 \xrightarrow{\text{coin/ -}} q_3 \xrightarrow{\text{cof-but / cof}} q_1$$

Finite State Machine (Moore machine)



condition		effect
current state	input	next state
q_1	coin	q_2
q_2	coin	q_3
q_3	cof-but	q_5
q_3	tea-but	q_4
q_5	cup-taken	q_1
q_4	cup-taken	q_1

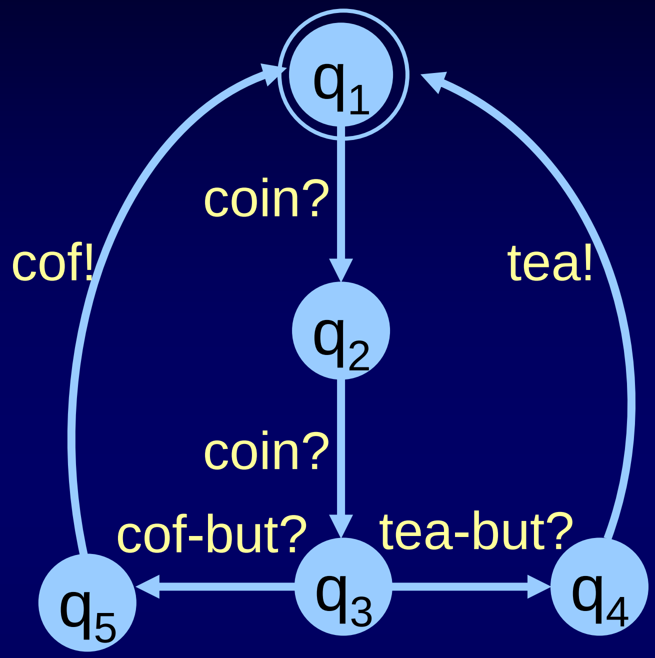
condition	effect
current state	activity
q_1	need2
q_2	need1
q_3	select
q_5	cof
q_4	tea

In Moore machine the **output** (**or "activity"**) depends on the **current state** only

Input sequence: coin.coin.cof-but.cup-taken.coin.cof-but
Output sequence: need2.need1.select.cof. need2.need1.select.cof

need2=display shows "insert two coins"

Input-Output FSM (IO-FSM)



condition		effect
current state	action	next state
q_1	coin?	q_2
q_2	coin?	q_3
q_3	cof-but?	q_5
q_3	tea-but?	q_4
q_4	tea!	q_1
q_5	cof!	q_1

Inputs = {cof-but, tea-but, coin}
Outputs = {cof,tea}
States: $\{q_1,q_2,q_3\}$
Initial state = q_1
Transitions= {
(q_1, coin, q_2),
(q_2, coin, q_3),
(q_3, cof-but, q_5),
(q_3, tea-but, q_4),
(q_4, tea, q_1),
(q_5, cof, q_1)
}

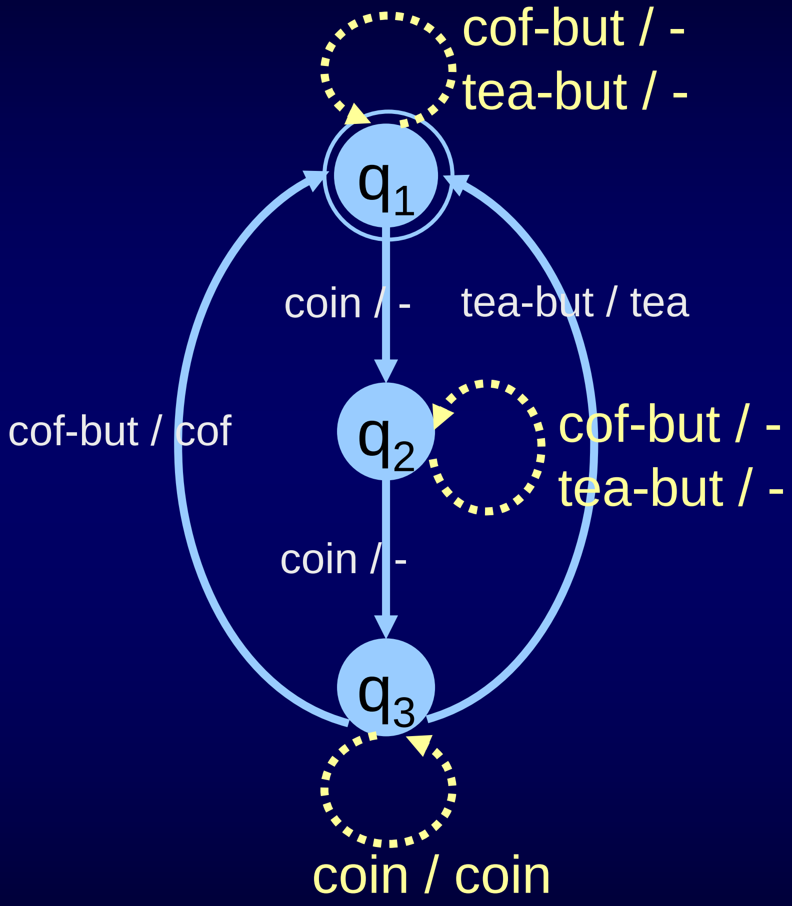
Sample run:

$q_1 \xrightarrow{\text{coin?}} q_2 \xrightarrow{\text{coin?}} q_3 \xrightarrow{\text{cof-but?}} q_5 \xrightarrow{\text{cof!}}$

$q_1 \xrightarrow{\text{coin?}} q_2 \xrightarrow{\text{coin?}} q_3 \xrightarrow{\text{cof-but?}} q_5 \xrightarrow{\text{cof!}} q_1$

action trace: coin?.coin?.cof-but?.cof!.coin?.coin?.cof-but?.cof!
input sequence: coin.coin.cof-but.coin.coin.cof-but
Output sequence: cof.cof

Fully Specified FSM (Mealy)

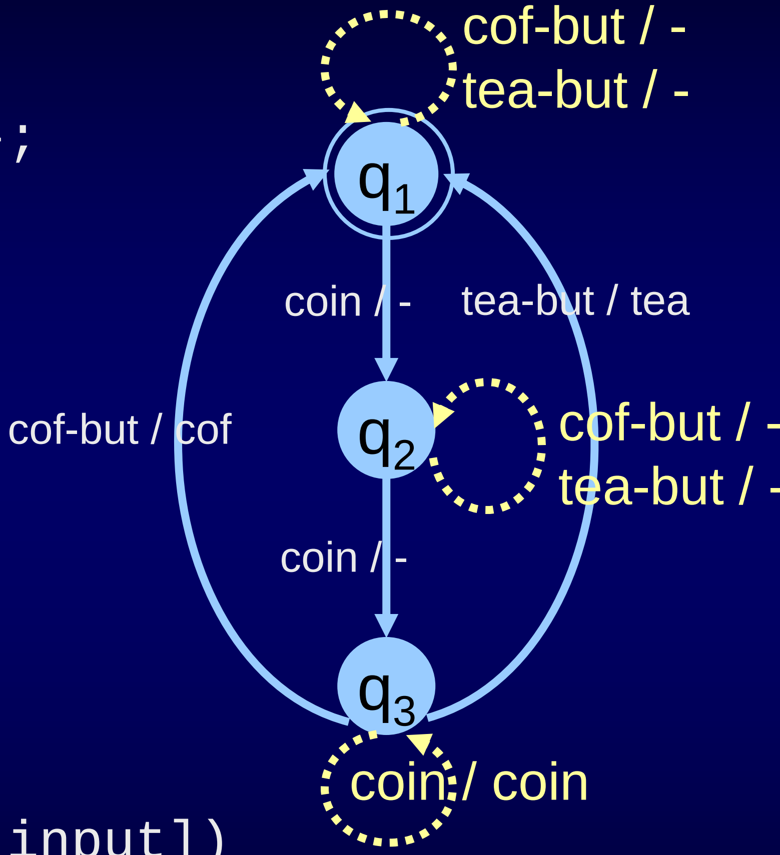


condition		effect	
current state	input	output	next state
q_1	coin	-	q_2
q_2	coin	-	q_3
q_3	cof-but	cof	q_1
q_3	tea-but	tea	q_1
q_1	cof-but	-	q_1
q_1	tea-but	-	q_1
q_2	cof-but	-	q_2
q_2	tea-but	-	q_2
q_3	coin	coin	q_3

```
for each state
   for each input
      ...
```

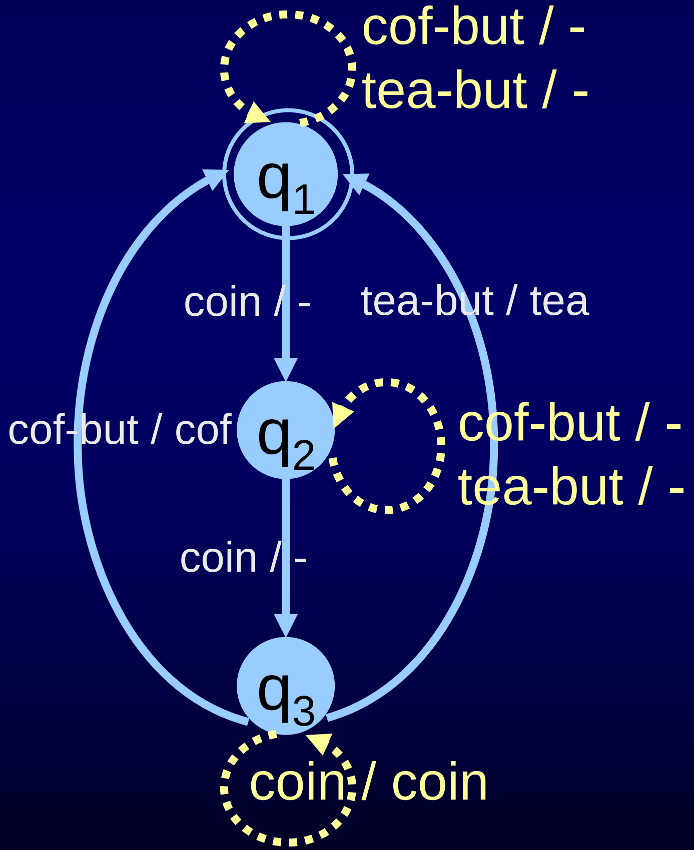
Mealy FSM as program (1)

```
enum currentState {q1,q2,q3};
enum input {coin, cof_but,tea_but};
int nextStateTable[3][3] = {
      q2,q1,q1,
      q3,q2,q2,
      q3,q1,q1 };

int outputTable[3][3] = {
      0,0,0,
      0,0,0,
      coin,cof,tea};

While(input=waitForInput()) {
  OUTPUT(outputTable[currentState,input])
  currentState:=nextStateTable[currentState,input];

}
```

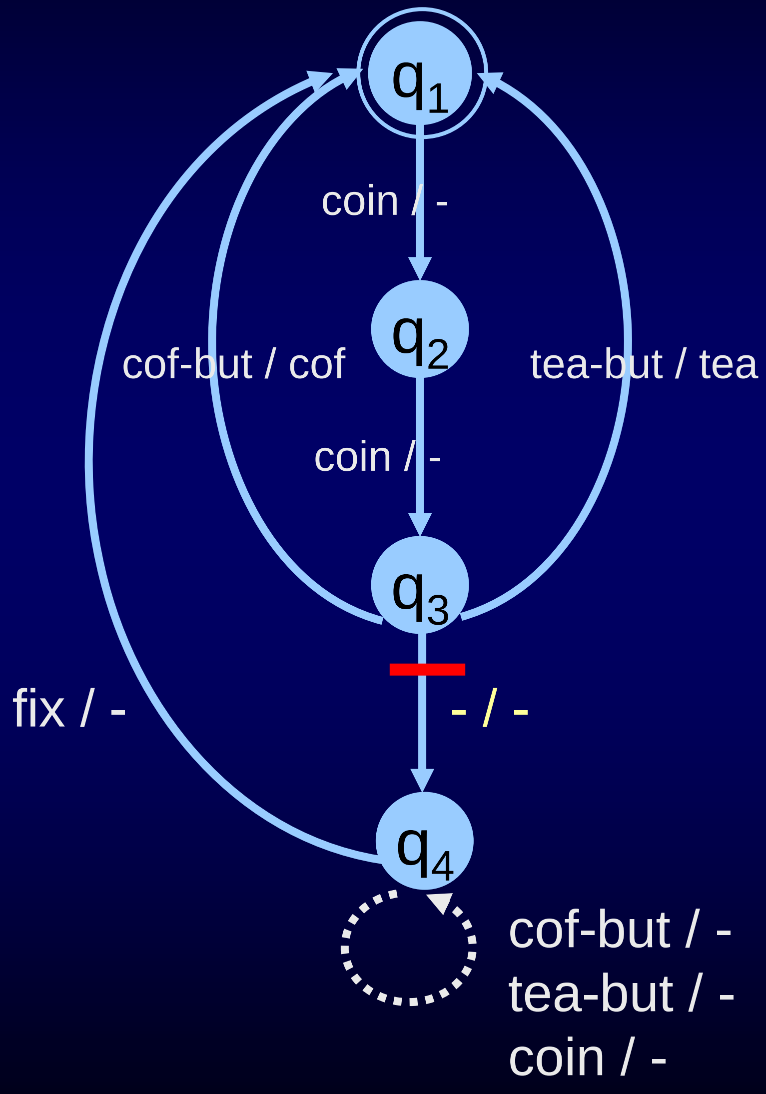


Mealy FSM as program (2)

```
enum currentState {q1,q2,q3};
enum input {coin,cof,tea_but,cof_but};

While(input=waitForInput){
  Switch(currentState){
  case q1: {
      switch (input) {
        case coin: currentState:=q2; break;
        case cuf_but:
         case tea_but: break;
        default: ERROR(”Unexpected Input”);
          }
       break;
  case q3: {
      switch(input) {
          case cof_buf: {currentState:=q3;
                         OUTPUT(cof);
                         break;}
  …
  default: ERROR(”unknown currentState”);

  } // end of switch

}
```



Spontaneous Transitions



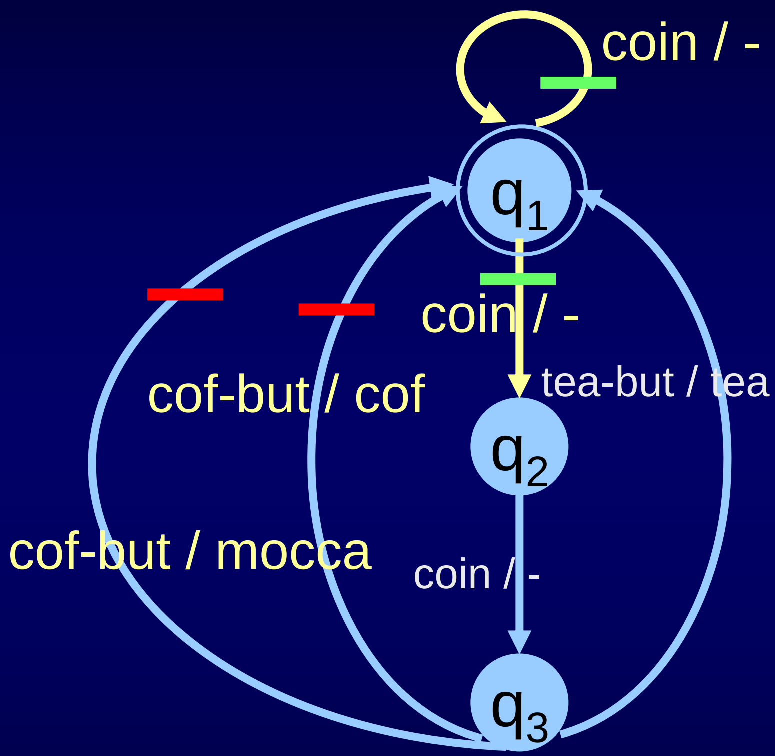
condition		effect	
current state	input	output	next state
q_1	coin	-	q_2
q_2	coin	-	q_3
q_3	cof-but	cof	q_1
q_3	tea-but	tea	q_1
q_3	-	-	q_4
q_4	fix	-	q_1

A **spontaneous** transition is a transition in response to **no** input at all.

alias: internal transition

alias: unobservable transition

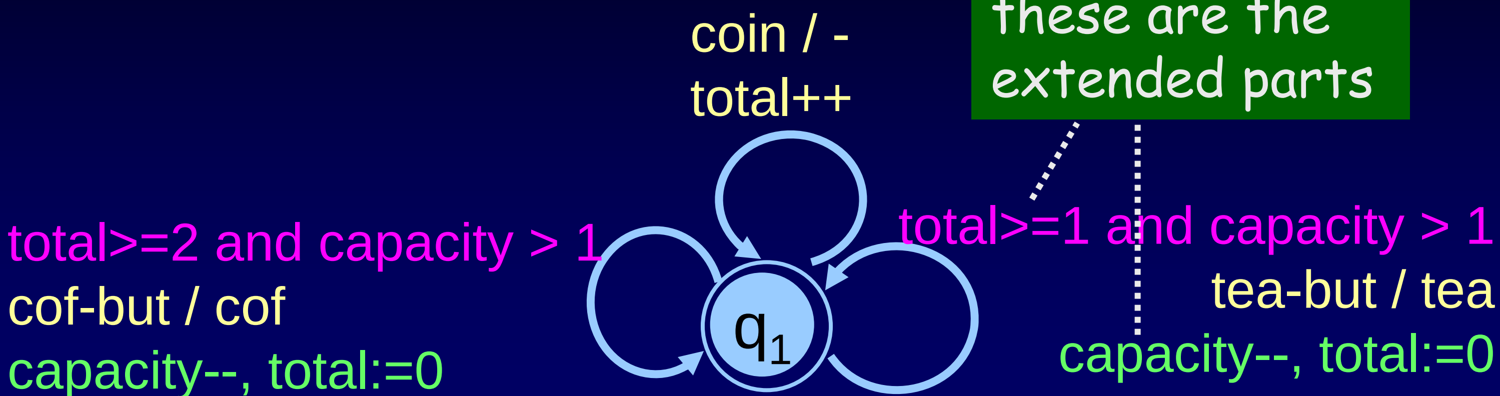
Non-deterministic FSM



condition		effect	
current state	input	output	next state
q_1	coin	-	q_2
q_1	coin	-	q_1
q_2	coin	-	q_3
q_3	tea-but	tea	q_1
q_3	cof-but	cof	q_1
q_3	cof-but	mocca	q_1

Extended FSM (EFSM)

these are the extended parts



or "guard"

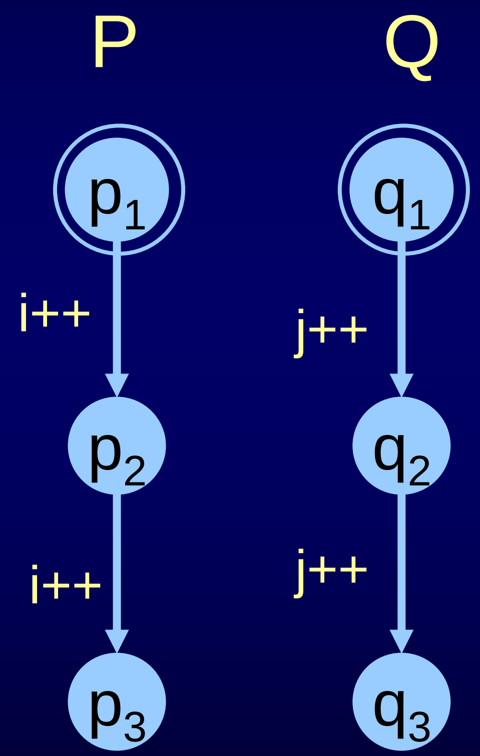
called “flattening"

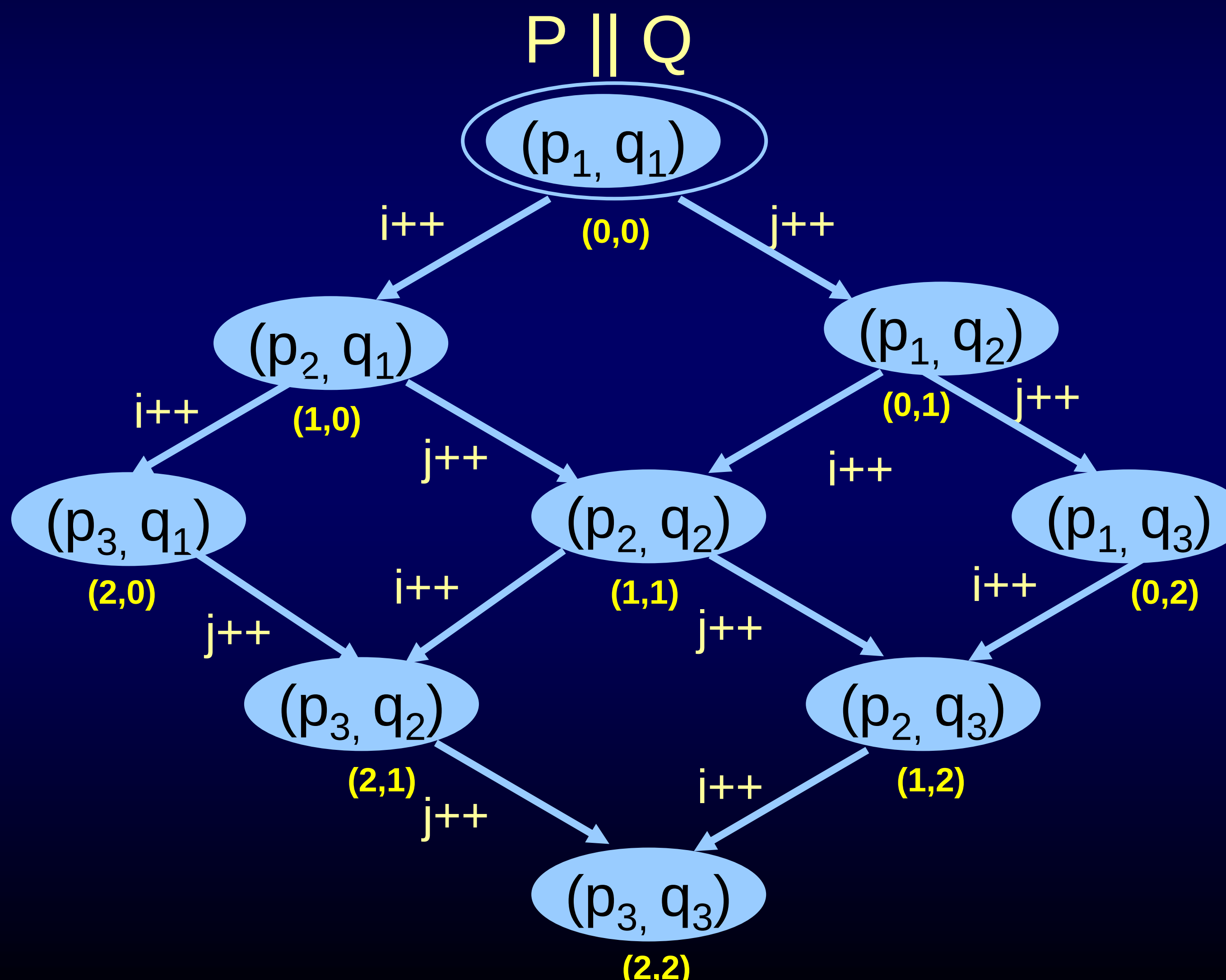
- EFSM = FSMs + <u>variables</u> + enabling conditions + assignments
- Can model the control aspect <u>as well as the data aspect</u>
- Can be translated into FSM if variables have bounded domains
- EFSM state: control location + variables’ valuation

(q,total,capacity)

$(q_1,0,10) \xrightarrow{\text{coin / -}} (q_1,1,10) \xrightarrow{\text{coin / -}} (q_1,2,10) \xrightarrow{\text{cof-but / cof}} (q_1,0,9)$

Parallel Composition (independent)

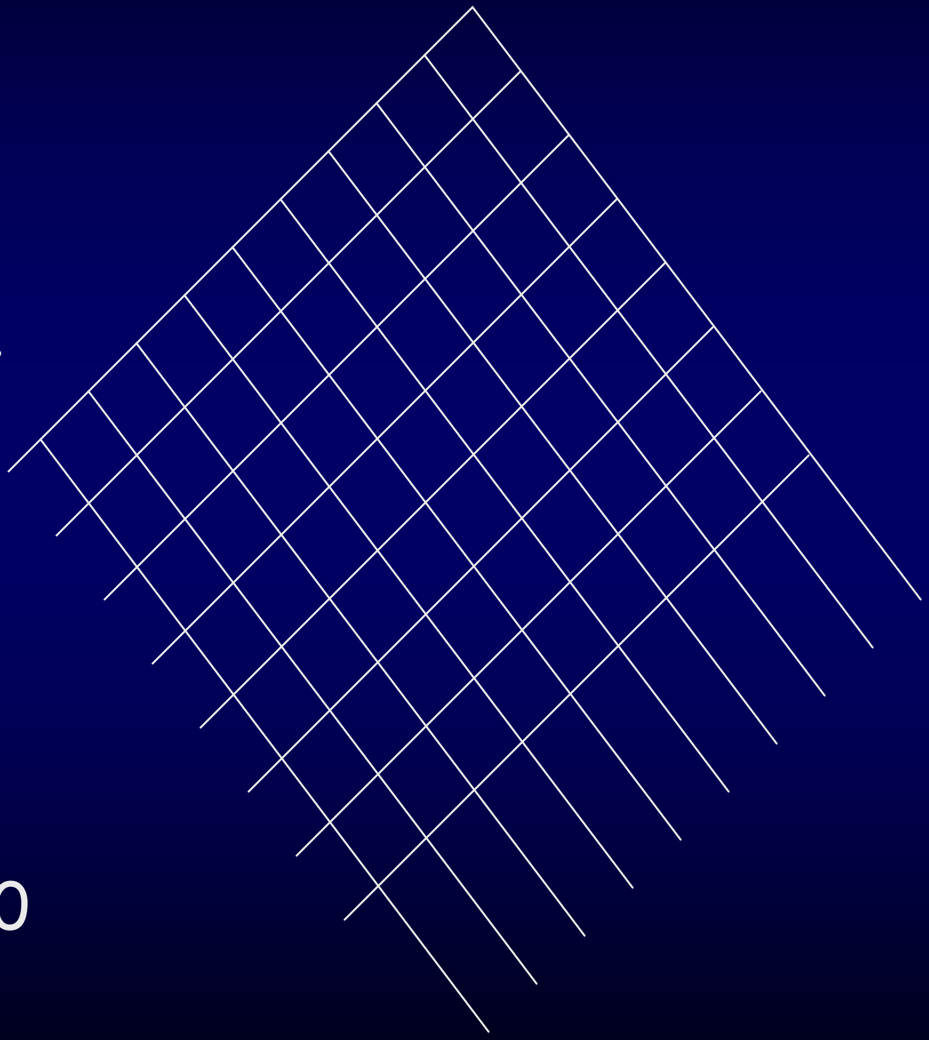




interleaving "execution"

State Explosion Problem

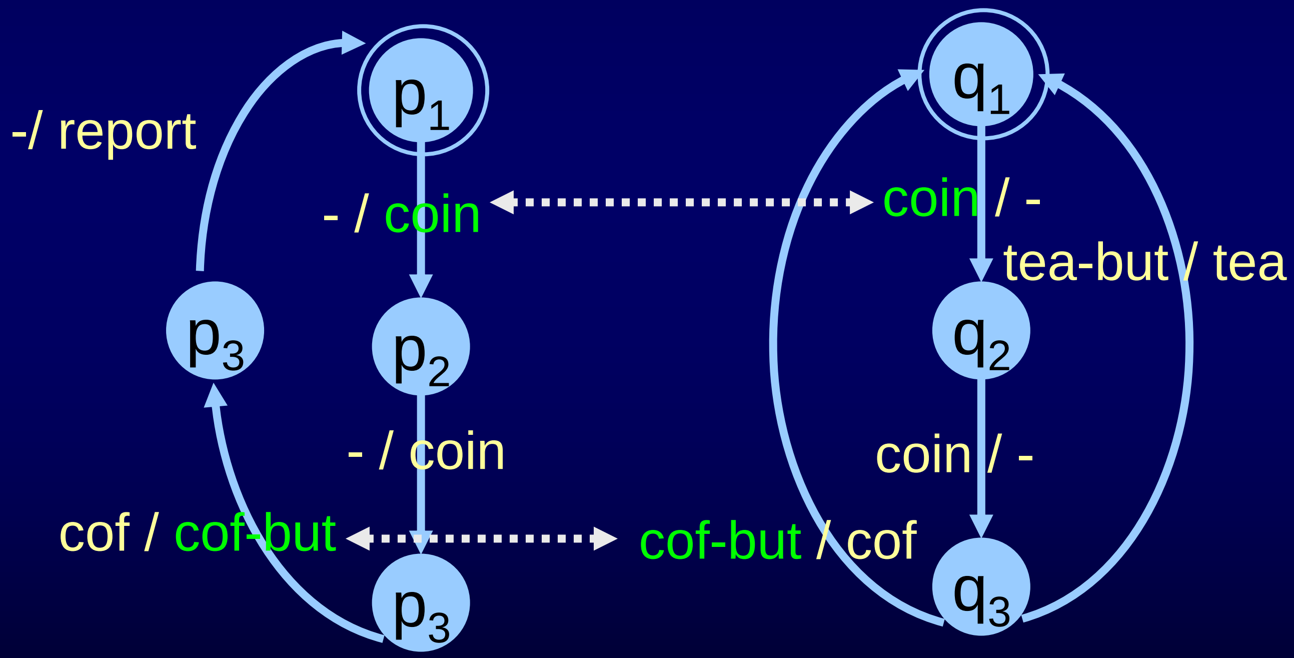
- *n* parallel FSMs or EFSMs
- Each with *k* states
- In parallel they have k^n states
- **EXPONENTIAL!**
  - 10^2 =100
  - 10^3 = 1000
  - 10^4 = 10000
  - 10^10 =10000000000



Synchronous Parallel Composition

Handshake on complementary actions

e.g., one "sending" with another "receiving"

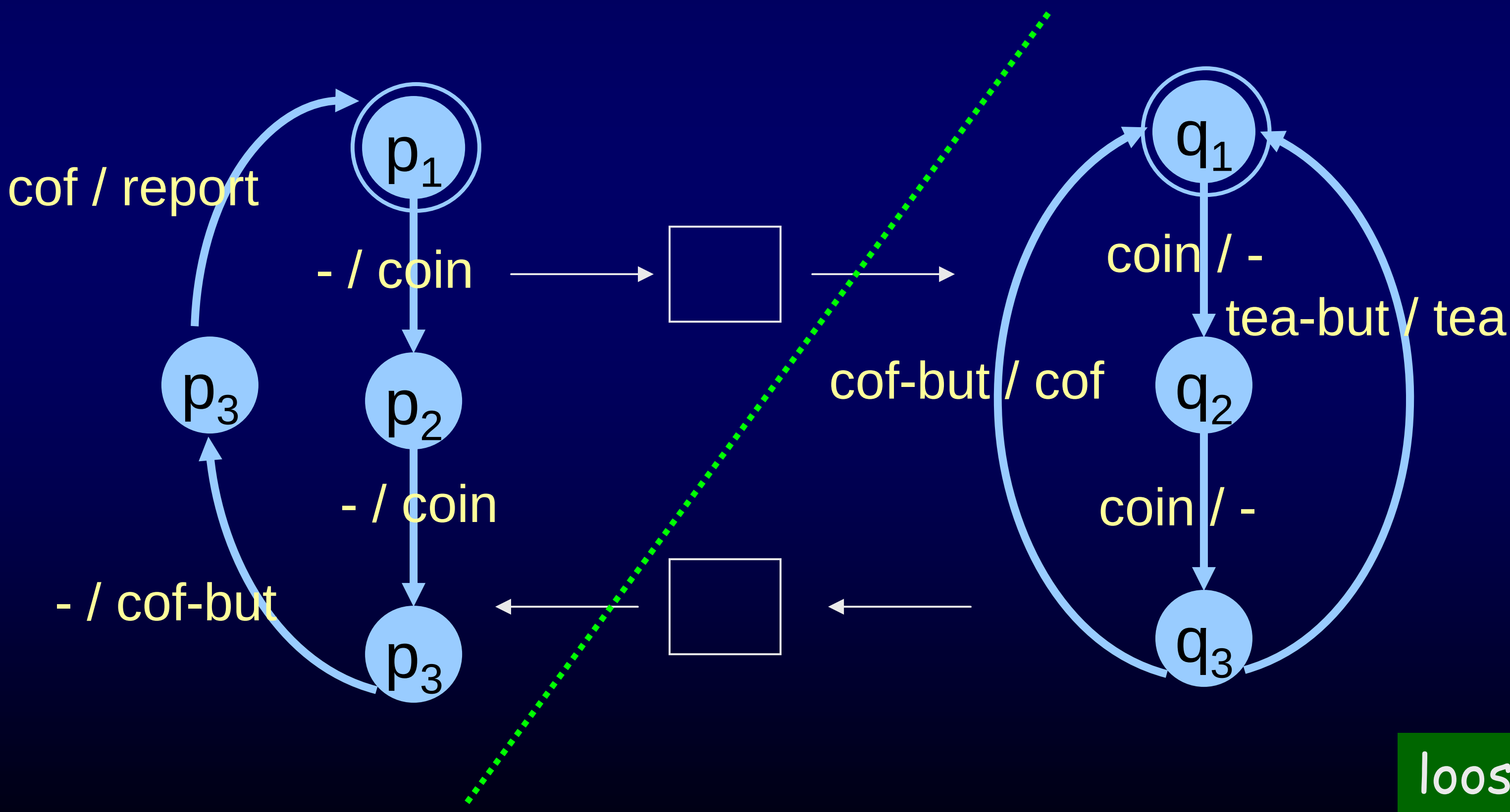


strict!

Asynchronous Parallel Composition

Single output variable <u>per FSM</u> holds last "written" output

no handshaking any more!

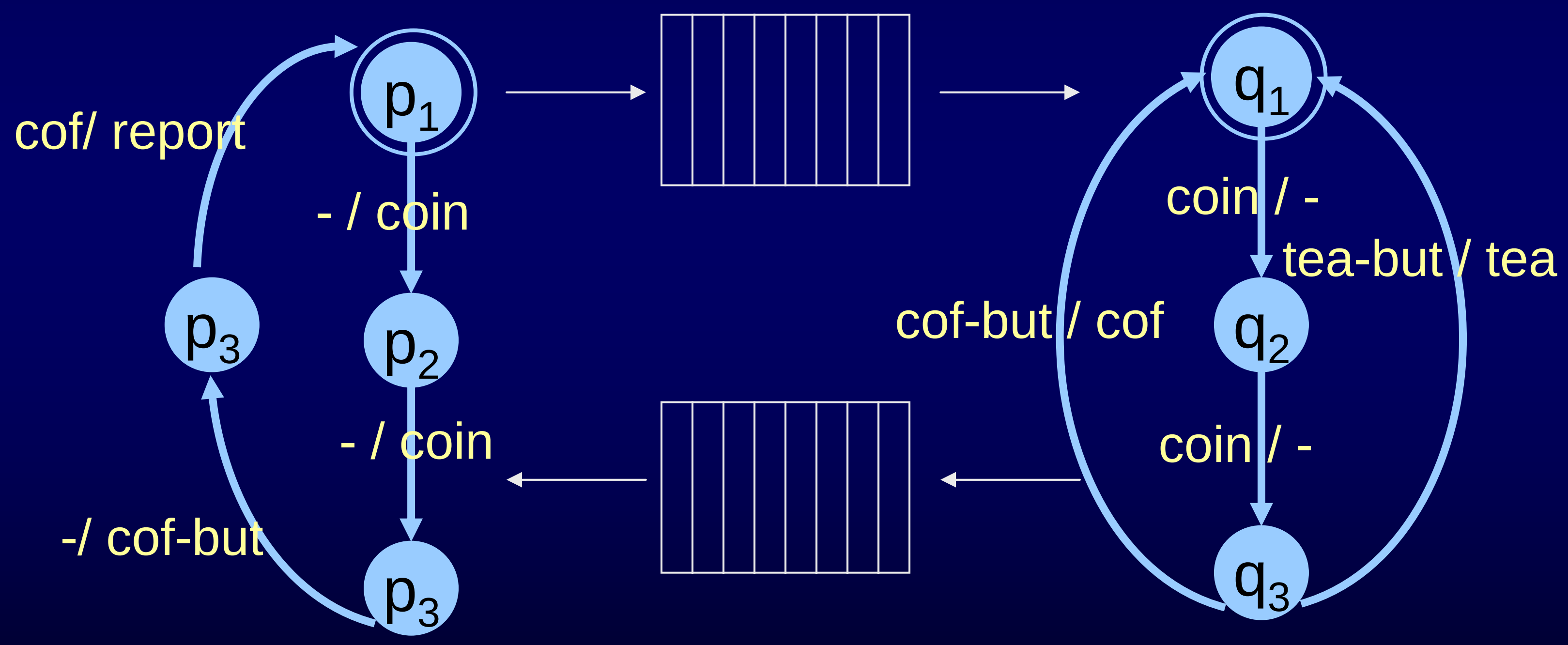


loose ..

Queued Parallel Composition

Output is queued in (un)bounded queue

The queue may be per process (component), per action, or explicitly defined



System state: a snapshot of all (E)FSMs and queues

looser ..

Blackboard exercise: Bank-box Code

O

B

Y

To open a bank box
the code must contain at least 2

To open a bank box
the code must end with

To open a bank box
the code most end with
or with

To open a bank box
the code must end with a palindrom
e.g:.

....

!!

Palindrome: Word that reads the same forth and back!

Notes

- Palindrome not recognizable by FSM: infinitely many/long palindromes
- Recognizes bank-box opening sequence:
- If non-deterministic:

  → determinize it → minimize it

Minimized FSM

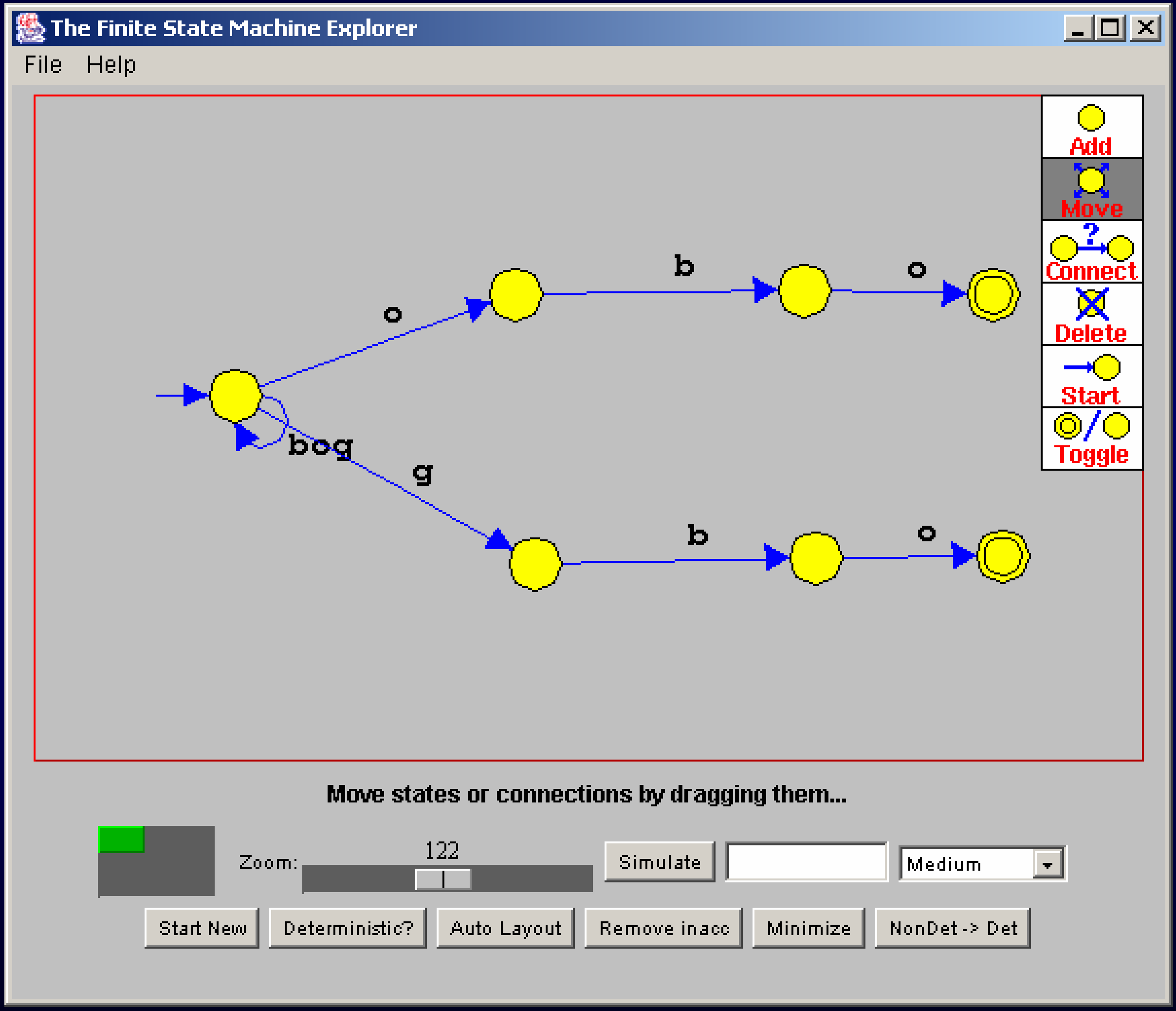
- Two states *s* and *t* are (language) equivalent iff
  - *s* and *t* accepts same language
  - have same traces: *tr(s) = tr(t)*
- Two Machines M0 and M1 are equivalent iff initial states are equivalent
- A minimized (or "reduced") M is one that has no equivalent states
  - for no two states *s,t*, *s!=t*, s equivalent t

Fundamental Results

- Every FSM may be determinized accepting the same language (potential explosion in size).
- For each FSM there exists a language-equivalent *minimal* deterministic FSM.
- FSM's are closed under $\cap$ and $\cup$
- FSM's may be described as regular expressions (and vice versa)

Determinization + Minimization

The Finite State Machine Explorer (http://www.belgarath.org/java/fsme.html)

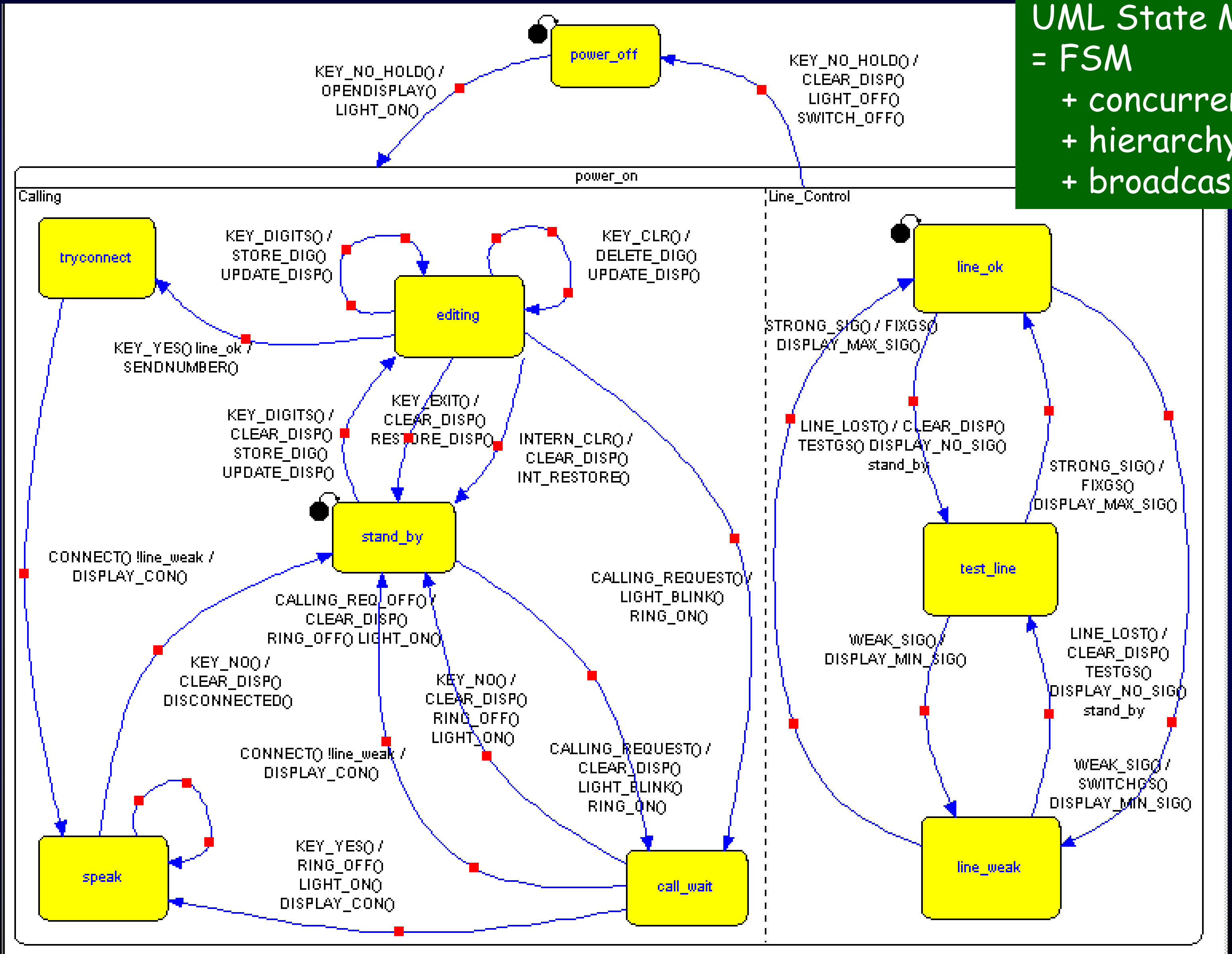


Many other tools for FSM editing, simulation, determinization, minimization, ...
(http://en.wikipedia.org/wiki/List_of_state_machine_CAD_tools)

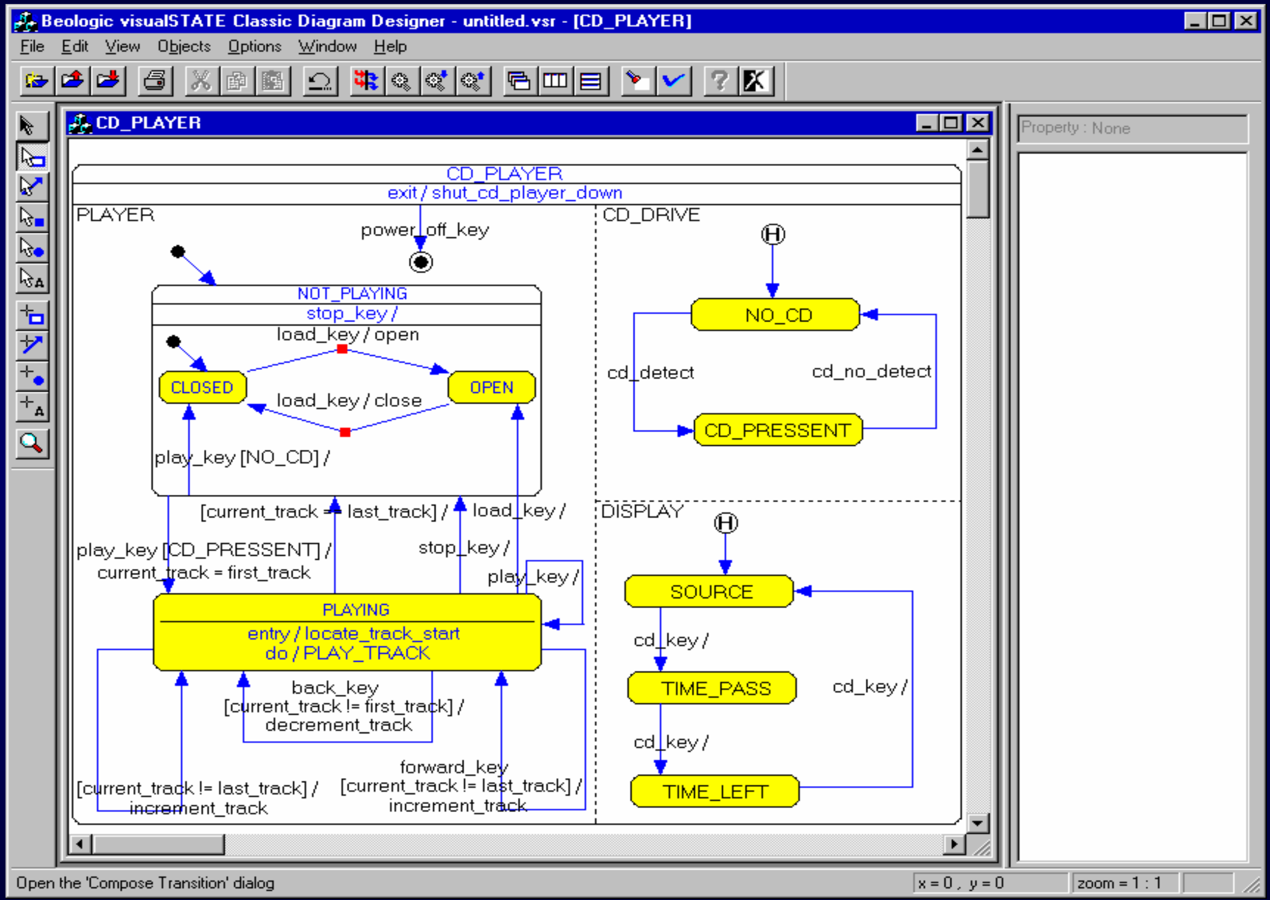
High-level FSM languages

UML State Machines

UML State Machine
= FSM
+ concurrency
+ hierarchy
+ broadcast communication



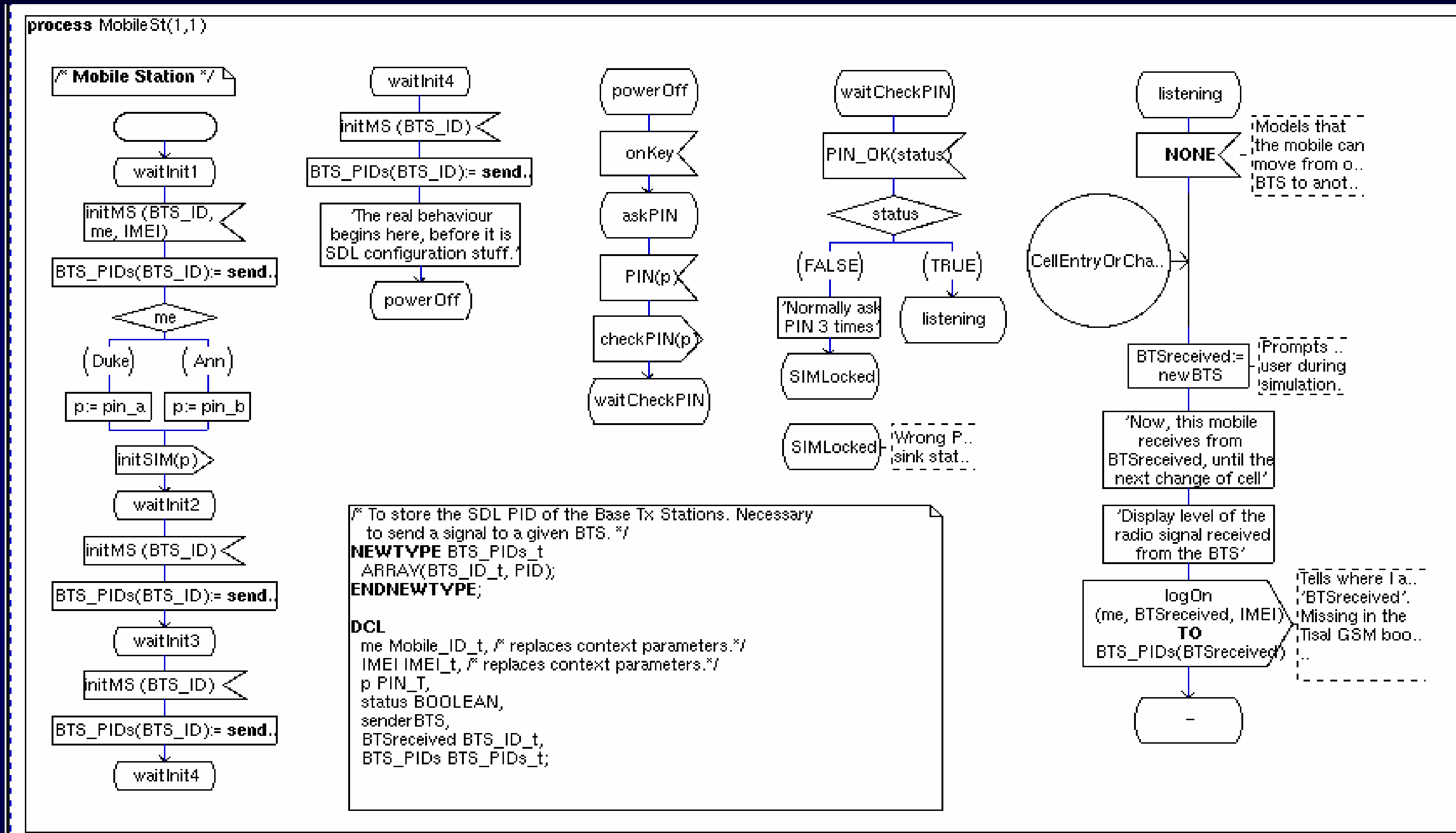
Tool: visualSTATE Designer



- Hierarchical state systems
- Flat state systems
- Multiple and inter-related state machines
- Supports UML notation

SDL

a system is specified as a set of interconnected abstract machines which are **extensions of FSM**

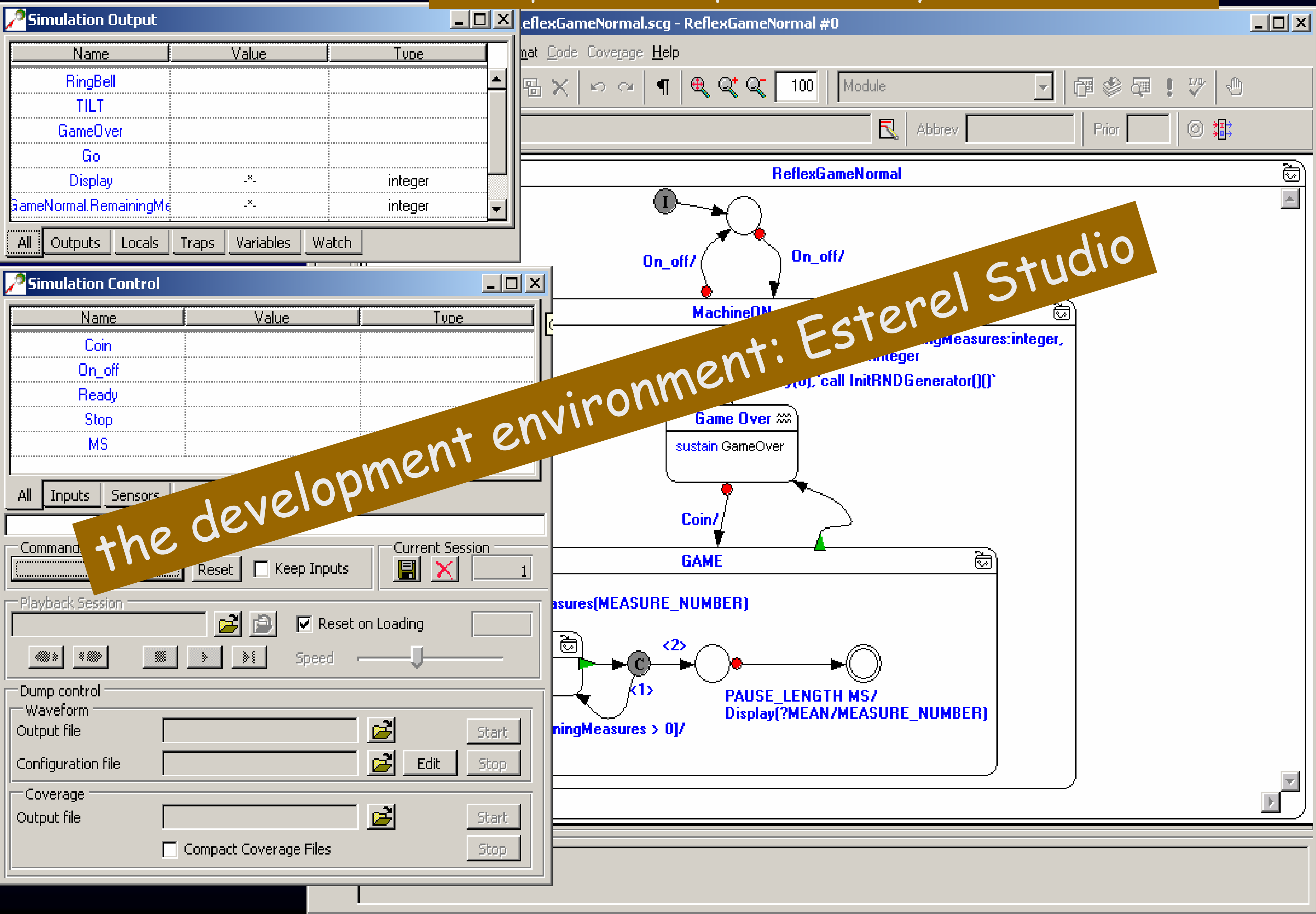


Specification and Description Language (SDL):

- for unambiguous specification and description of the behaviour of reactive and distributed systems
- defined by the ITU-T (Recommendation Z.100.)
- originally focused on telecommunication systems
- current areas of application include process control and real-time applications in general

Esterel

a synchronous programming language for the development of complex reactive systems



the development environment: Esterel Studio

Textual Notations for FSM

In: Promela/SPIN

```
int x;
proctype P(){
  do
  :: x<200 --> x=x+1
  od}

proctype Q(){
  do
  :: x>0 --> x=x-1
  od}

proctype R(){
  do
  :: x==200 --> x=0
  od}

init
{run P(); run Q(); run
R()}
```

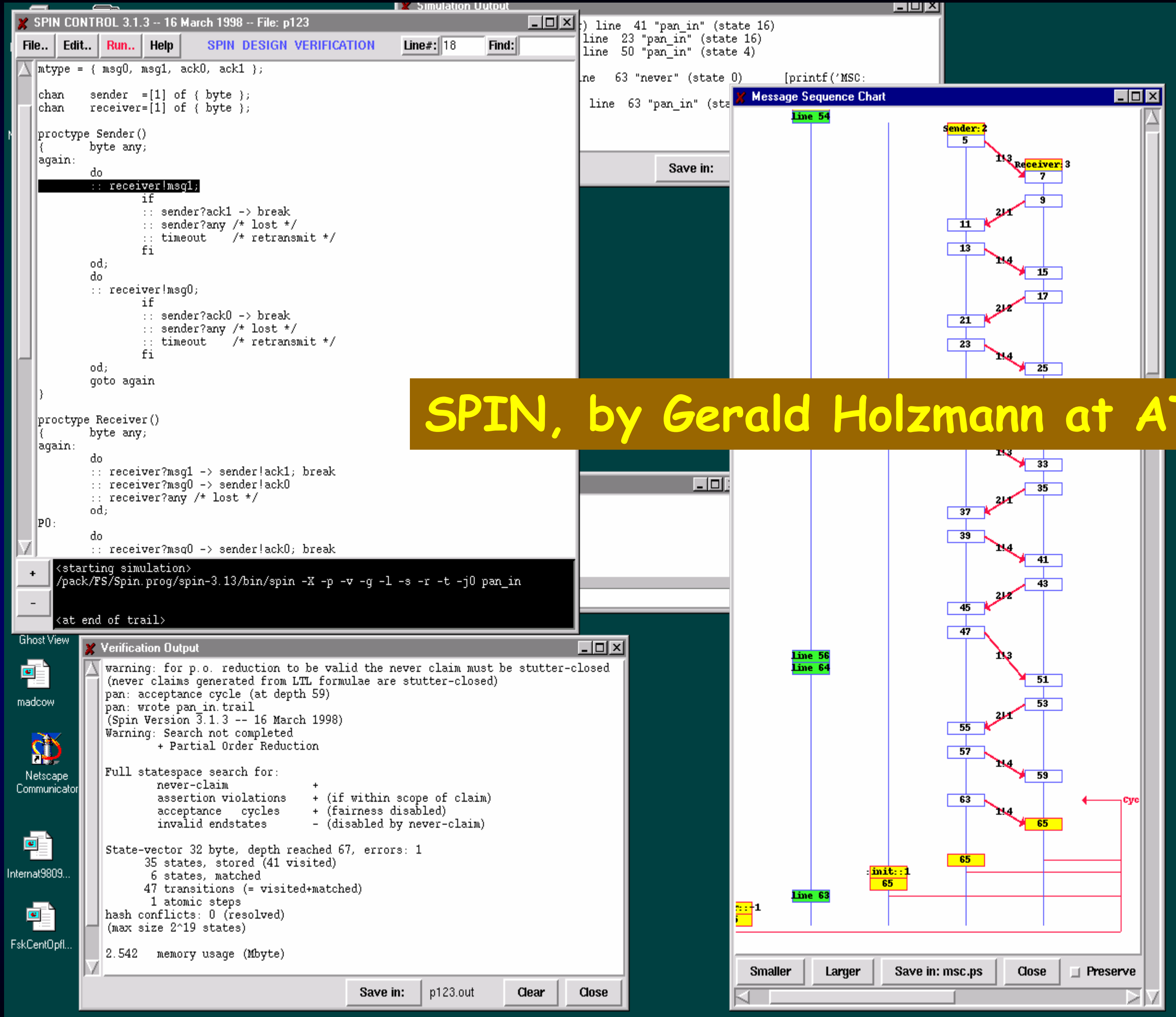
In: FSP/LTSA

```
SERVERv2 = (accept.request
           ->service>accept.reply->SERVERv2).
CLIENTv2 = (call.request
           ->call.reply->continue->CLIENTv2).

||CLIENT_SERVERv2 = (CLIENTv2 || SERVERv2)
                    /{call/accept}.
```

FSP: Finite State Processes
LTSA: Labelled Transition System Analyser

Promela: the input language of tool SPIN

SPIN, by Gerald Holzmann at AT&T

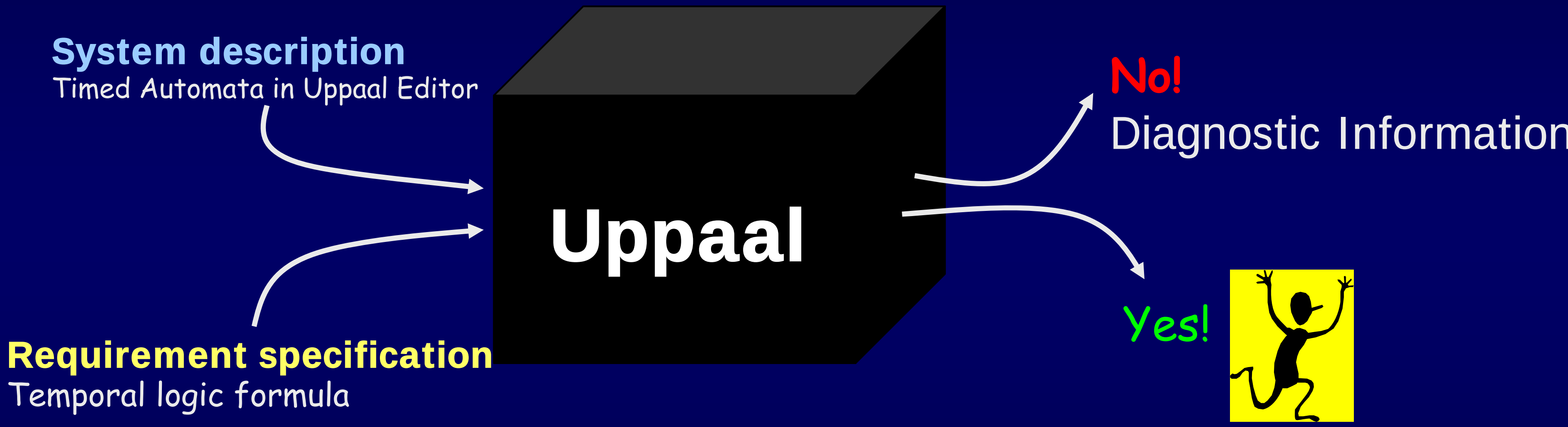


Modelling Untimed Systems using Uppaal

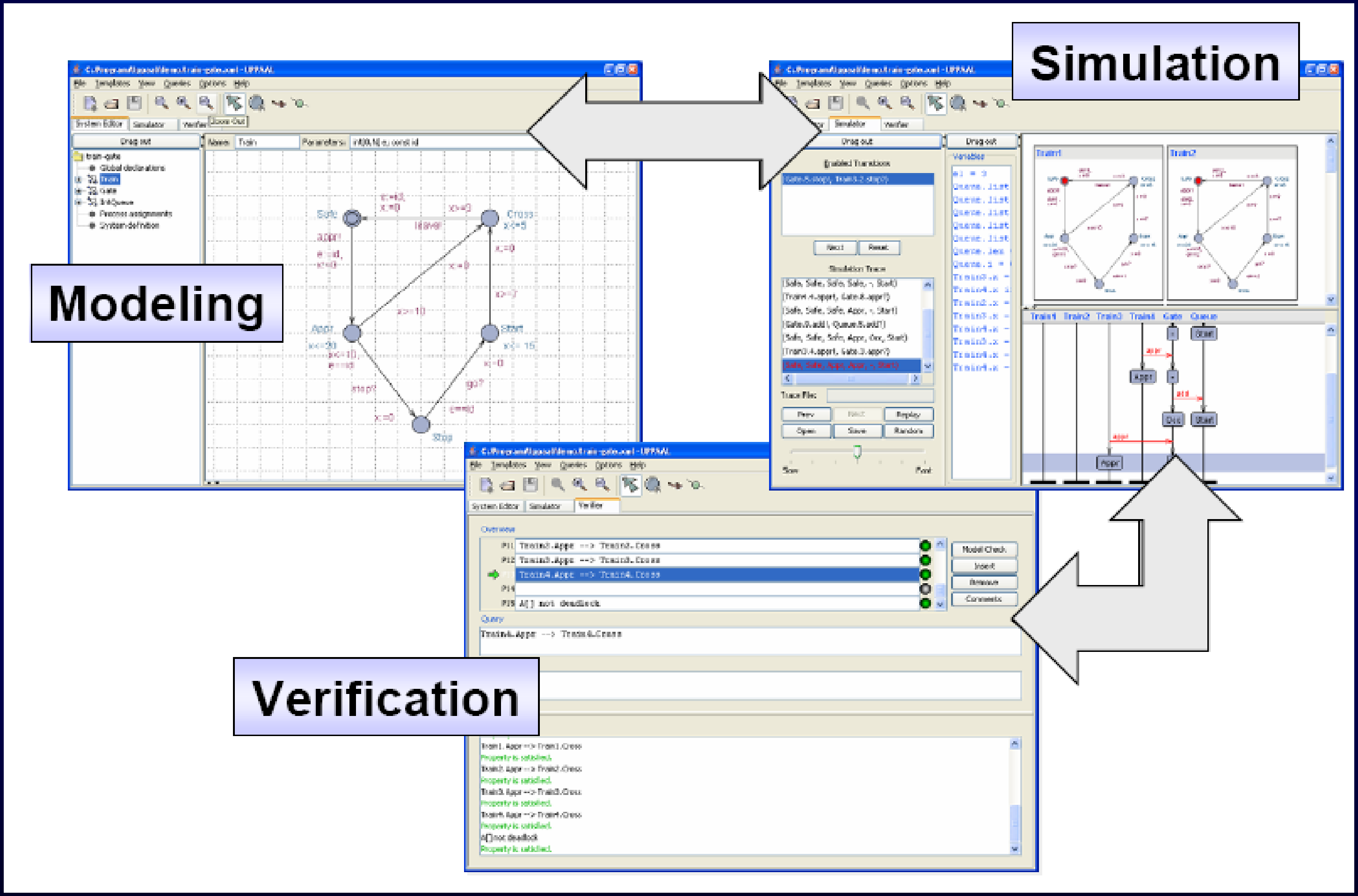
Uppaal

- An integrated tool environment for modeling, simulation and verification of real-time systems modelled as networks of timed automata, extended with data types
- However, it is also capable of untimed system modelling, simulation and verification

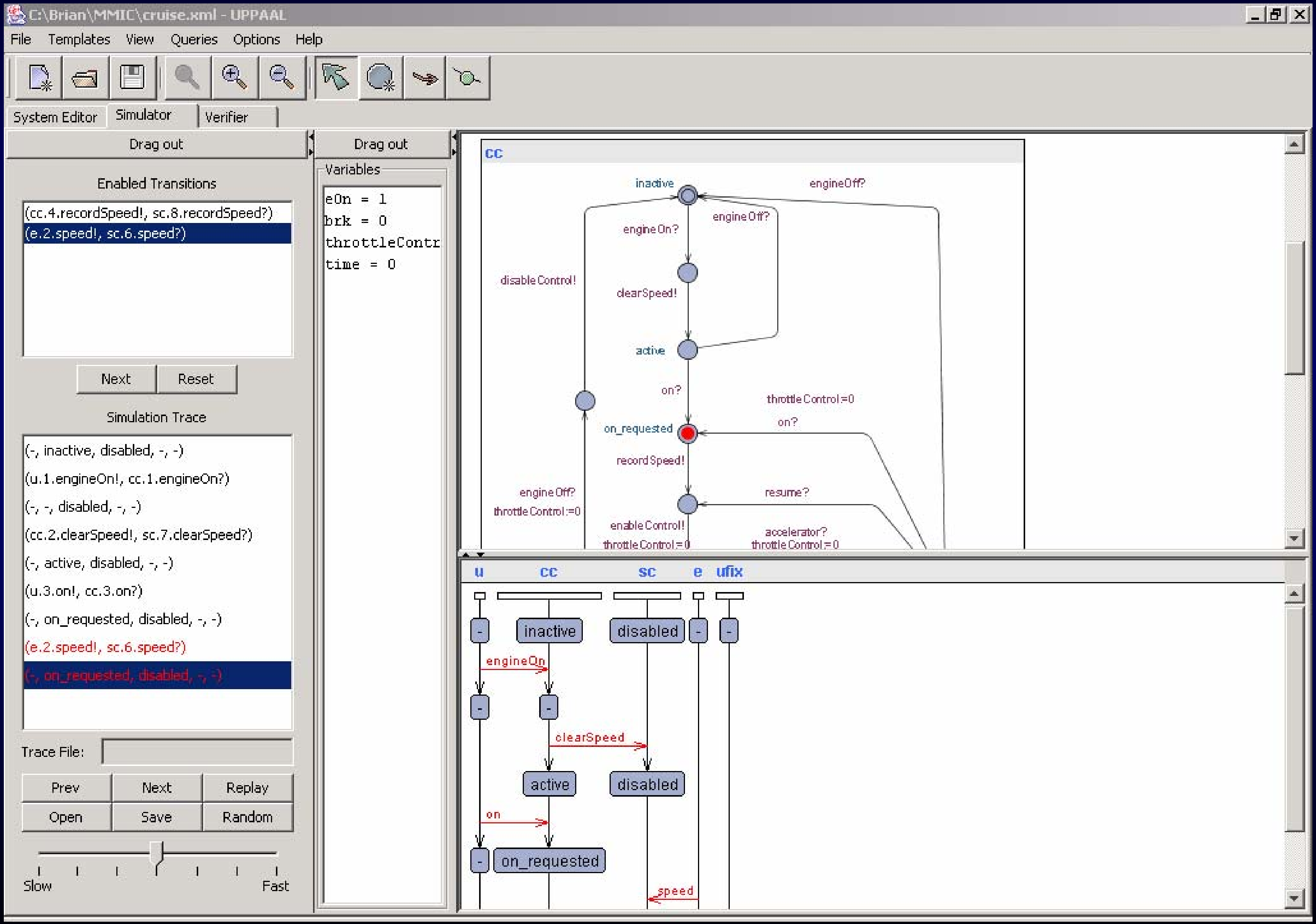
Uppaal Verification as a box…



Working Modes of Uppaal



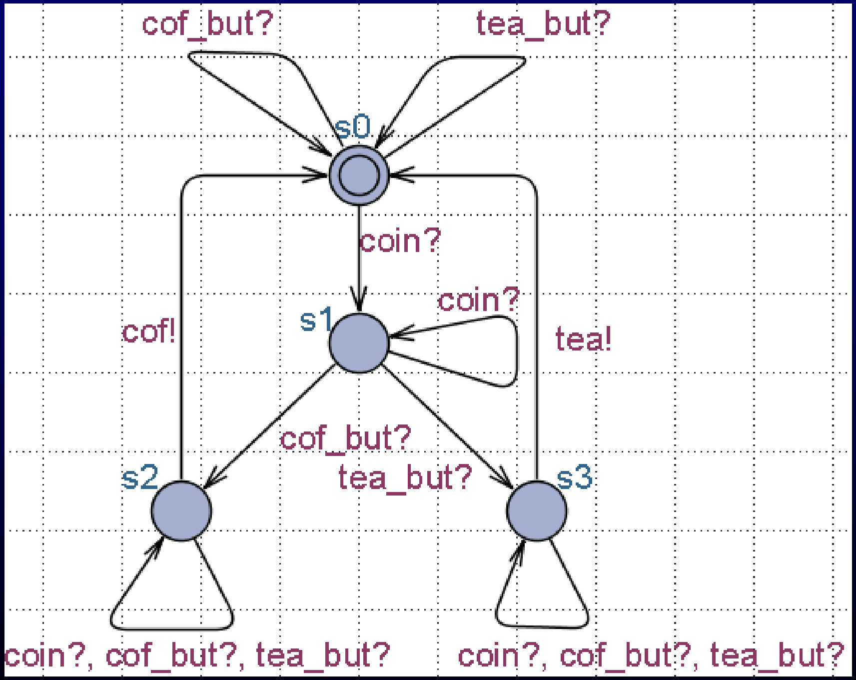
Uppaal Simulator Screenshot



FSM in Uppaal

- Basically an Extended FSM (variables, guards, assignments)
- Also may be thought of as an LTS, or IO Automaton
  - actions are either inputs or outputs
  - internal actions are not explicitly given

LTS can be viewed as a **degradation** of **finite state machine** (FSM)



Home-Banking?

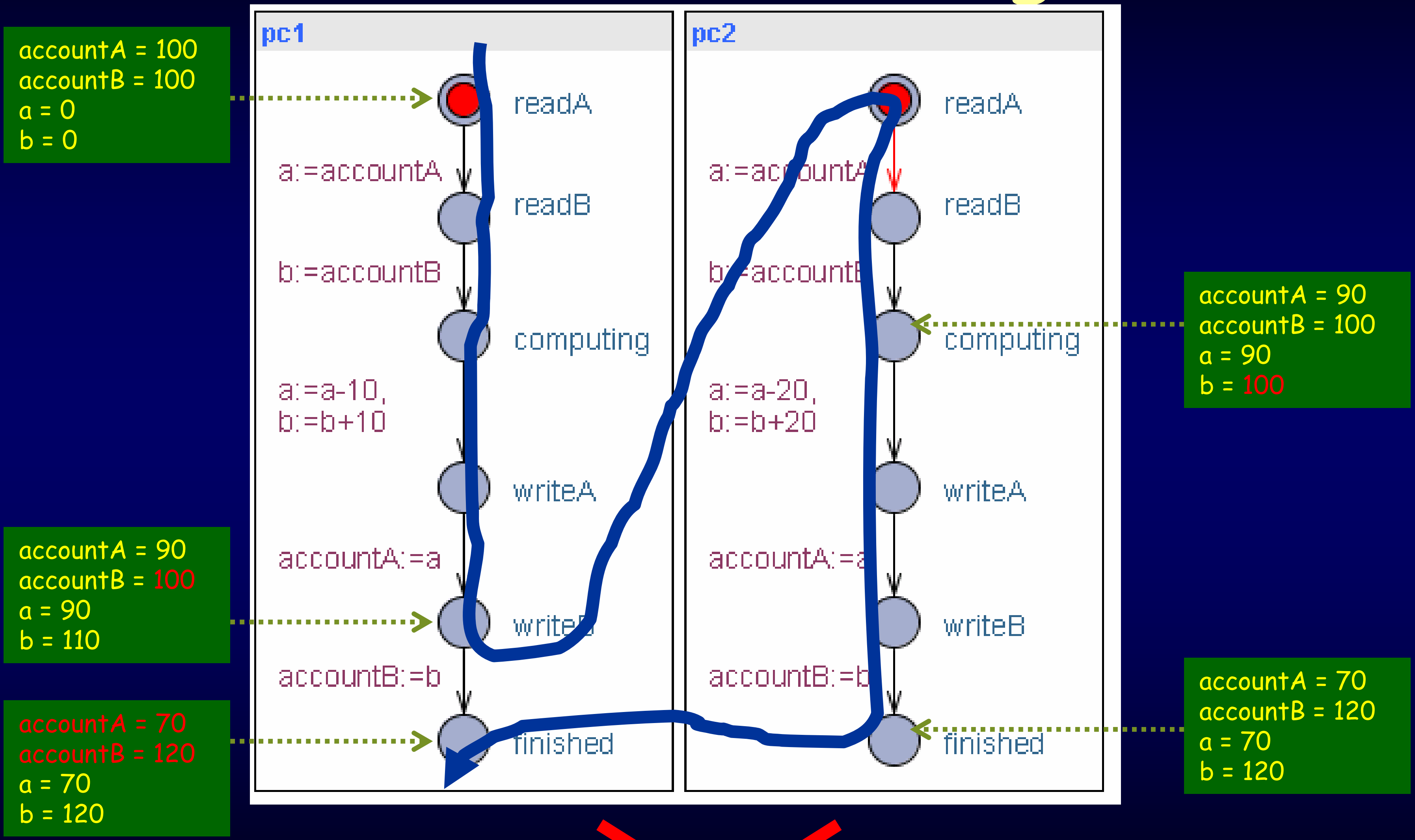
```
int accountA, accountB; //Shared global variables

//Two concurrent bank costumers
```

```
Thread costumer1 () {
  int a,b; //local tmp copy

  a=accountA;
  b=accountB;
  a=a-10;b=b+10;
  accountA=a;
  accountB=b;
}
```

```
Thread costumer2 () {
  int a,b;

  a=accountA;
  b=accountB;
  a=a-20; b=b+20;
  accountA=a;
  accountB=b;
}
```

- Are the accounts in balance after the transactions?
  - Suppose initially: accountA + accountB = 200
  - Note that local variables a, b are shared by the two threads

Home-Banking



~~A[] (pc1.finished and pc2.finished) imply (accountA+accountB==200)?~~

Home-Banking: another attempt

```
int accountA, accountB; //Shared global variables
Semaphore A,B;          //Protected by sem A,B

//Two concurrent bank costumers
```

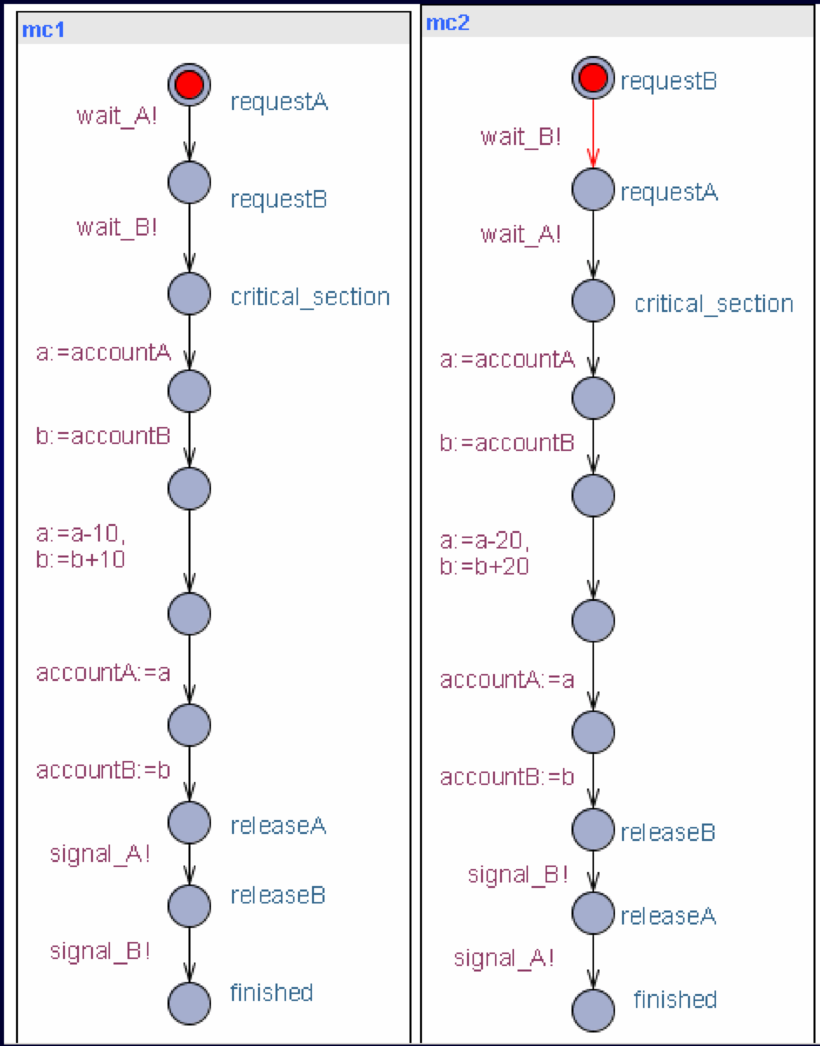
exclusive access to shared variables via semaphore

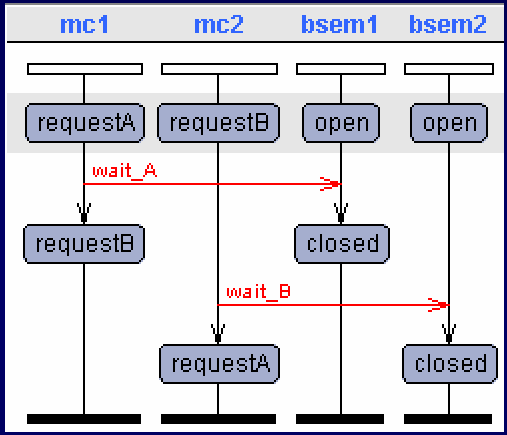
```
Thread costumer1 () {
  int a,b; //local tmp copy

  wait(A);
  wait(B);
  a=accountA;
  b=accountB;
  a=a-10;b=b+10;
  accountA=a;
  accountB=b;
  signal(A);
  signal(B);
}
```

```
Thread costumer2 () {
  int a,b;

  wait(B);
  wait(A);
  a=accountA;
  b=accountB;
  a=a-20; b=b+20;
  accountA=a;
  accountB=b;
  signal(B);
  signal(A);
}
```

- semaphore: a special kind of boolean variables.
- wait(A): if A is true, go to next sentence and set A to false; if A is false, just wait here until A becomes true
- signal(A): set A to true

Home-Banking: another attempt





1. Consistency? (Balance)
2. Race conditions?
3. Deadlock?

Semaphore Really Works!

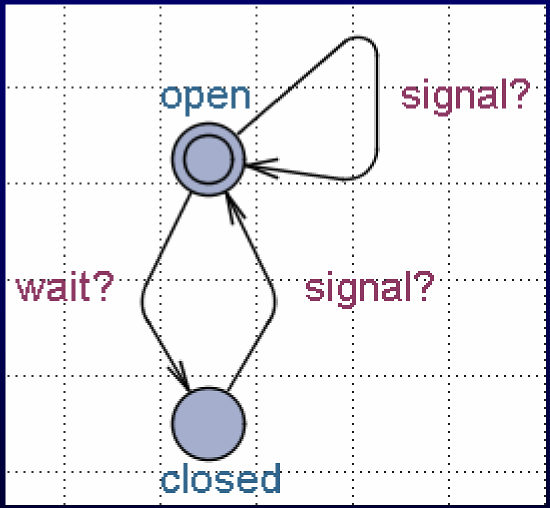
1. A[] (mc1.finished and mc2.finished) imply (accountA+accountB==200) ✓
2. E<> mc1.critical_section and mc2.critical_section ✓
3. A[] not (mc1.finished and mc2.finished) imply not deadlock

Semaphore FSM Model

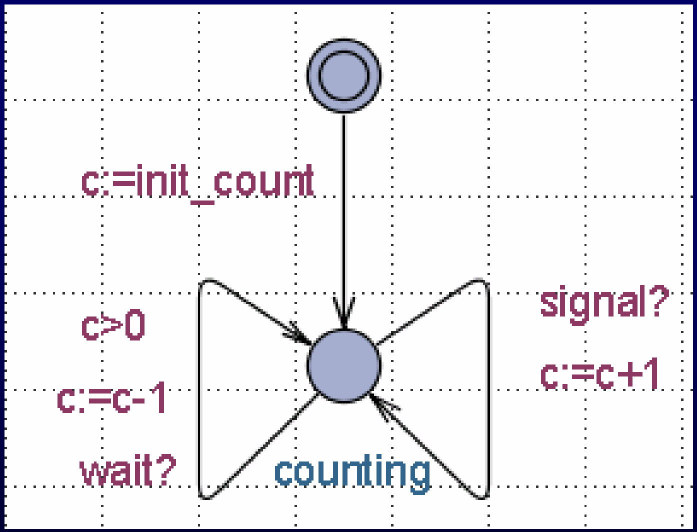
The critical resource can be accessed by only one thread! (exclusive access)

The critical resource can be simultaneously accessed by at most n threads! (restricted shared access)

Binary Semaphore



Counting Semaphore



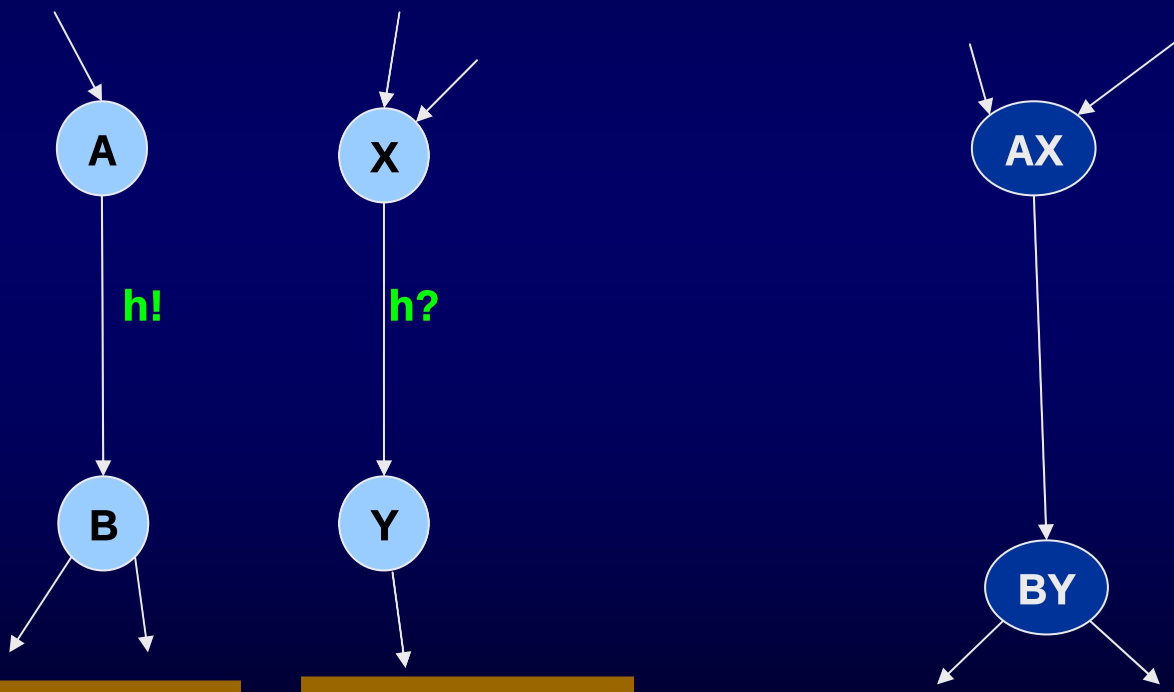
wait: a thread wants to occupy this semaphore
signal: a thread wants to release this semaphore

Composition

IO Automata (2-way synchronization)

or pairwise synchronization

or “handshaking”

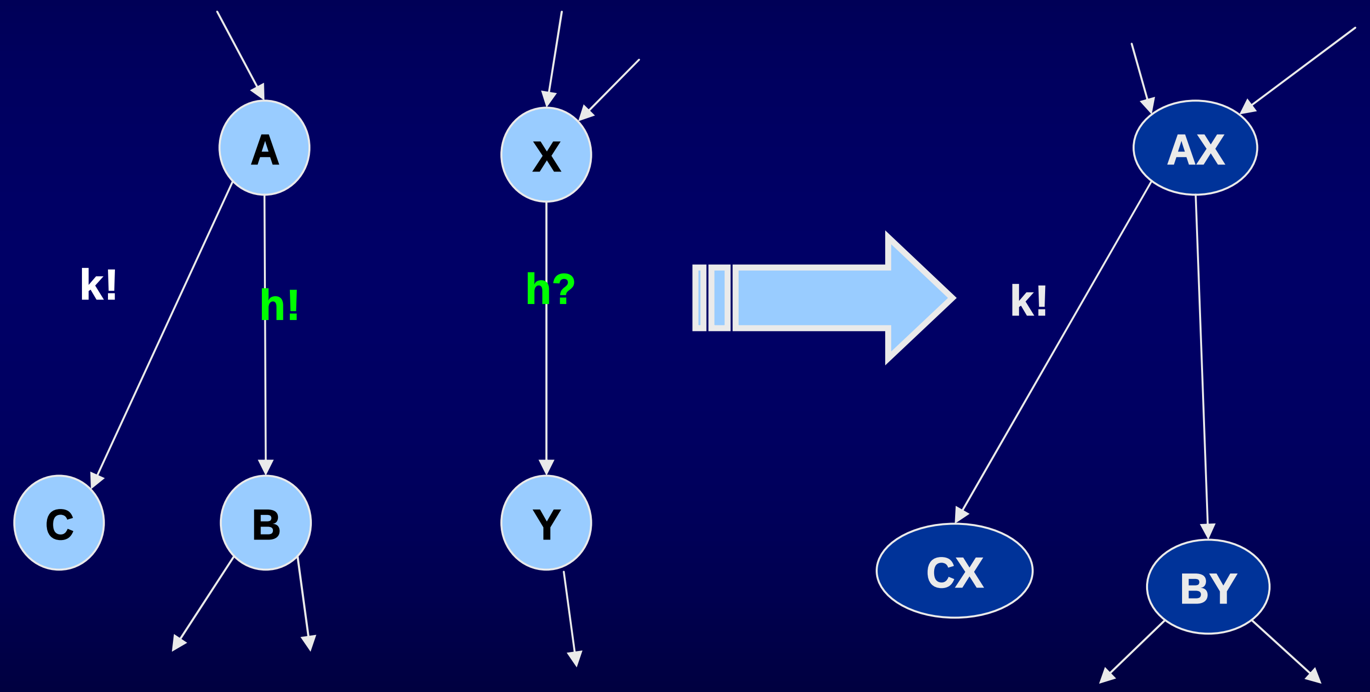


sending or writing

receiving or reading

Composition

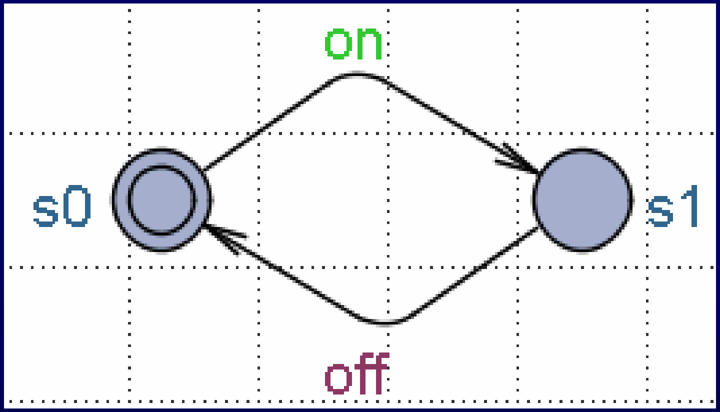
IO Automata



Modelling Processes

- A process is the execution of a <u>sequential</u> program
- modelled as a labelled transition system (LTS)
  - transits from state to state
  - by executing a sequence of *atomic* actions.

a light switch
LTS



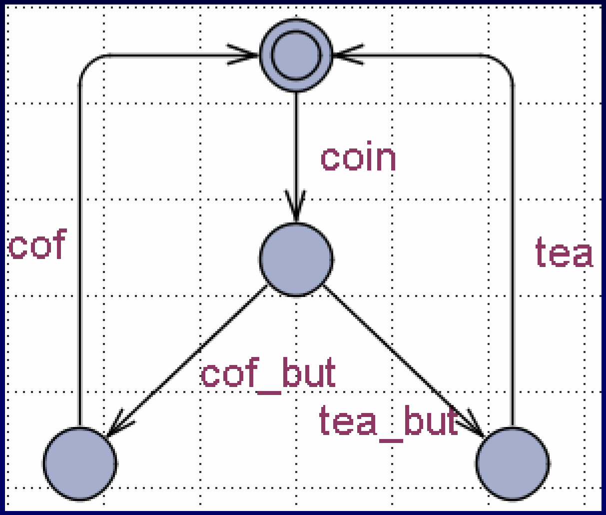
on→off→on→off→on→off→ ……….

a sequence of actions

or

a *trace*

Modelling Choices

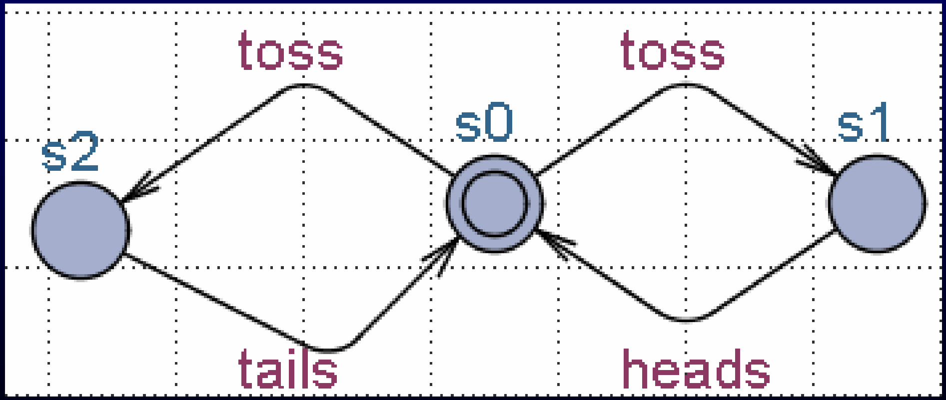


- Who or what makes the choice?
- Is there a difference between input and output actions?

Non-deterministic Choice

- Tossing a coin

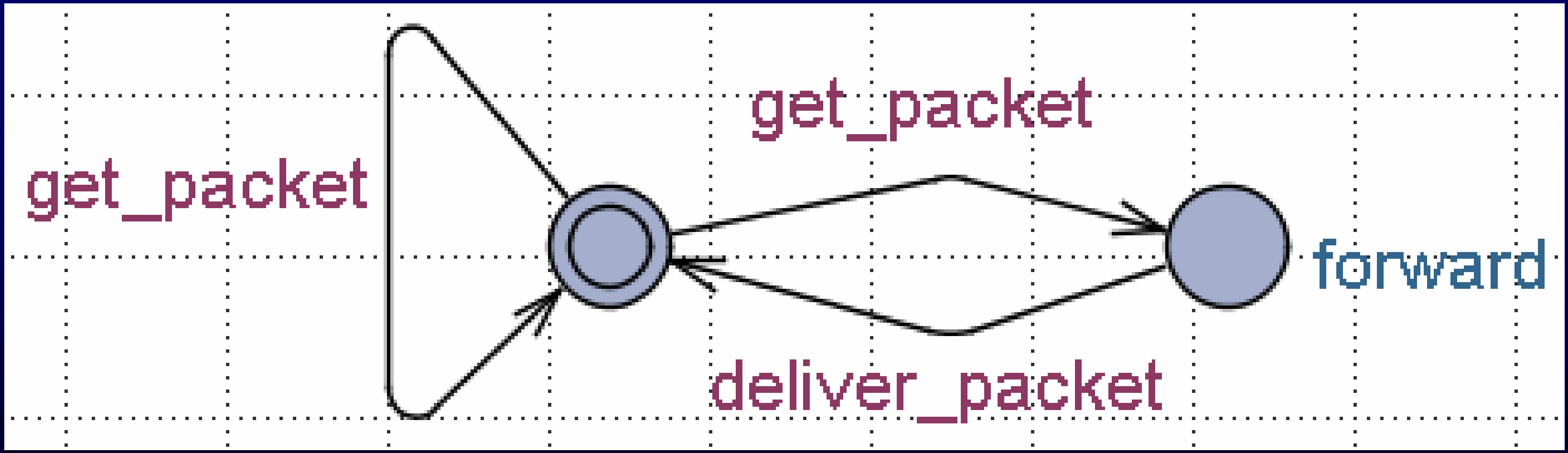
- Possible traces?
  - Both outcomes possible
  - Nothing said about relative frequency
  - If coin is fair, the outcome is 50/50



Non-deterministic Choice modelling failure

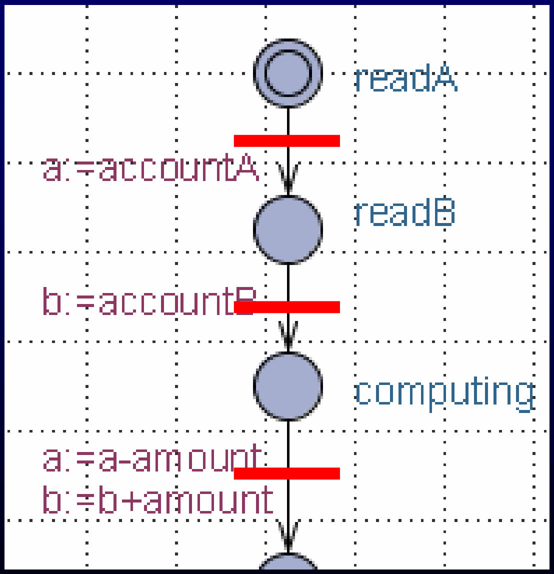
How do we model an unreliable communication channel which accepts **packets**, and if a failure occurs produces no output, otherwise delivers the packet to the receiver?

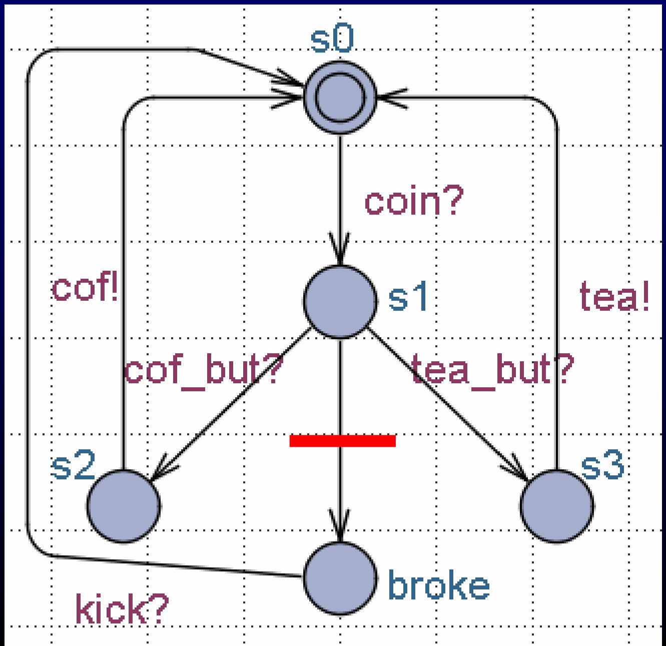
Use non-determinism...

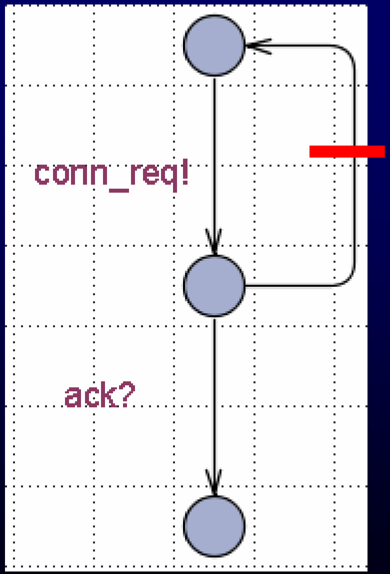


Internal Actions

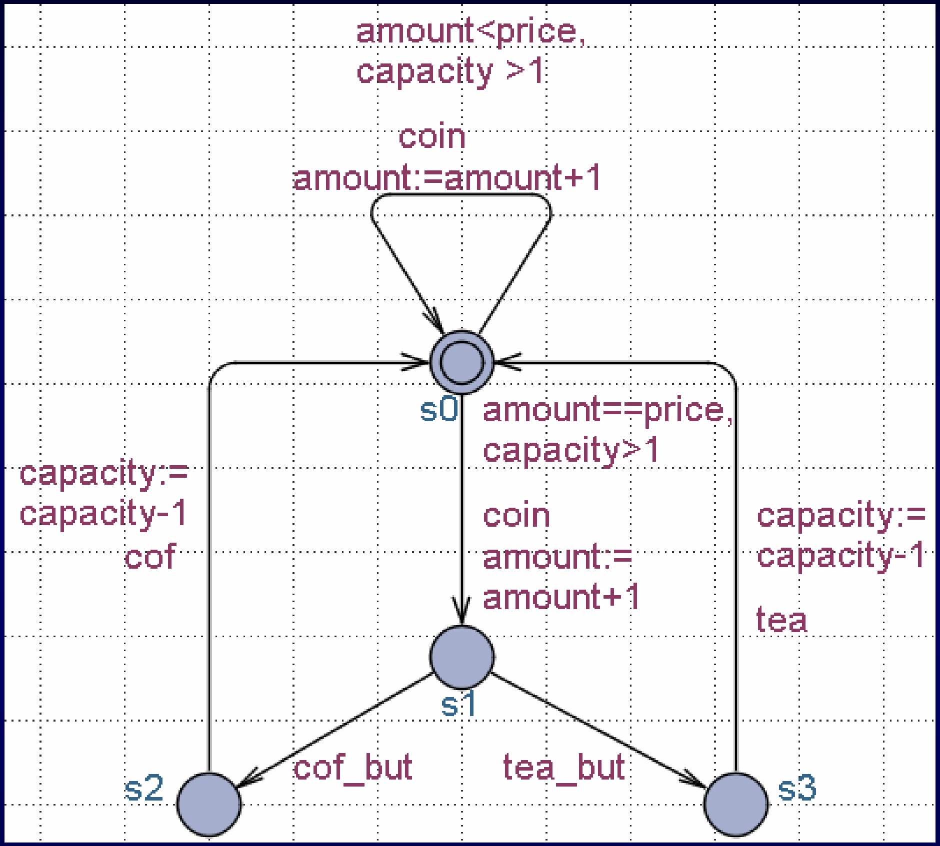
- Internal actions also called
  - spontaneous actions, or
  - tau-actions
- Internal transitions can be taken on the initiative of a single machine without coupling with another one





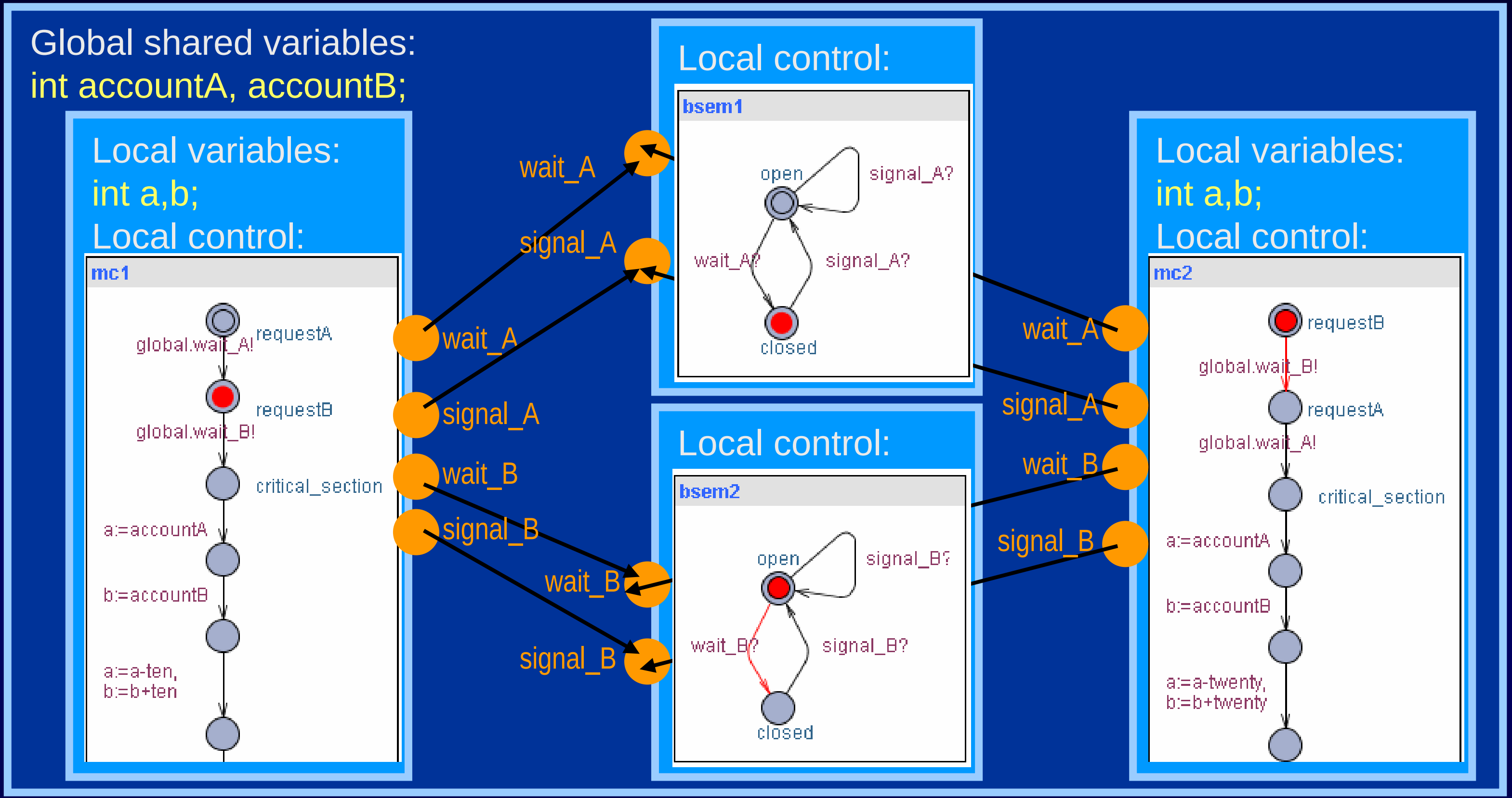


Modelling Extended FSM (EFSM)



- EFSM = FSM + variables + enabling conditions + assignments
- Transition still atomic
- Can be translated into FSM if variables have bounded domains
- State: control location + variables' valuation
- (state, total, capacity), e.g.: (s0, 5, 10)

Uppaal Network of Automata



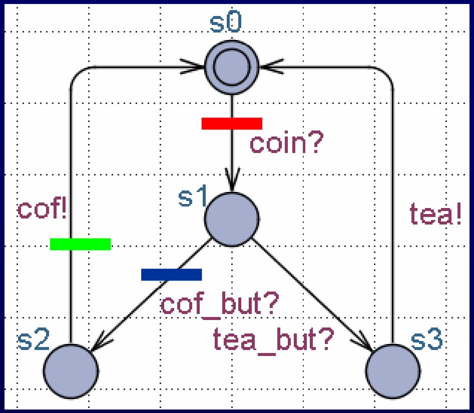
- system state = snapshot of (all machines' control locations + local variables + global variables)

```
e.g.: mc1.control=requestB, mc1.a=0, mc1.b=0,
      mc2.control=requestB, mc2.a=0, mc2.b=0,
      bsem1.control=closed, bsem2.control=open,
      accountA=100, accountB=100
```

Process Interaction

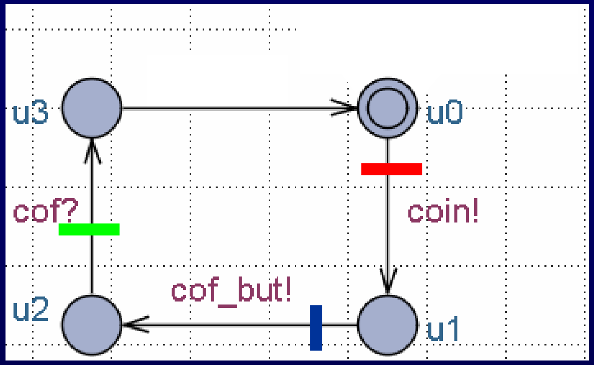
- "!" denotes output, "?" denotes input
- Handshake communication
- Two-way

Coffee Machine



4 states

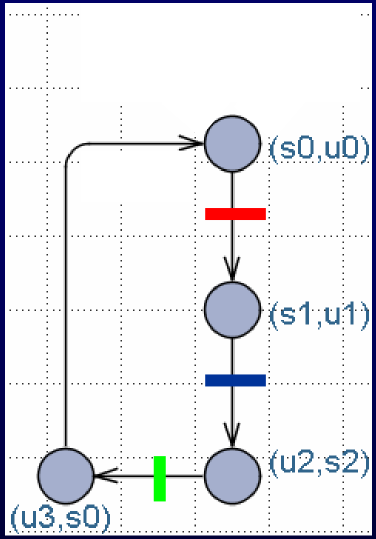
Lecturer



4 states

=

University=
Coffee Machine || Lecturer



synchronization results in internal actions

LTS?
How many states?
Traces ?

4 states:
(interactions constrain overall behavior)

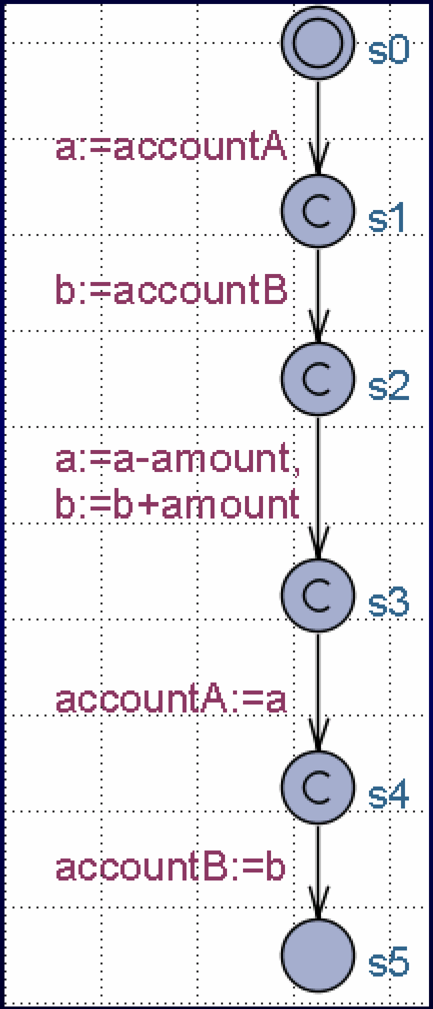
Broadcasts

```
chan coin, cof, cofBut;
broadcast chan join;
```

- the sending party: one automaton outputs join!
- the receiving party: several automata accept join!,
  - each of them makes a move upon receiving join!,
  - ie. every automaton with enabled "join?" transition moves in one step
- the number of recipients may be 0 (one "speaker", but no "audience")

Committed Locations

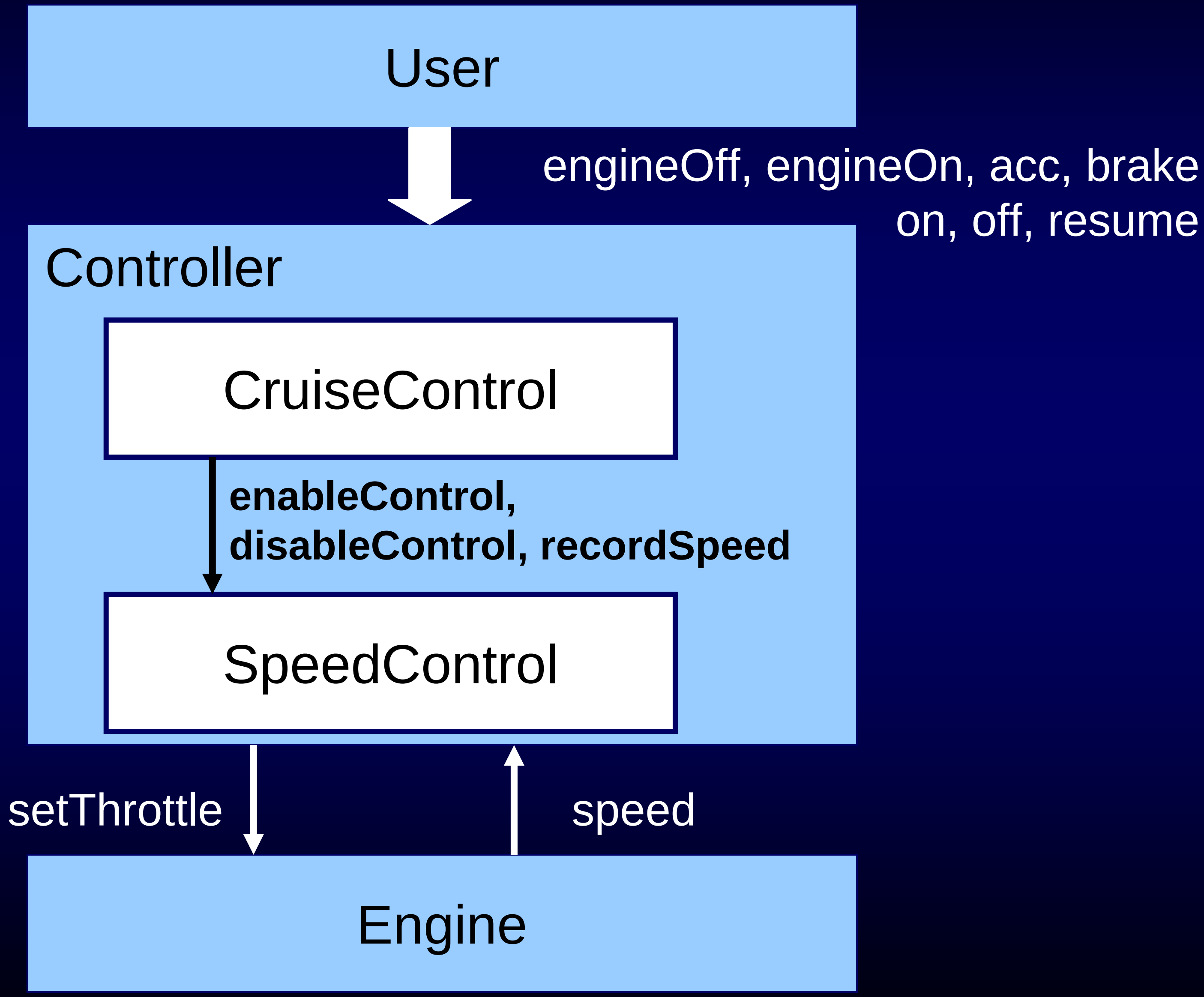
- Locations marked "*C*"
  - ***No delay*** in committed location
  - Next transition must involve one of those automata in ***committed locations***
- Handy to model atomic sequences
  - An "input/output"-style transition of Mealy machine can be modelled by 2 atomic actions "input?" and "output!", which are connected by a committed location
- The use of committed locations significantly reduces the state space of a model, thus allows for more efficient analysis and verification



s0 to s5 executed atomically

they will not be interrupted

The Cruise Controller

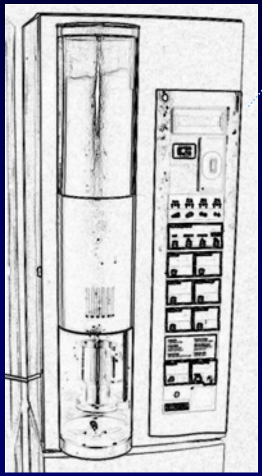


Timed Automata

Real-time Systems

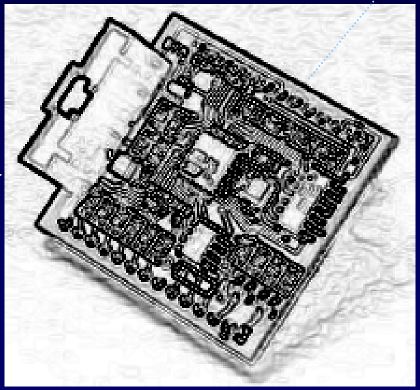
The "environment"

We are interested in this one!



sensors

actuators



Plant

Continuous

Controller Program

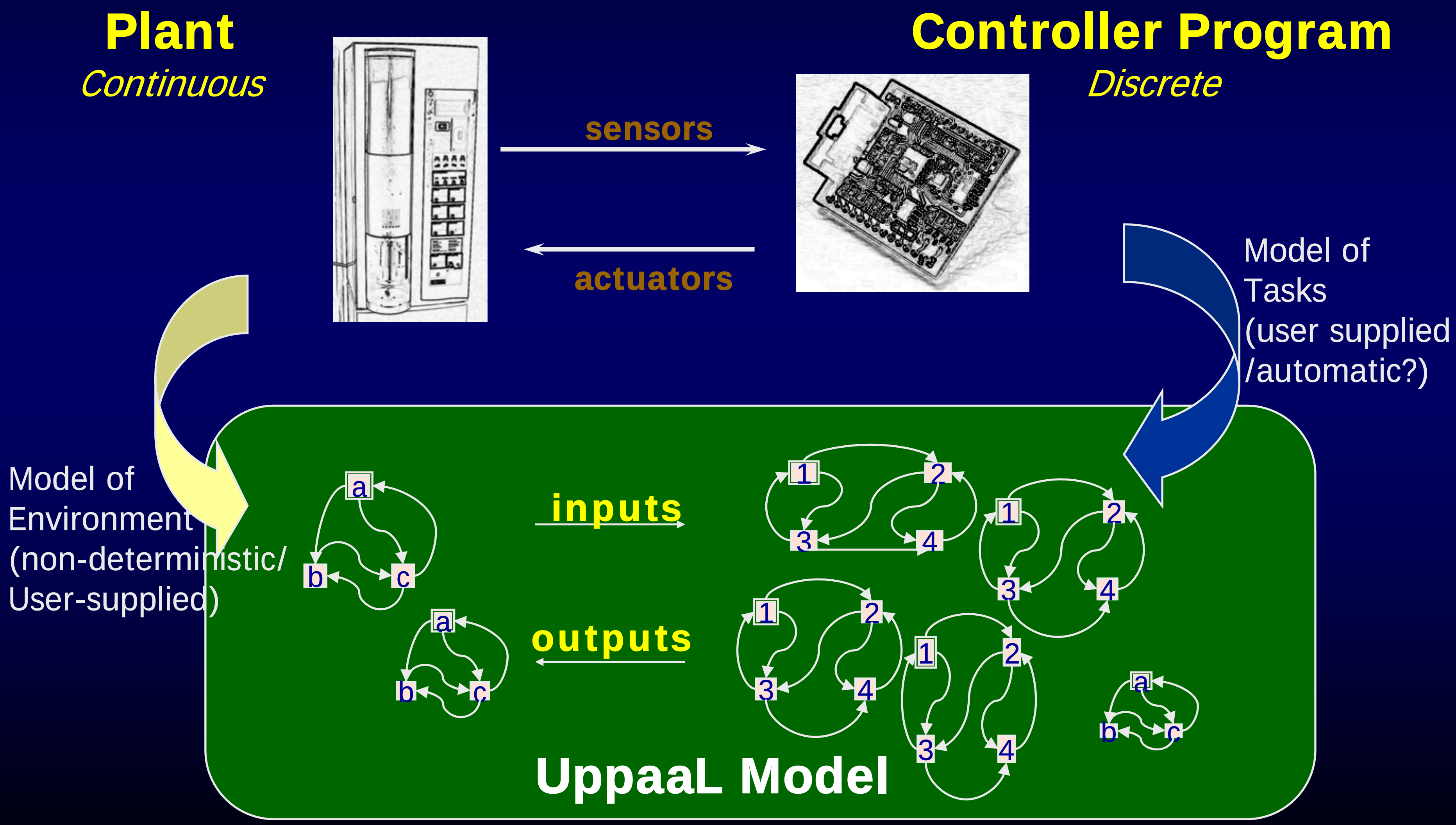
Discrete

Eg.:

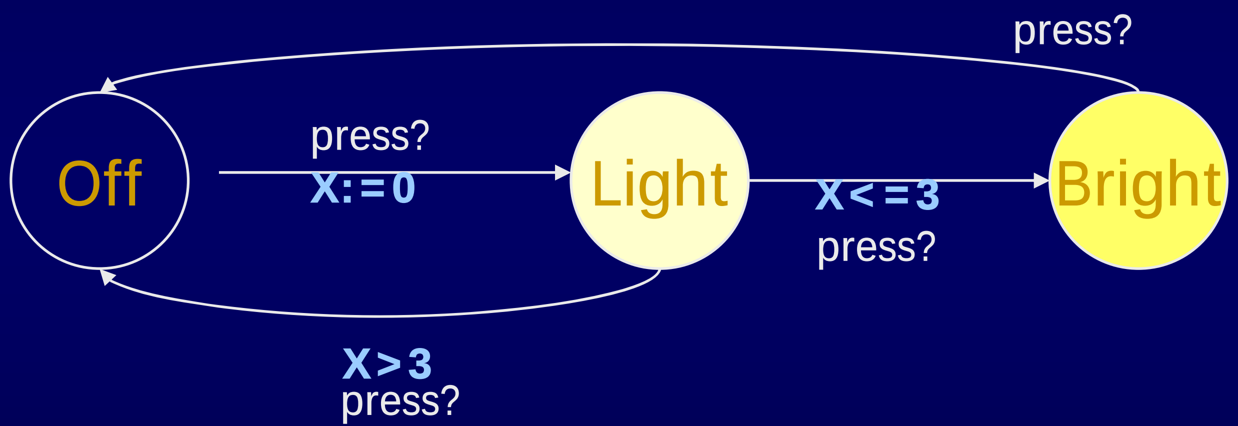
- Realtime Protocols
- Pump Control
- Air Bags
- Robots
- Cruise Control
- ABS
- CD Players
- Production Lines

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

Real-time System Modelling



An Intelligent Light Control

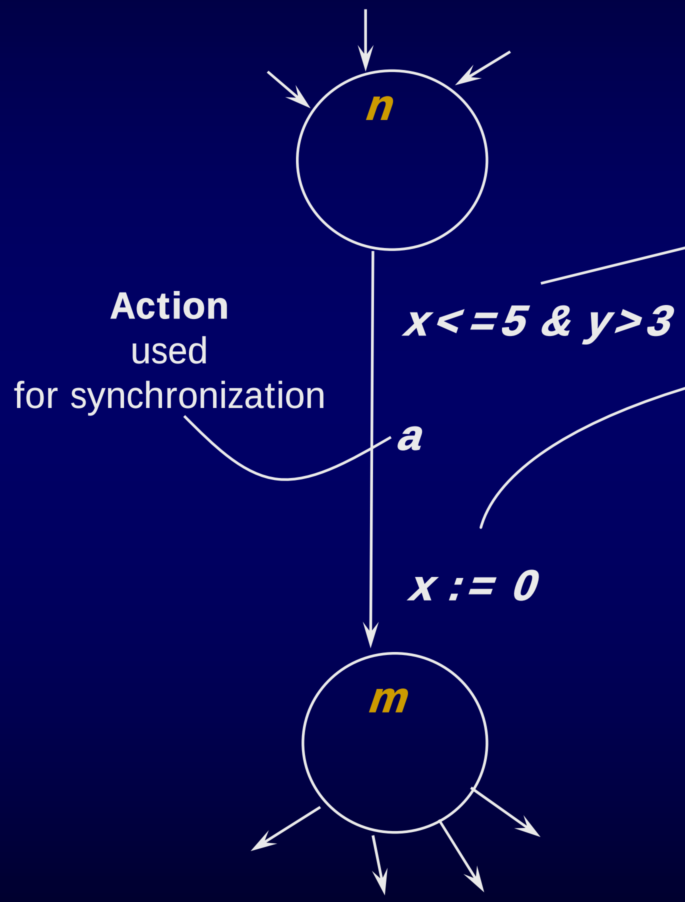


WANT: if "press" is issued twice quickly then the light will get brighter; if "press" is issued twice slowly the light is turned off.

Solution: *Add a real-type variable (a real-valued clock) x*

Timed Automata

(Alur & Dill 1990)



Clocks: ***x, y***

Guard
Boolean combination of comp with integer bounds

Reset
Action performed on clocks

State

(***location*** , ***x***=v , ***y***=u) where v,u are in $\mathbb{R}$

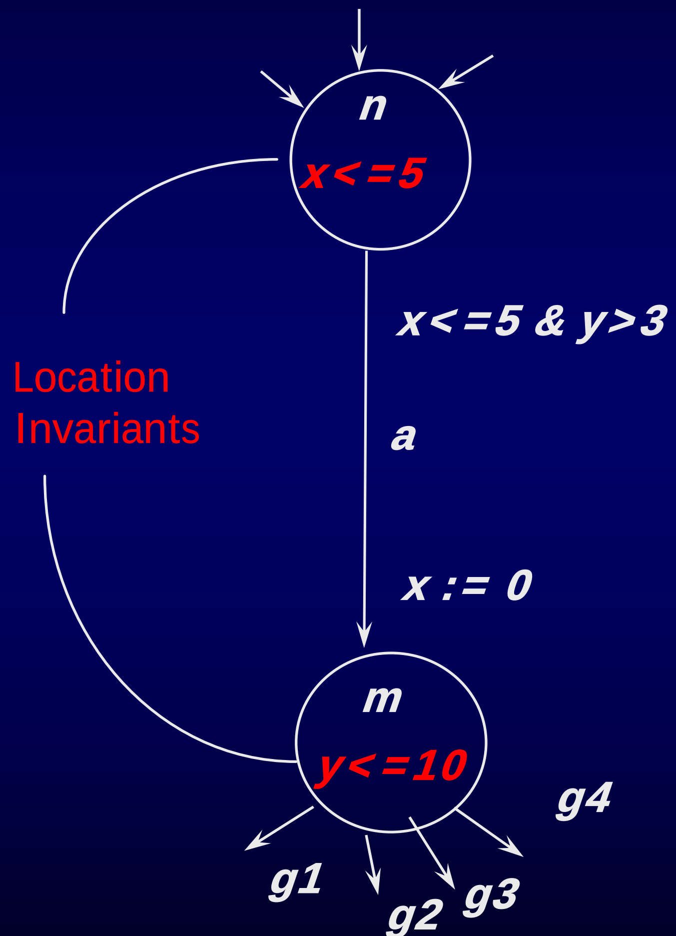
Transitions

(***n*** , ***x***=2.4 , ***y***=3.1415) $\xrightarrow{a}$ (***m*** , ***x***=0 , ***y***=3.1415)

(***n*** , ***x***=2.4 , ***y***=3.1415) $\xrightarrow{e(1.1)}$ (***n*** , ***x***=3.5 , ***y***=4.2415)

Timed Automata

location invariants



Clocks: *x, y*

Transitions

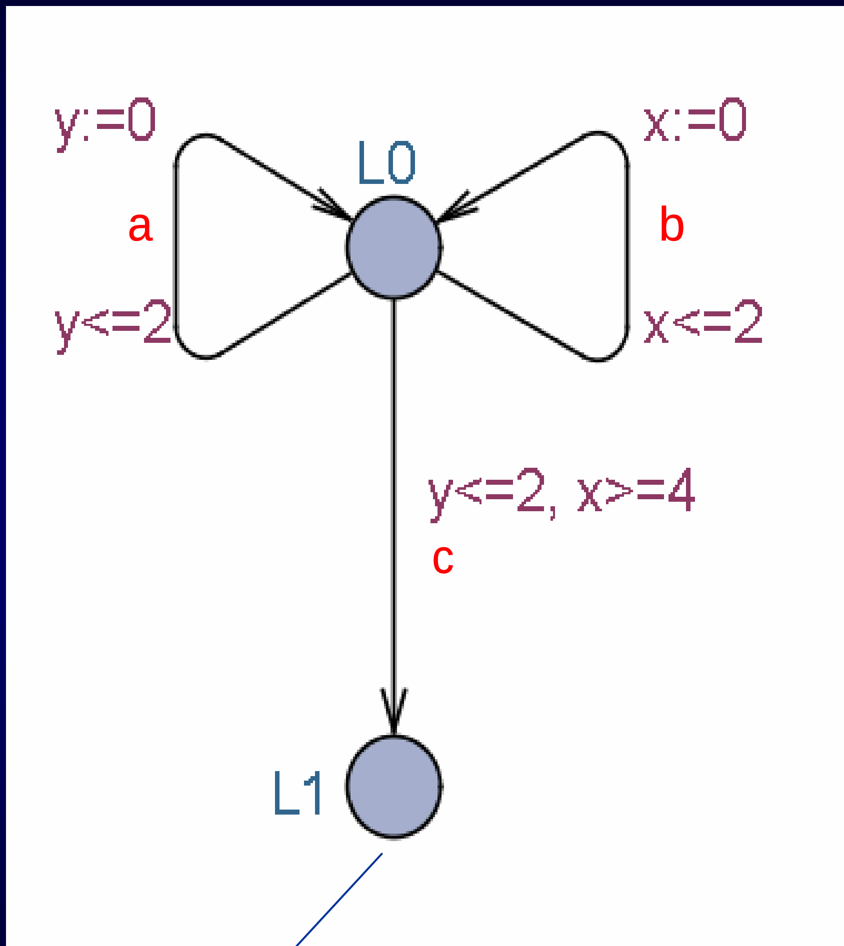
$(\, n\,,\ x=2.4\,,\ y=3.1415\,) \xrightarrow{\cancel{e(3.2)}}$

$(\, n\,,\ x=2.4\,,\ y=3.1415\,) \xrightarrow{e(1.1)} (\, n\,,\ x=3.5\,,\ y=4.2415\,)$

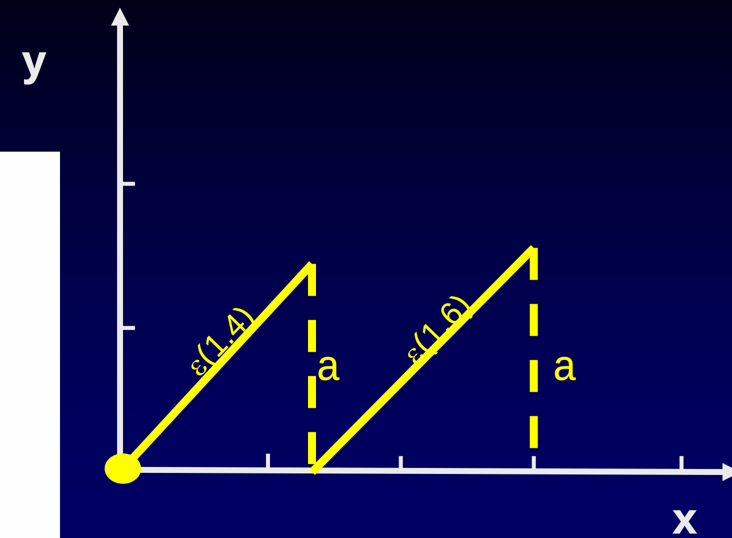
Invariants ensure progress!!

you cannot stay in this location forever;
you must leave before the deadline!

Example



Reachable?



(L0,x=0,y=0)

$\rightarrow_{\varepsilon(1.4)}$

(L0,x=1.4,y=1.4)

$\rightarrow_{a}$

(L0,x=1.4,y=0)

$\rightarrow_{\varepsilon(1.6)}$

(L0,x=3.0,y=1.6)

$\rightarrow_{a}$

(L0,x=3.0,y=0)

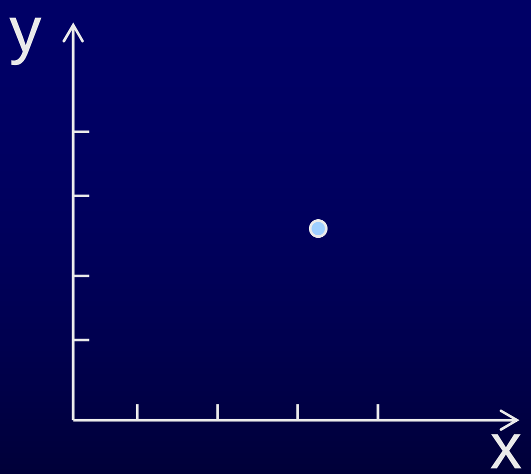
Zones

from infinite to finite

a bunch of concrete states

a state

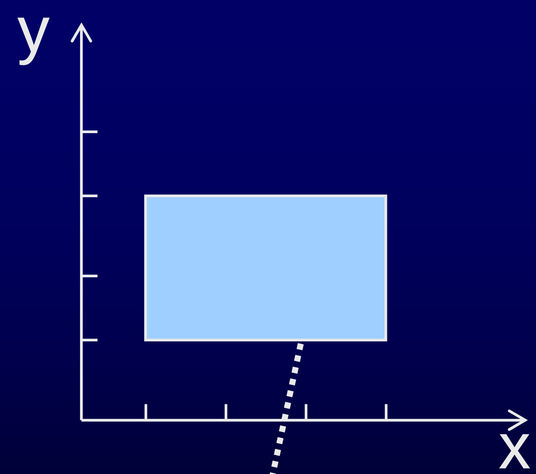
(n, x=3.2, y=2.5)



a symbolic state (set)

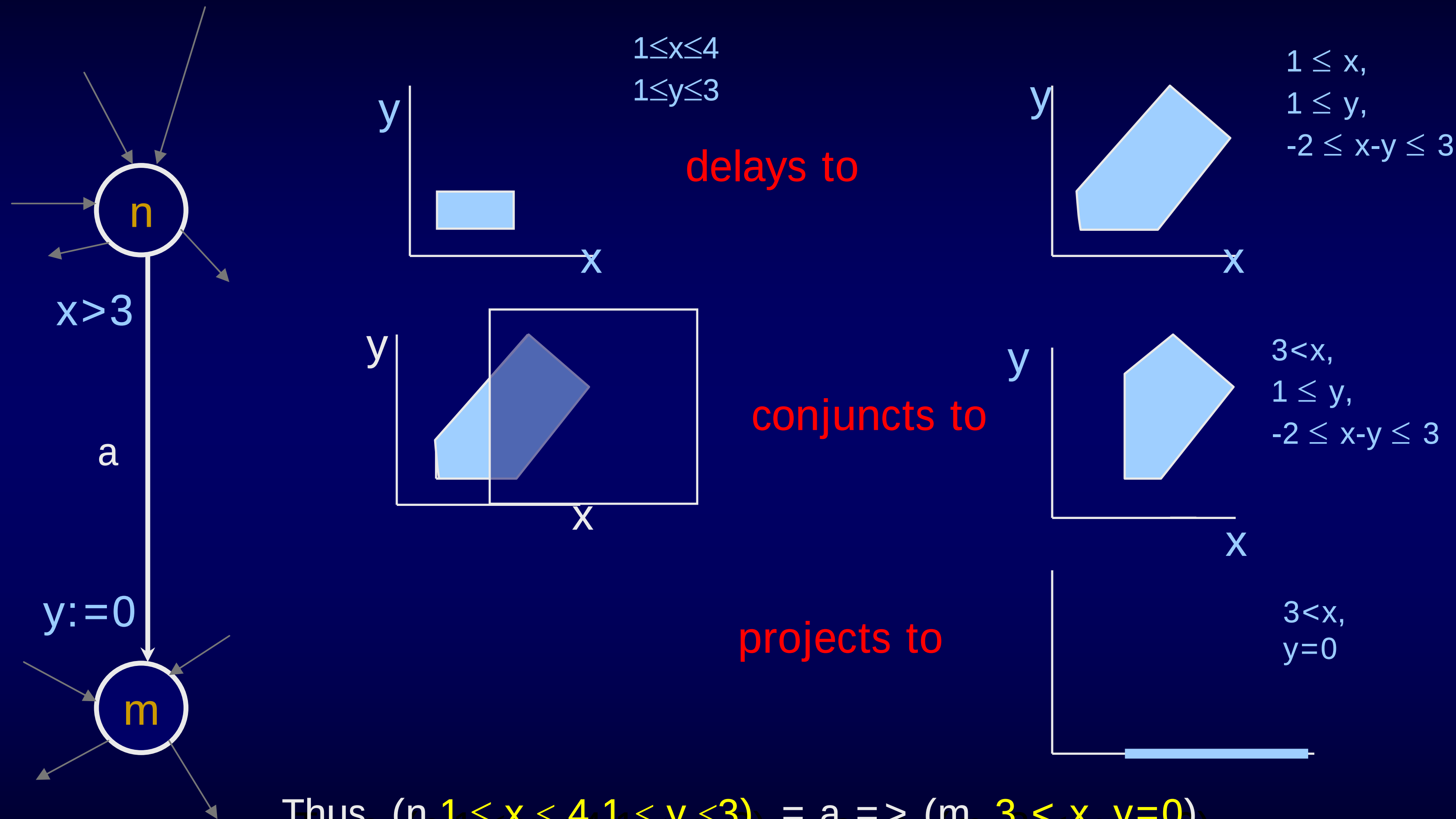
(n, $1 \le x \le 4$, $1 \le y \le 3$)

Zone:
conjunction of
x-y<=n, x<=>n



this is a time zone

Symbolic Transition



Thus (n, $1 \le x \le 4, 1 \le y \le 3$) = a => (m, $3 < x$, $y=0$)

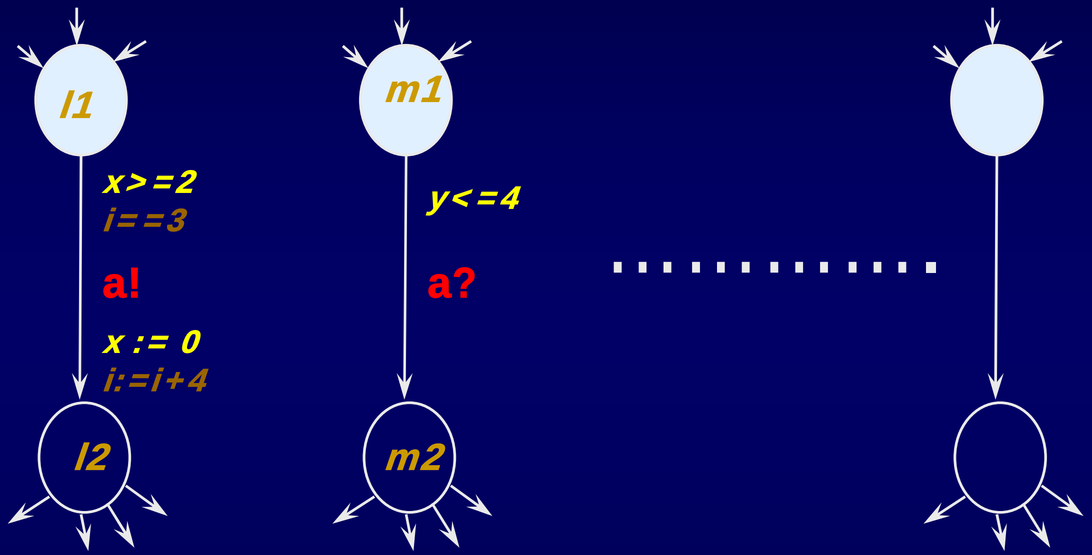
Finite symbolic simulation graph and reachable states can be computed

this is a symbolic transition (a bunch of concrete transitions)

ModellingTimed Systems using Uppaal

The Uppaal Model

= Networks of Timed Automata + Integer Variables +....



Two-way synchronization on *complementary* actions.

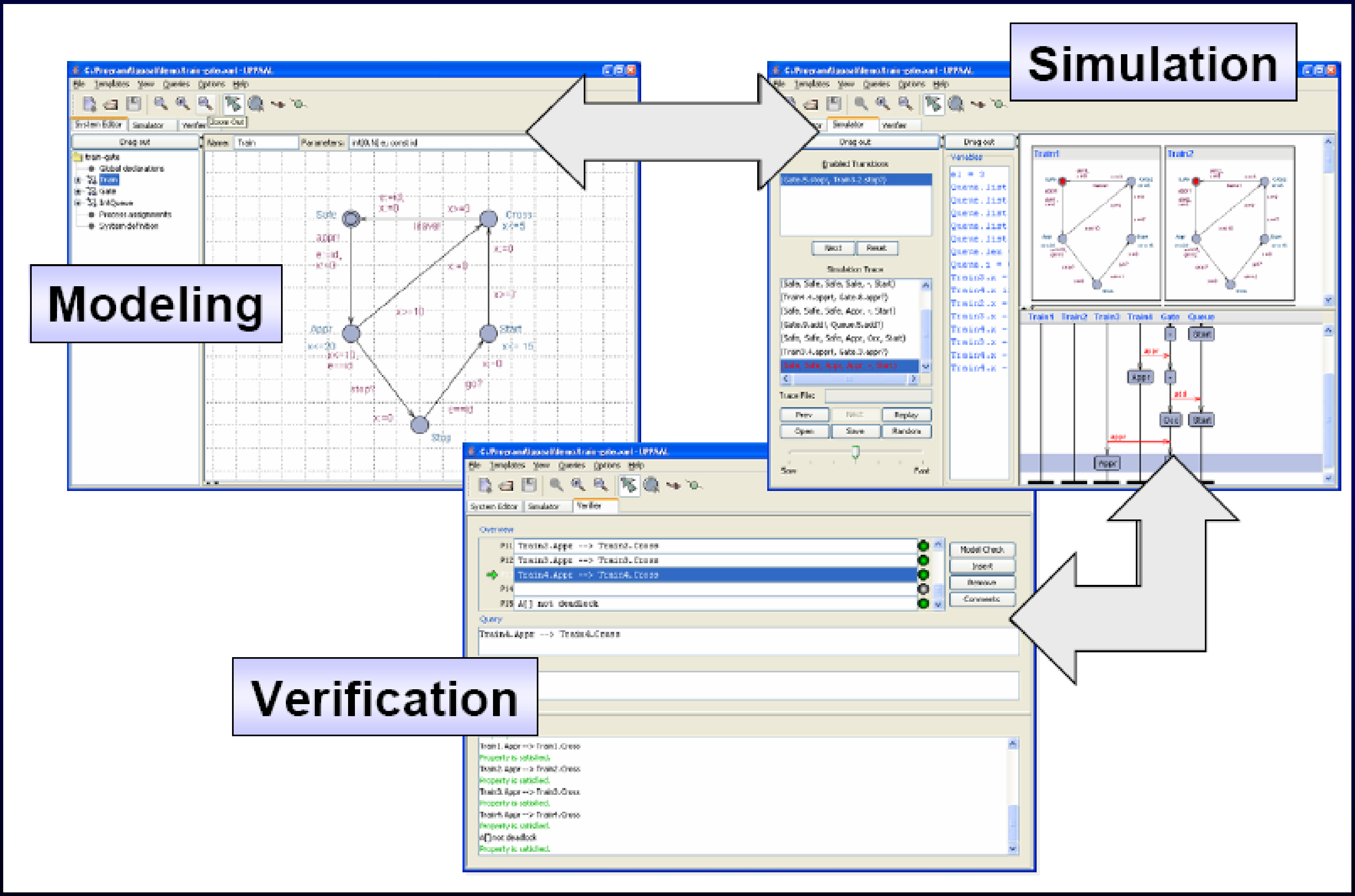
Closed Systems!

Example transitions

(***l1***, ***m1***,........, *x=2, y=3.5, i=3,.....*) $\xrightarrow{\text{tau}}$ (***l2,m2***,........,*x=0, y=3.5, i=7,.....*)

$\xrightarrow{0.2}$ (***l1,m1***,........,*x=2.2, y=3.7, i=3,.....*)

Modelling using Uppaal …



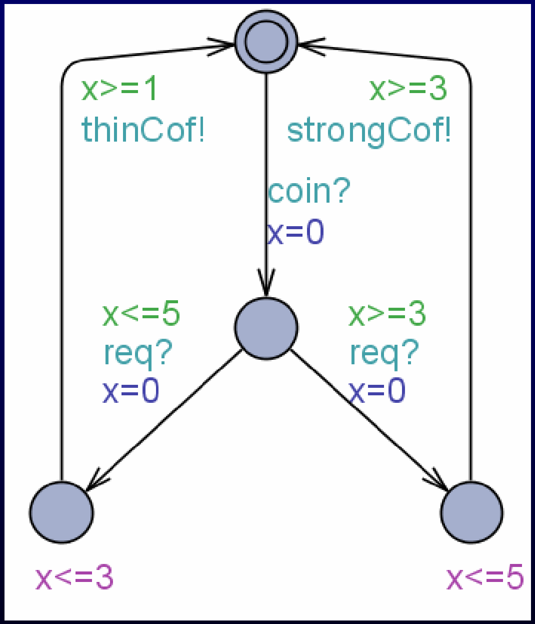
Timed Automaton of Coffee Machine

coin?

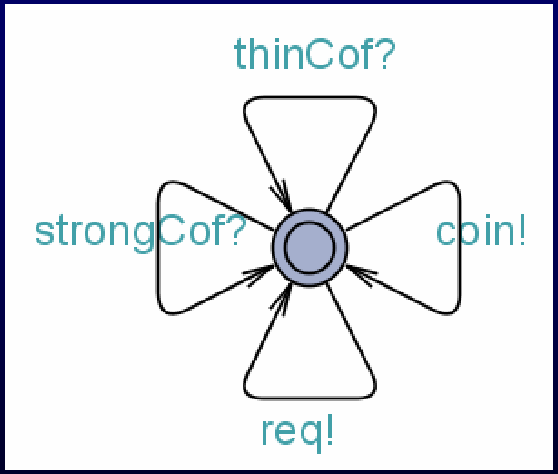
request?

thinCof!

strongCof!

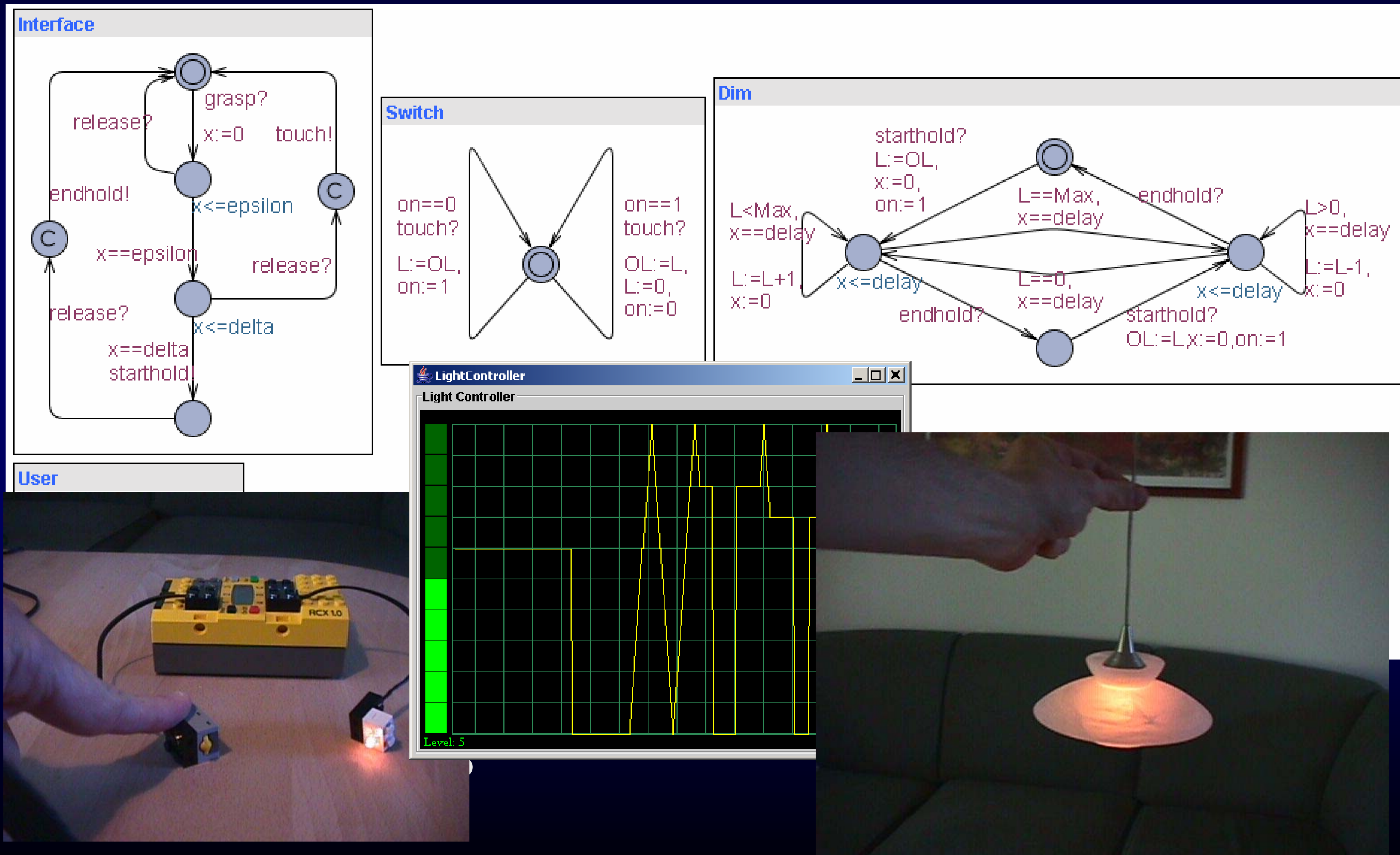


Machine Model



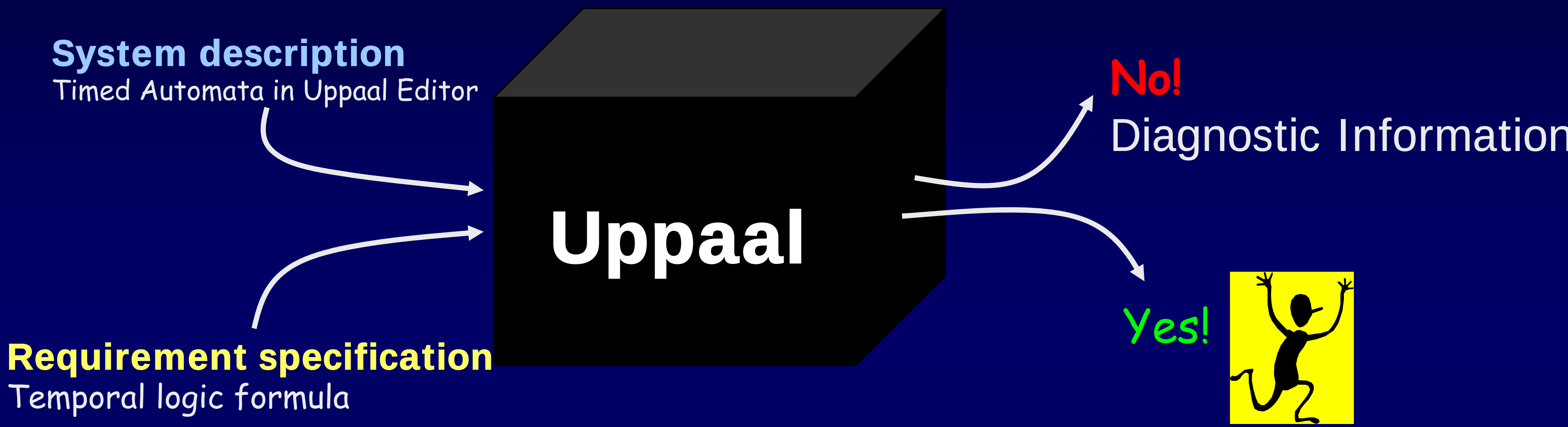
Possible users-model

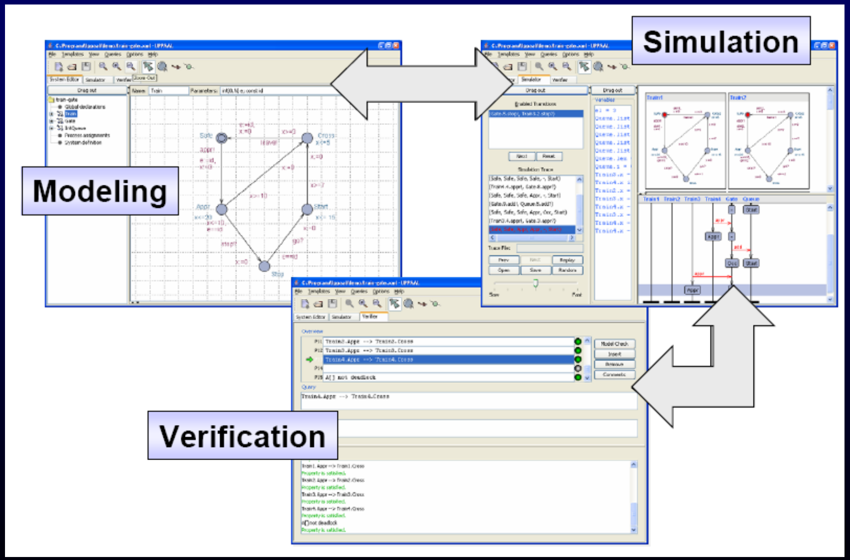
Touch Sensative Light Controller



Verification using Uppaal

Uppaal as a box…





What does Verification do

- Compute *all* possible execution sequences
- And consequently to examine *all* states of the system
- *Exhaustive search => proof*
- Check if
  - every state encountered does not have the undesired property --> safety property
  - some state encountered has the desired property --> reachability property

Properties

- ***Safety***
  - Nothing bad happens during execution
  - System never enters a bad state
    - Eg. mutual exclusion on shared resource
- ***Liveness***

  diffent from reachability property

  - Something good eventually happens
  - Eventually reaching a desired state
    - Eg. a process' request for a shared resource is eventually granted

UPPAAL Property Specification Language

- **A[] p**
- **A<> p**
- **E<> p**
- **E[] p**
- **P --> q**

process location

data guards

clock guards

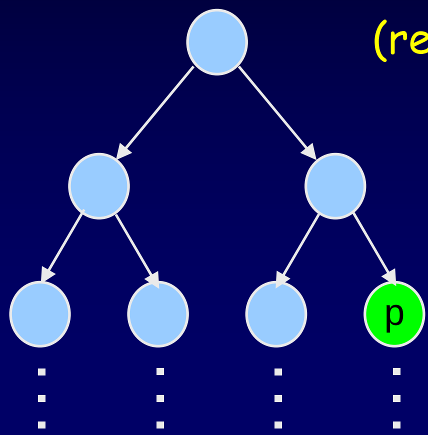
“p leads to p”:
A[ ] (p imply A< > q)

p::= a.l | g_d | g_c | p and p |
p or p | not p | p imply p |
(p) | deadlock(only for A[],E<>)

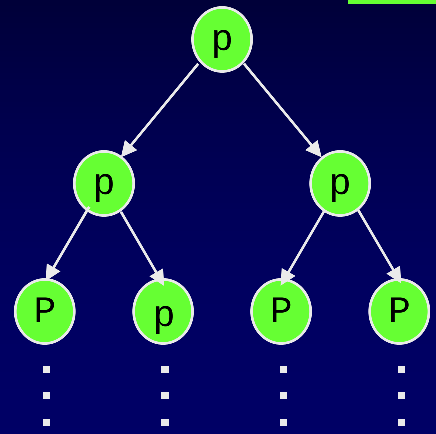
`A[] (mc1.finished and mc2.finished) imply (accountA+accountB==200)`

Uppaal "Computation Tree Logic"

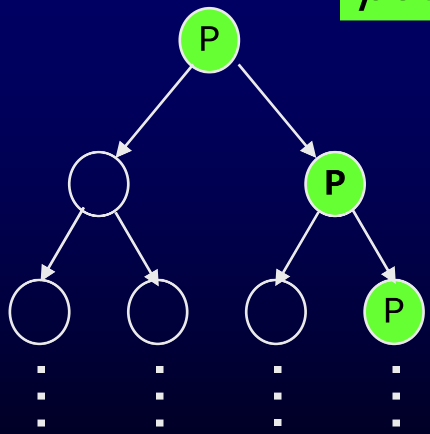
`E<> p` *Possible* (reachability)



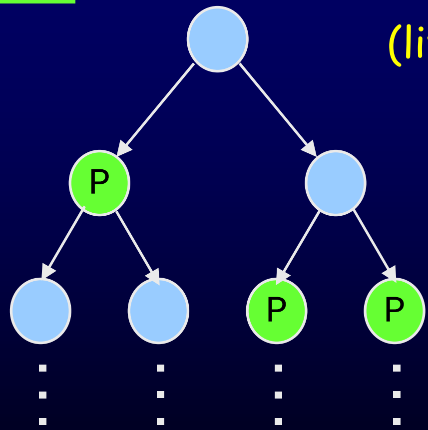
`A[] p` *always* (safety)



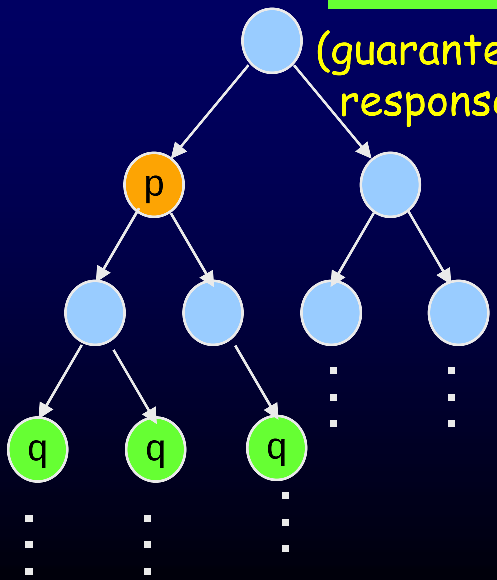
`E[] p` *potentially always*



`A<> p` *inevitable* (liveness)

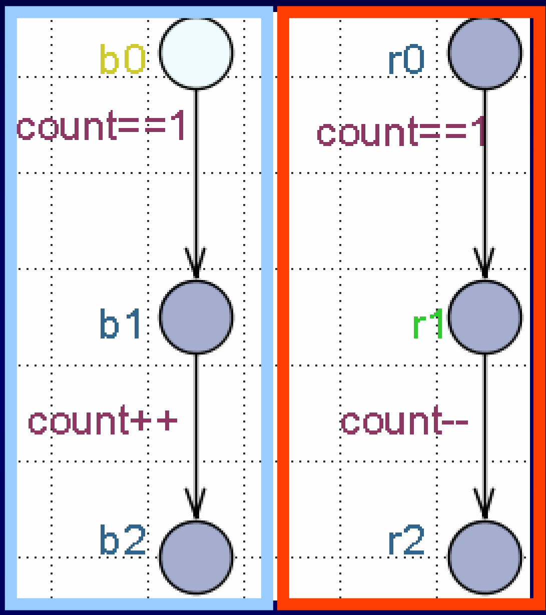


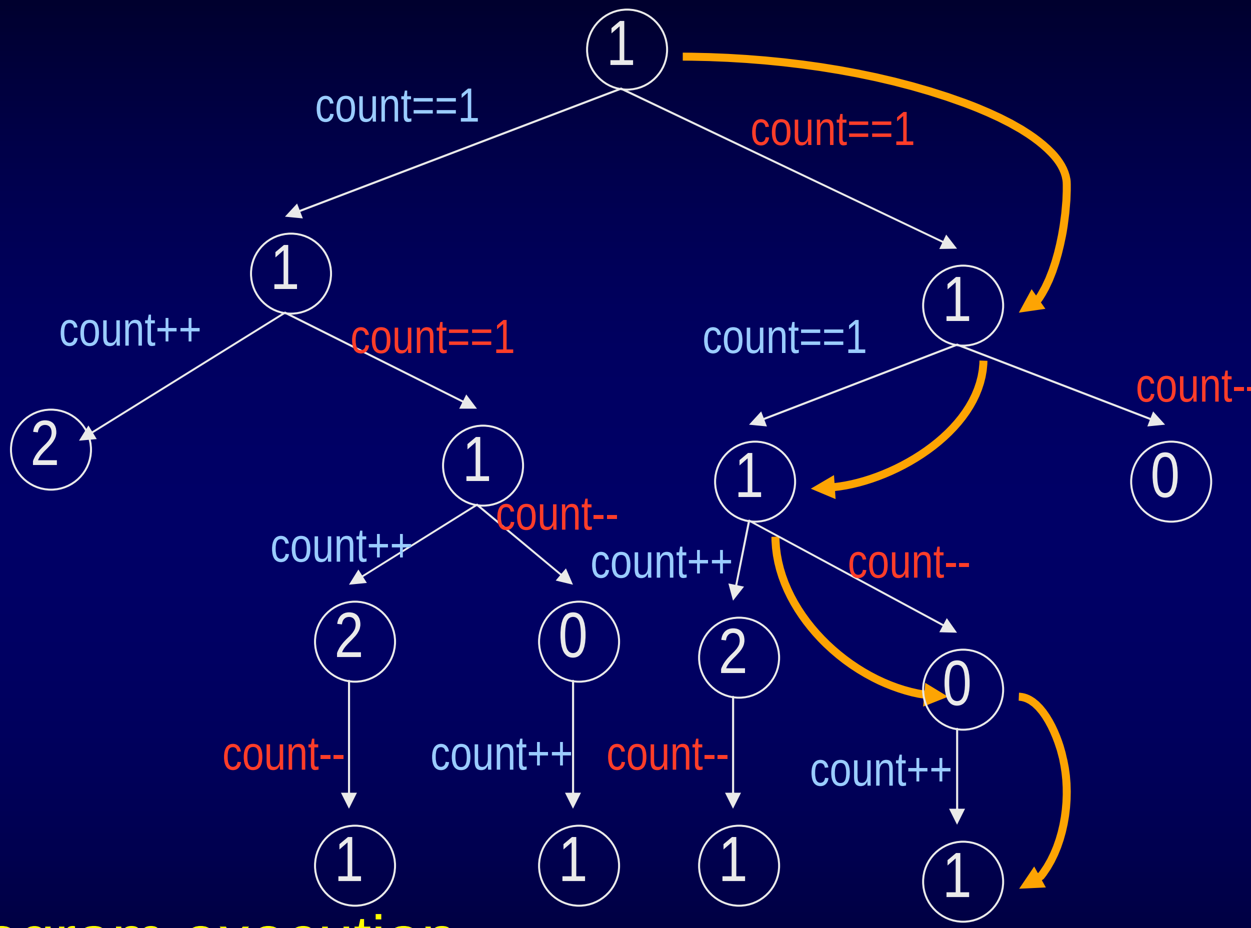
`p --> q` *leads-to* (guaranteed response)



State Space Exploration

`Int count:=1`

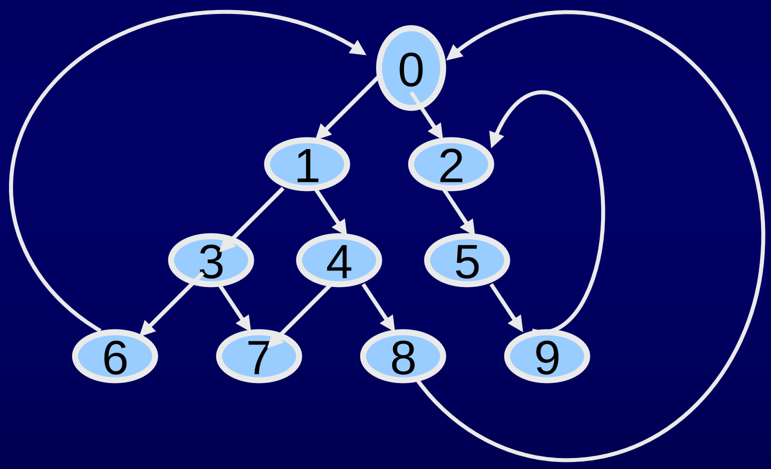




- Each trace = a program execution
- Uppaal checks *all* traces
  - Is count *possibly* 3 ? `E<> count==3`
  - Is count *always* 1 ? `A[] count==1`

Reachability Analysis

```
Passed:=Ø           //already seen states
waiting:={S_0}      //states not examined yet
While(waiting!=Ø) {
  waiting:=waiting\{s_i}
  if s_i ∉ Passed
     whenever (s_j → s_j) then
        waiting:=waiting ∪ s_j
  }
```



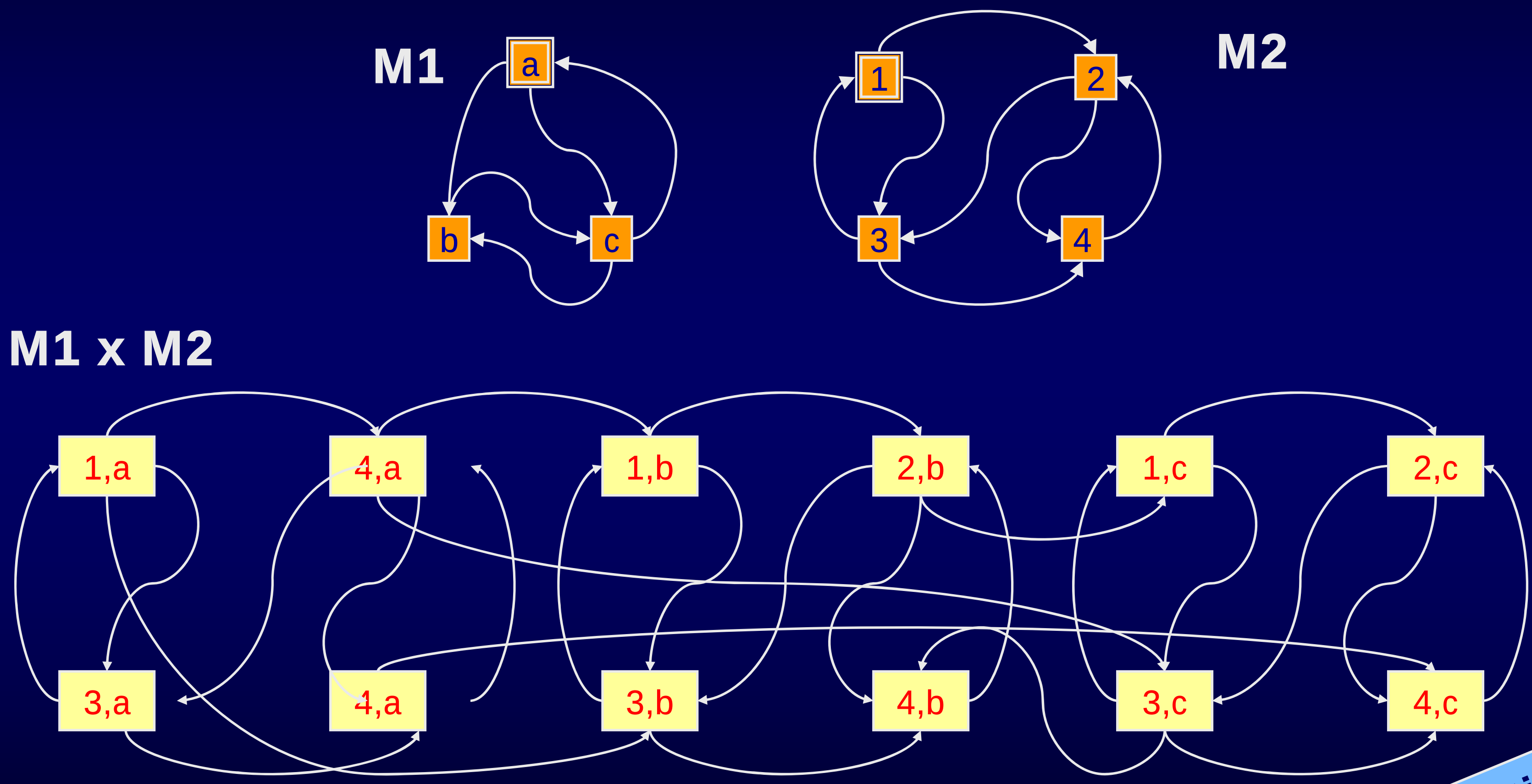
Depth-First: maintain waiting as a stack

Order: 0 1 3 6 7 4 8 2 5 9

Breadth-First: maintain waiting as a queue
(shortest counter example)

Order: 0 1 2 3 4 5 6 7 8 9

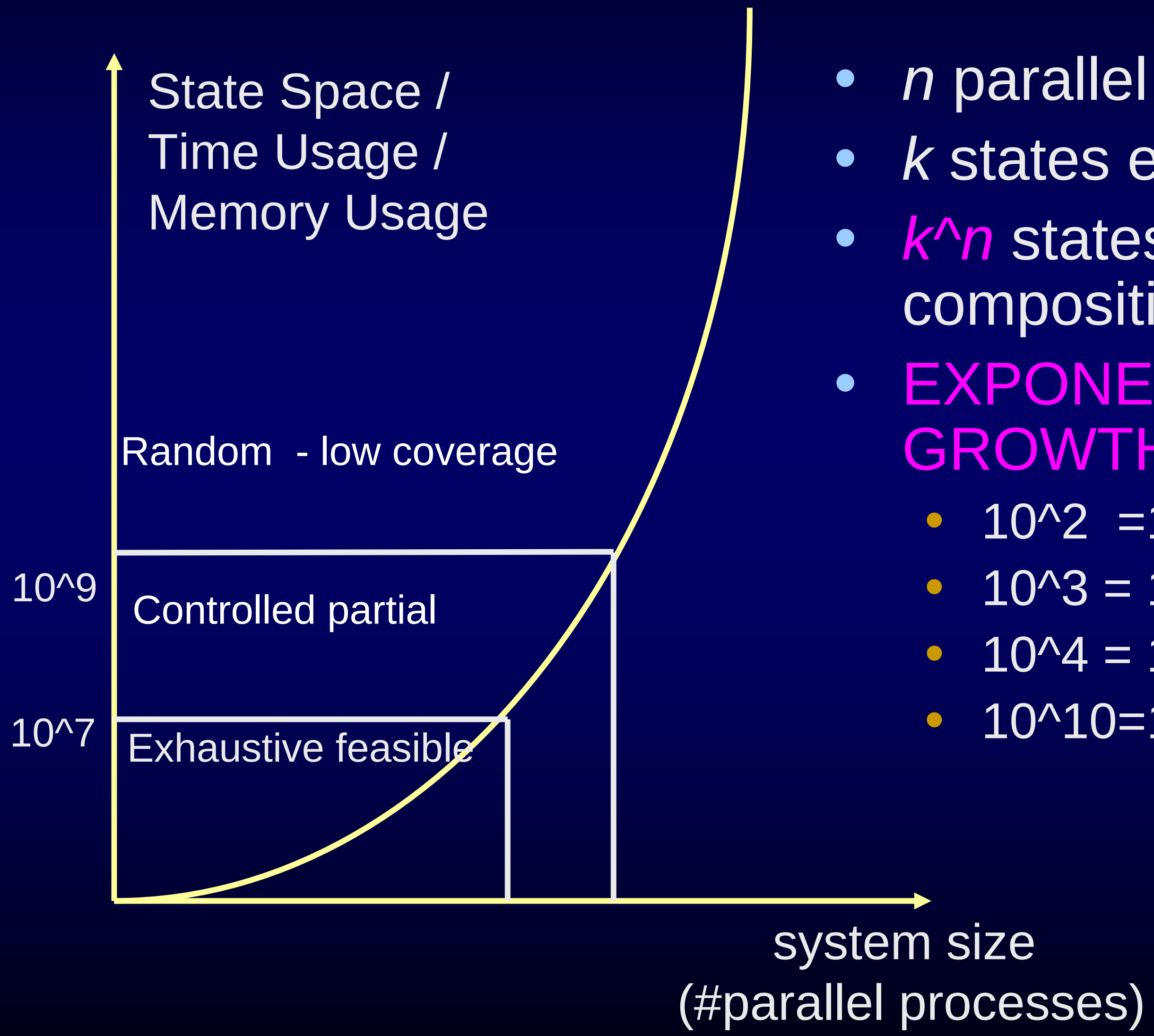
'State Explosion' problem



All combinations = exponential in no. of components

Provably theoretical intractable

Limitations to Reachability Analysis



- *n* parallel FSMs
- *k* states each
- *k^n* states in parallel composition
- EXPONENTIAL GROWTH
  - 10^2 =100
  - 10^3 = 1000
  - 10^4 = 10000
  - 10^10=10000000000

What Influences System Size?

- Number of parallel processes
- Amount of non-determinism
- Queue sizes
- Range of discrete data values
- Environment assumptions
  - Speed
  - Kinds of messages that can be sent in what states
  - Data values

Counter Measures

- Use abstraction, simplification
  - Only model the aspects relevant for the property in question
- Economize with (loosely synch'ed) parallel processes
- Make precise assumptions and restrictions
- Range of data values
  - Use *bounded* data values: integer (0:4);
  - *Reset variables* to initial value whenever possible
  - Avoid complex data structures
- Partial (controlled) search heuristics
  - Bit-State hashing
  - Limit search depth
  - Restrict scheduling
    - Priority to internal transitions over env input
    - Schedule process in FIFO style rathar than ALL interleavings

Does verification guarantee correctness?

- Only models verified, not (physical) implementations
- Made the right model?
- Properties correctly formulated?
- The right properties?
- Enough properties?
- System size too large for exhaustive check

- Modelling effort itself revealing
- Increased confidence earlier
- Cheaper
- Even partial and random search increases confidence

Next lecture
- Model-Based Testing!