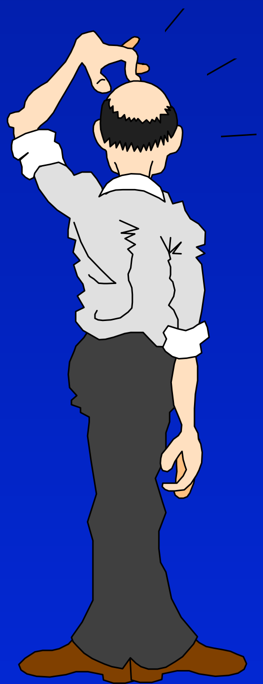
Model-based design and analysis of concurrent and adaptive software



Jeff Kramer

Imperial College London

Microsoft Research Summer School, 2012

Engineering distributed software?

- **Structure**

  Programming-in-the-small Vs Programming-in-the-large

  deRemer and Kron, TSE 1975

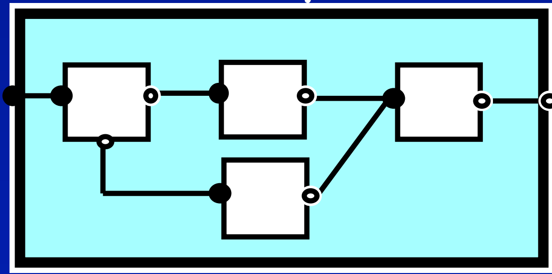
- **Composition**

  "Having divided to conquer, we must reunite to rule"

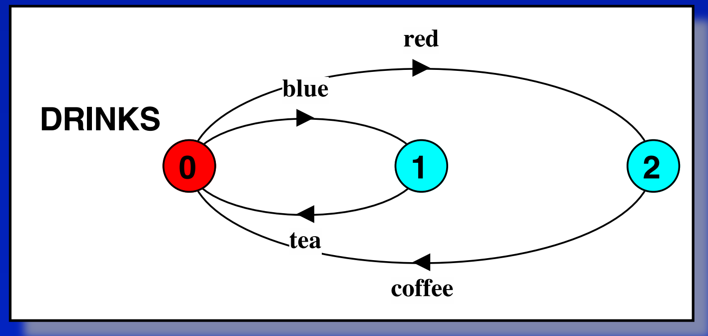
  Jackson, CompEuro 1990

How? our approach is …. **Model Based Design**

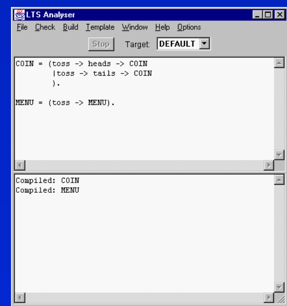
- integrate modelling into the software lifecycle:
  - Software Architectures of components, translatable to models



- Relatively easy to learn and use:
  - State Machines in form of LTS (Labelled Transition Systems)



- Lightweight Tool support:
  - Model Checking in form of CRA (Compositional Reachability Analysis) with animation



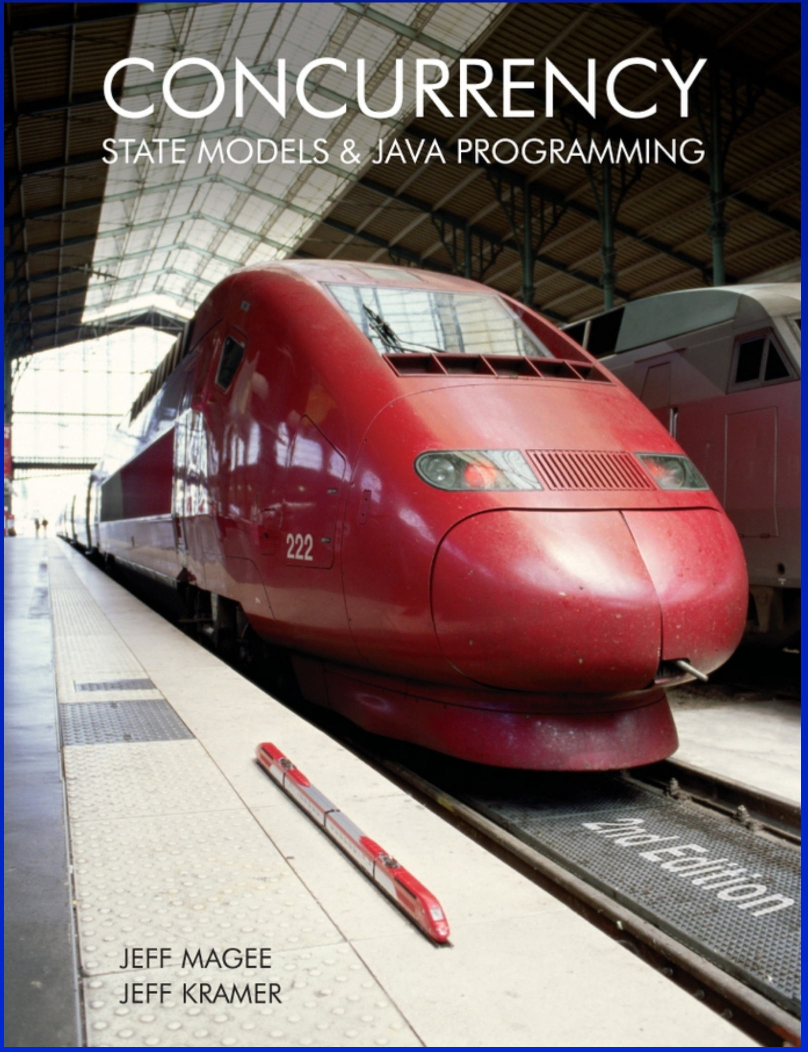
Background: Book

Concurrency: State Models & Java Programs

Jeff Magee & Jeff Kramer

WILEY

2006 (2nd edition)

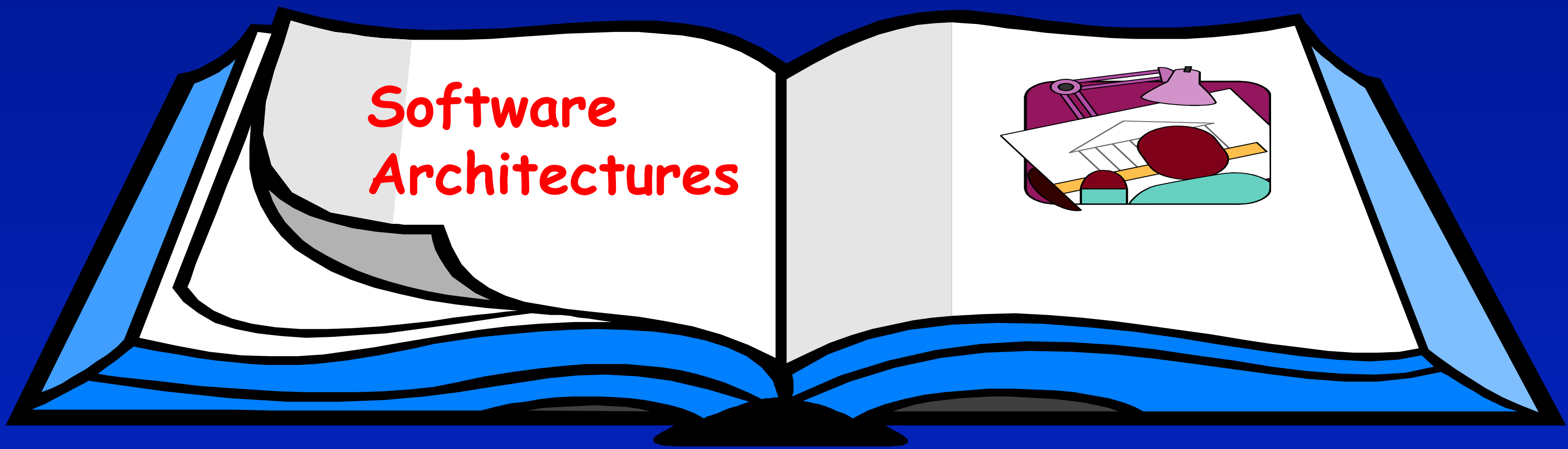


Background: Web based course material

http://www.doc.ic.ac.uk/~jnm/book/

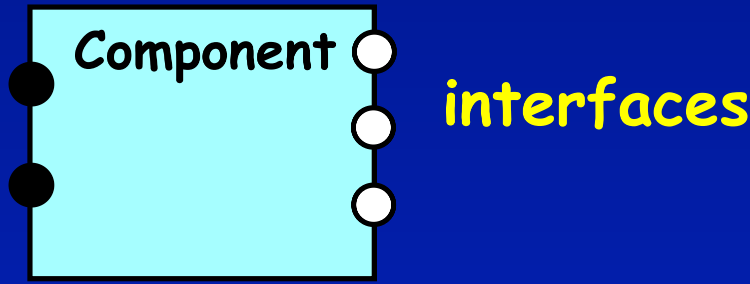
- Java examples and demonstration programs
- State models for the examples
- Labelled Transition System Analyser (***LTSA***) for modelling concurrency, model animation and model property checking.

Chapter 1. Context and experience

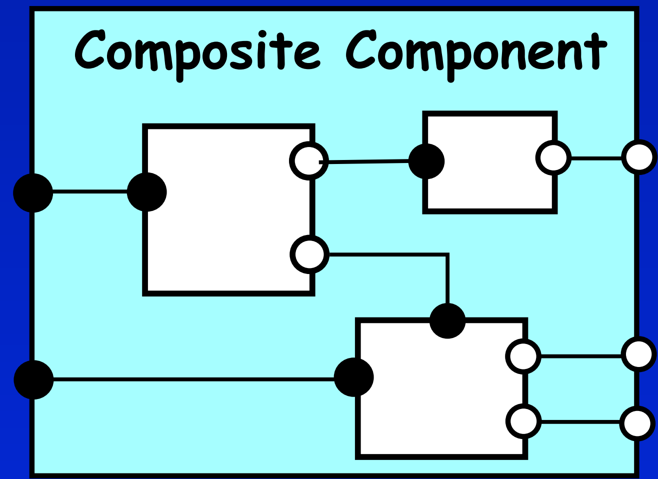


structural view - Darwin ADL (Architecture Description Language)

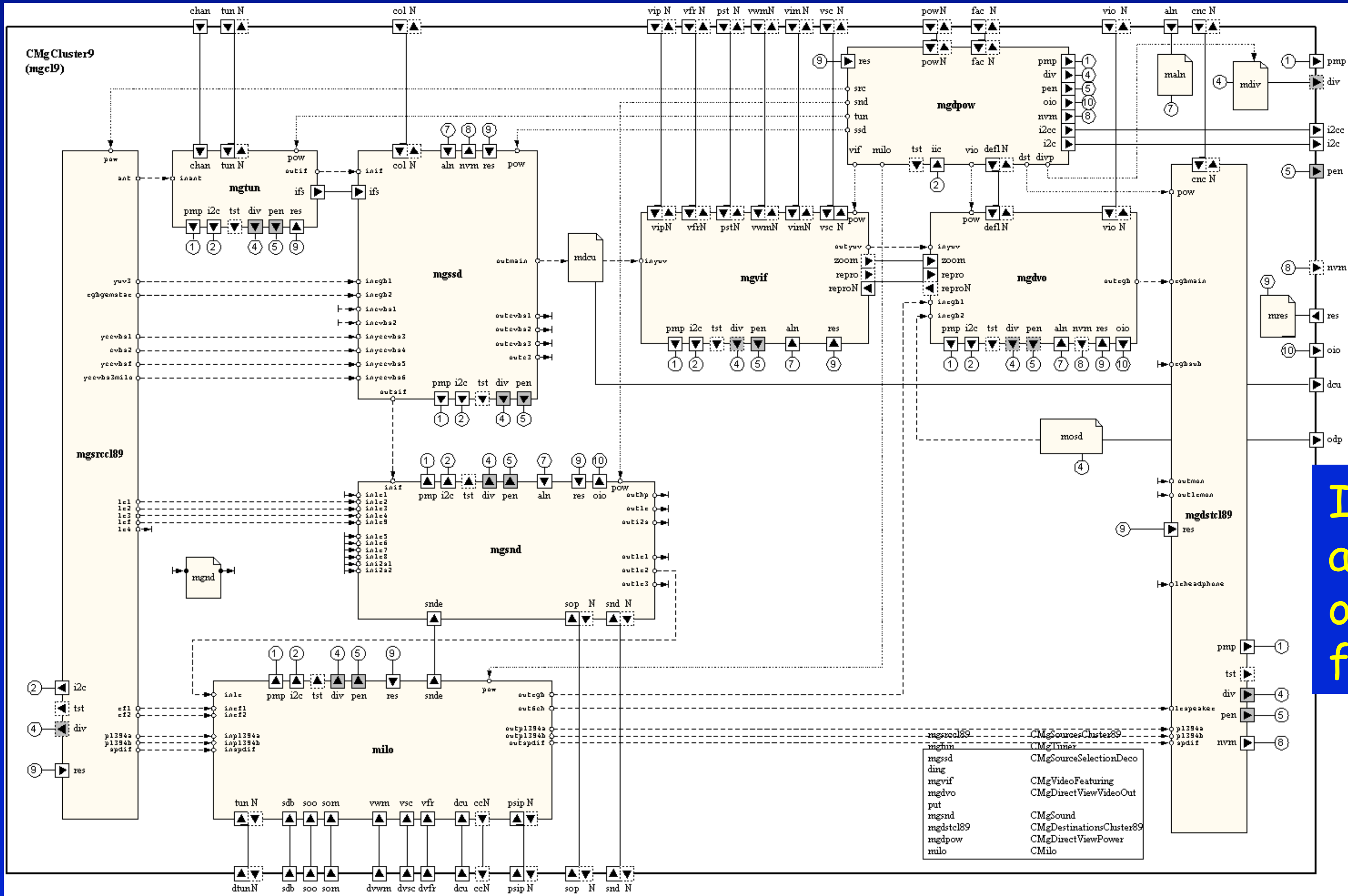
- Component types have one or more interfaces. An interface is simply a set of names referring to actions in a specification or services in an implementation, **provided** ● or **required** ○ by the component.



- Systems / composite components are **composed** hierarchically by component **instantiation** and interface **binding**.



construction view - **Koala** ADL for consumer electronics



Interfaces are sets of C functions

... based on ***Darwin***, *in use by Philips for product families* (IEEE Computer 2000)

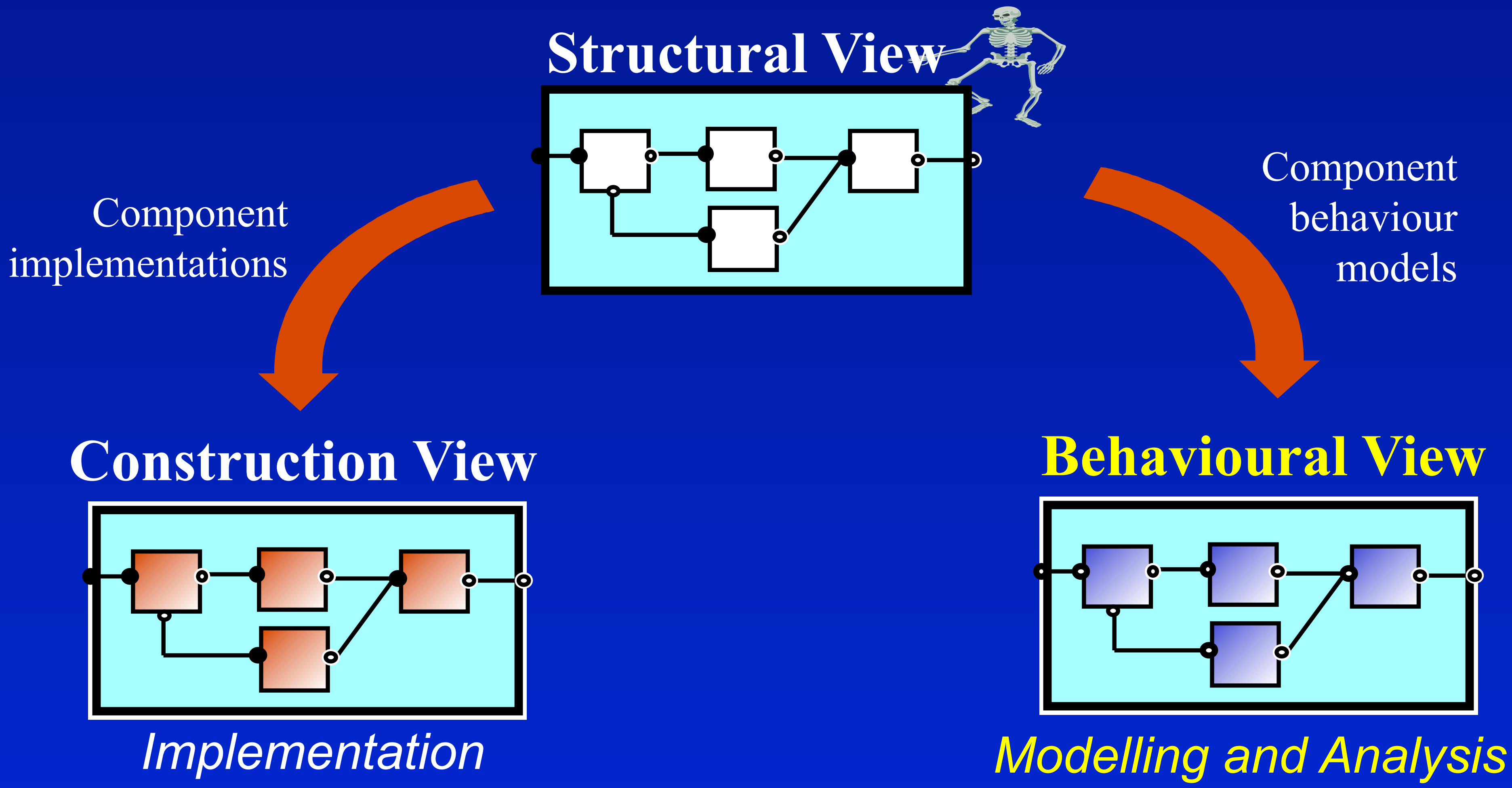
Koala experience

- "It turns out to be very simple to make different configurations. We are profiting from the composability in that it is very easy to create small environments in which to test parts of the software."

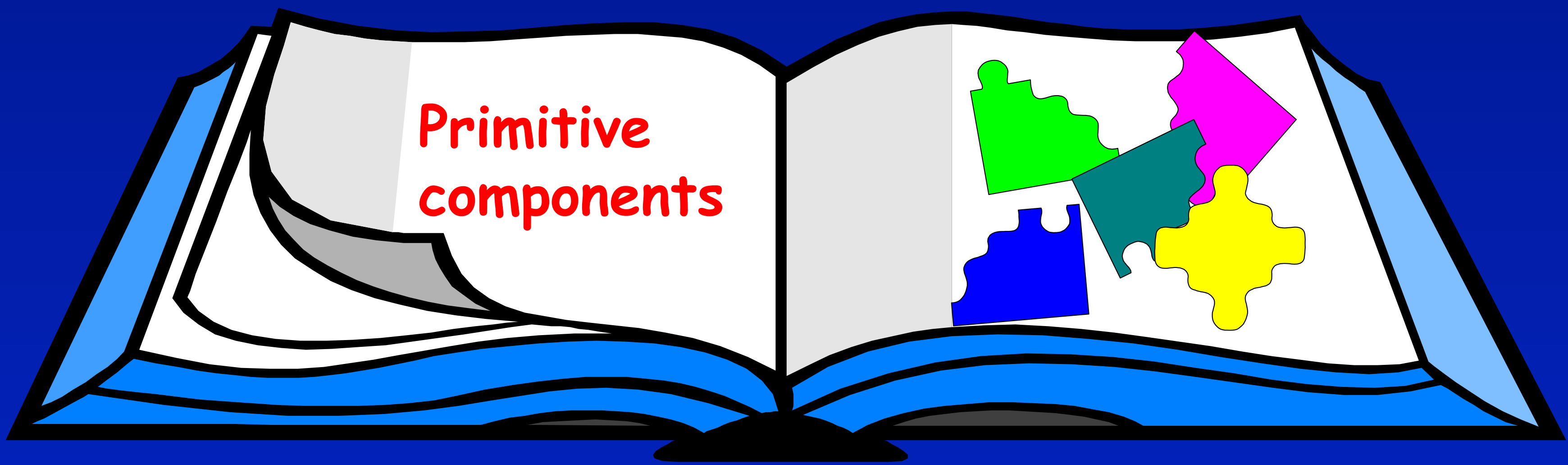
- The individual processes are really quite simple state machines. **What we really need is a way to compose these state machines, and perform some sort of analysis on the composition...**"

Rob van Ommering
Philips Research Eindhoven

Architectural description - multiple views



Chapter 2. Modelling processes



processes and threads

Concepts: component processes
- units of sequential execution.

Models: finite state processes (FSP)
to model processes as sequences of actions.
labelled transition systems (LTS)
to analyse, display and animate behavior.

Practice: Java threads

FSP – finite state processes

Component/Process:

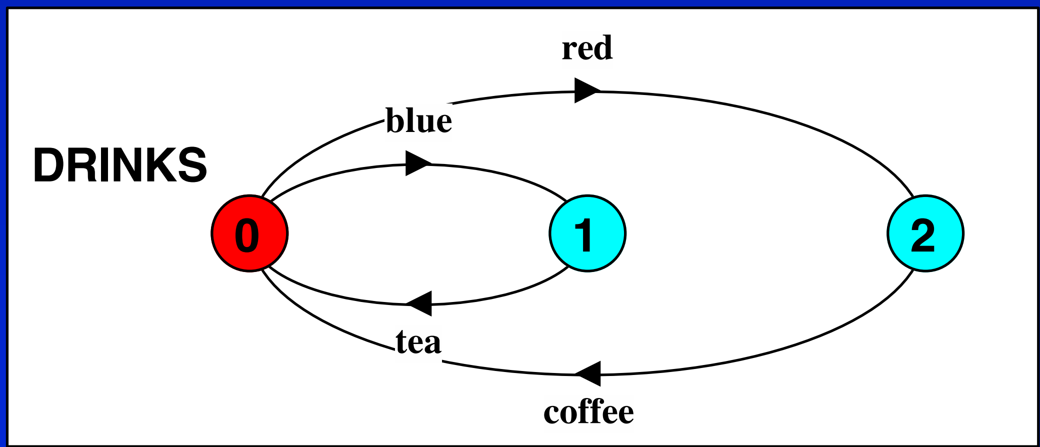
component DRINKS {
provides red; blue;
requires tea; coffee;
}

FSP to model behaviour of the drinks machine :

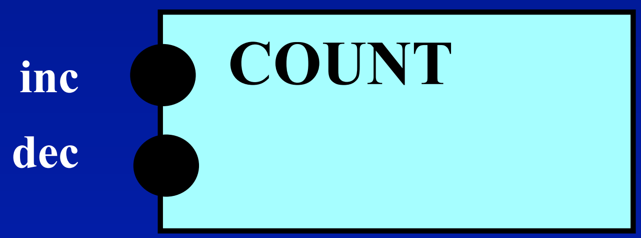
```
DRINKS = ( red->coffee->DRINKS
         | blue->tea->DRINKS
         ).
```

-> action prefix
| choice
recursion

LTS :



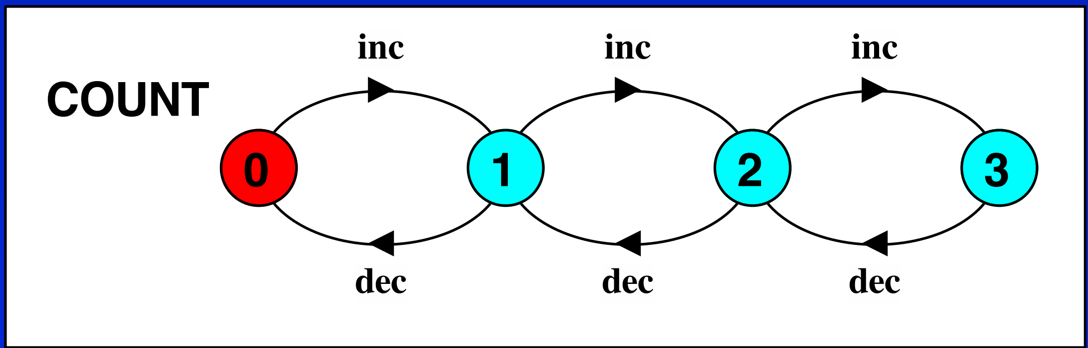
FSP - guarded actions



component COUNT {
provides inc; dec;
}

```
COUNT (N=3)    = COUNT[0],
COUNT[i:0..N] = ( when(i<N) inc->COUNT[i+1]
                | when(i>0) dec->COUNT[i-1]
                ).
```

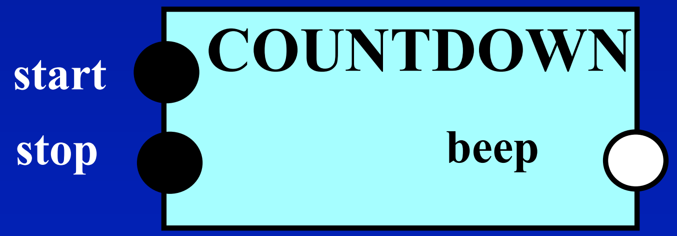
when guarded choice
process parameter
Process labelling



A countdown timer

A countdown timer which beeps after N ticks, or can be stopped.

Java Demo



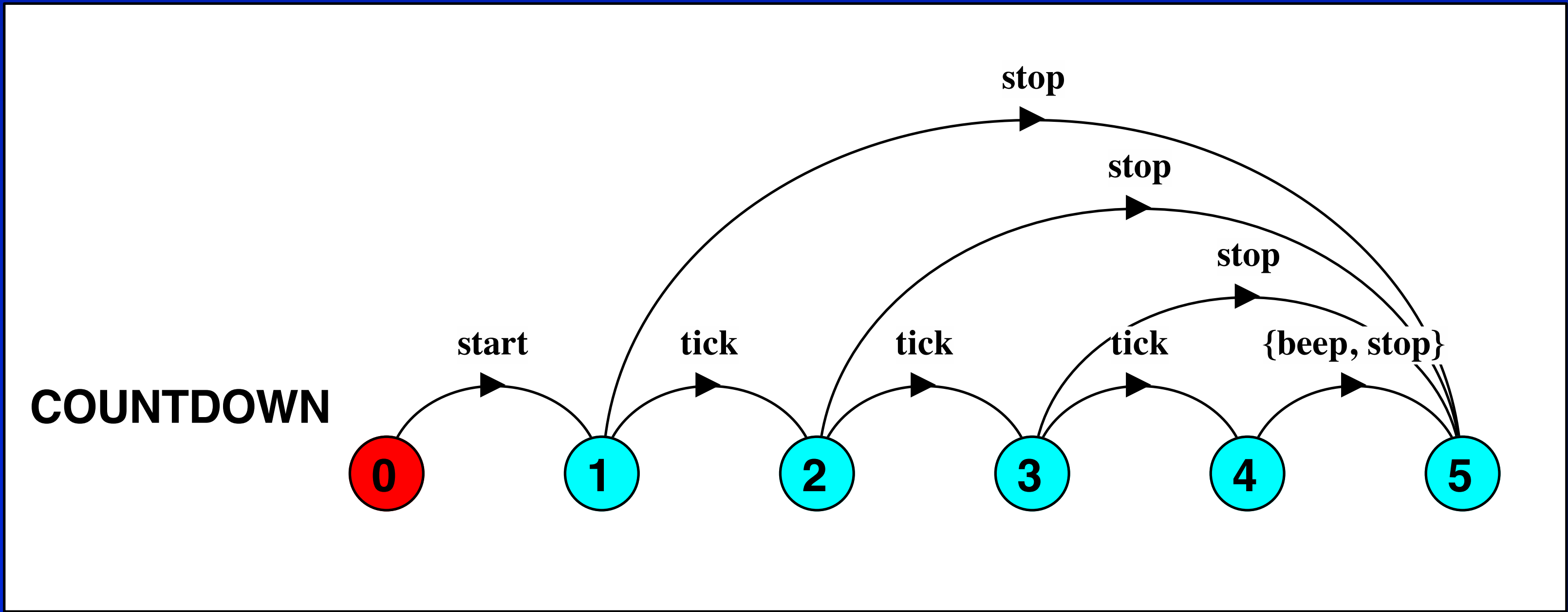
component COUNTDOWN {
    provides start; stop;
    requires beep;
}

FSP?

LTS?

A countdown timer

```
COUNTDOWN (N=3)   = (start->COUNTDOWN[N]),
COUNTDOWN[i:0..N] =
        ( when(i>0) tick->COUNTDOWN[i-1]
        | when(i==0)beep->STOP
         | stop->STOP
        ).
```



component PERSON - behaviour

component PERSON {
    requires enter; exit;
}

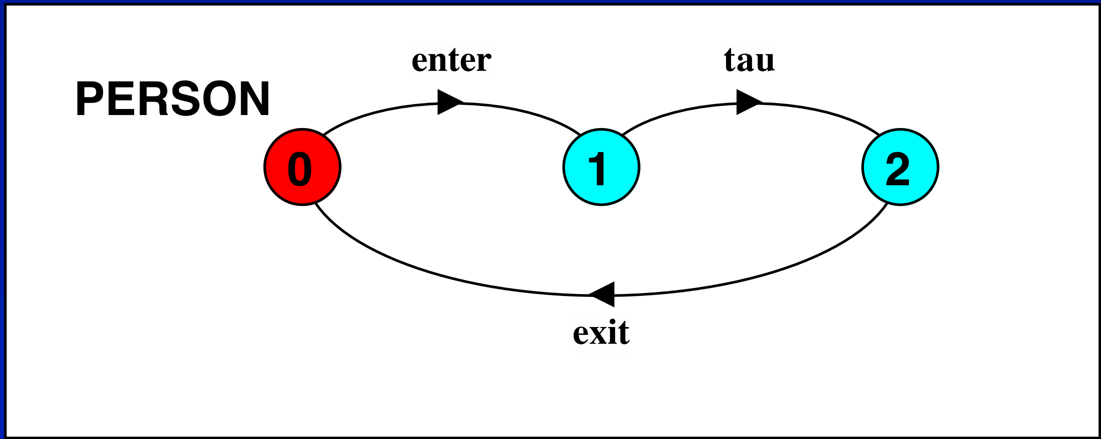
```
PERSON = ( enter -> bathe -> exit -> PERSON
         ) @{enter,exit}.
```

@ interface

Actions {enter,exit} are exposed,
***bathe** is hidden.*

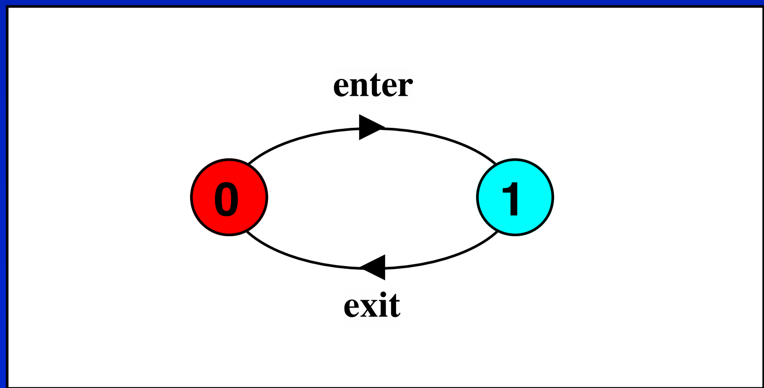
component PERSON - behaviour

Labelled transition system LTS:

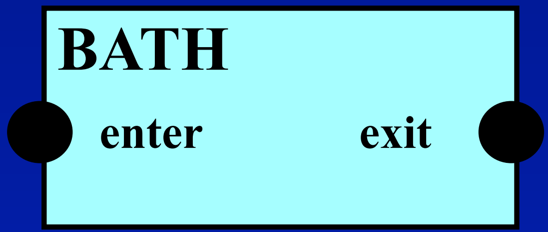


LTS Animation can be used to step through the actions to test specific scenarios.

PERSON can be minimised with respect to Milner's observational equivalence.

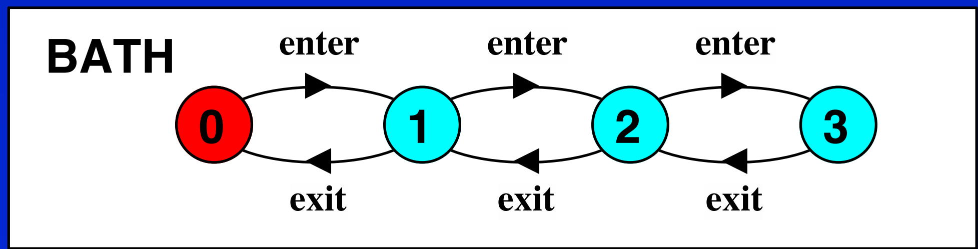


component BATH - behaviour

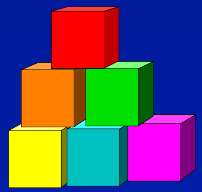


component BATH (N=Max) {
    provides enter; exit;
}

```
const Max = 3
range Int = 0..Max

BATH(N=Max) = BATH[N],
BATH[v:Int] = ( when(v>0) enter-> BATH[v-1]
              | when(v<N) exit -> BATH[v+1]
              ).
```

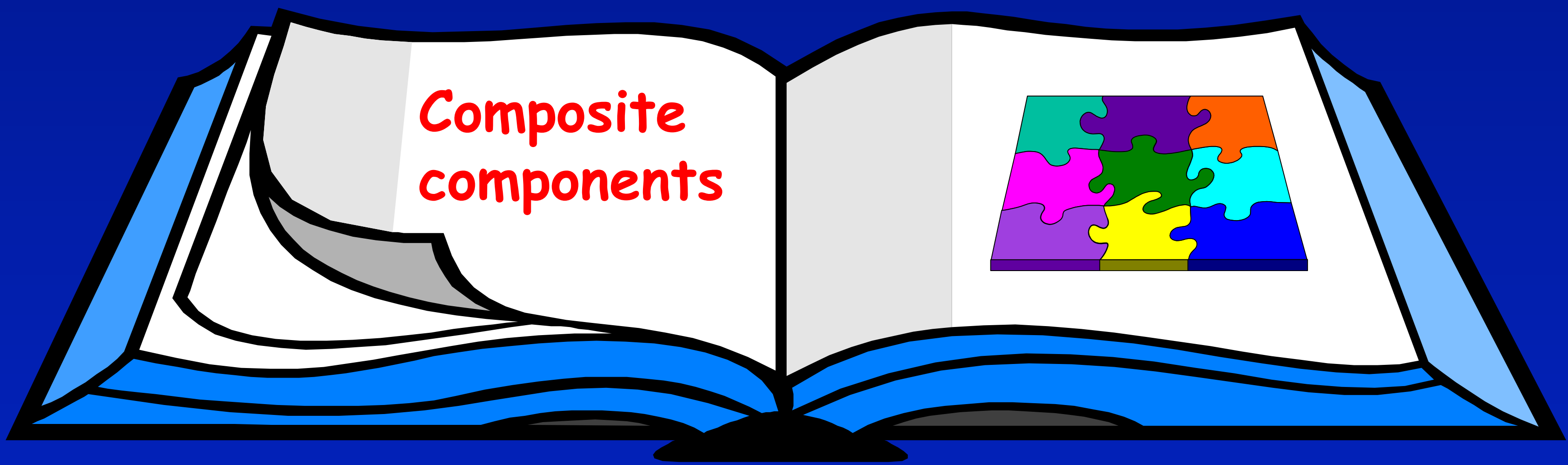


Primitive Components - summary



- Component behaviour is modelled using Labelled Transition Systems (LTS).
- Primitive components are described as finite state processes (FSP) using the dynamic operators of the process algebra:
  - **action prefix ->**
  - **(guarded) choice |**
  - **recursion**
- Interface **@** represents an action (or set of actions) in which the component can engage (ie. constrains the visible alphabet of the process).

Chapter 3.   Modelling systems



Concurrent execution

Concepts: processes - concurrent execution
and interleaving.
process interaction.

Models: **parallel composition** of asynchronous processes
- interleaving

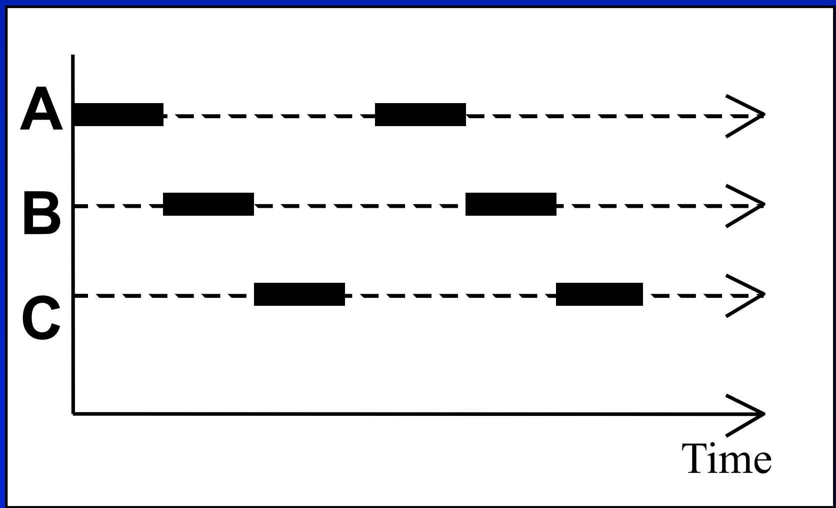
interaction - shared actions

Practice: Multithreaded Java programs

Definition

- ***Concurrency***
  - *Logically* simultaneous processing.

Does not imply multiple processing elements. Requires interleaved execution on a single processing element.



Modeling Concurrency

- How should we model process execution speed?
  - arbitrary speed

    (we abstract away time)

- How do we model concurrency?
  - arbitrary relative order of actions from different processes

    (**interleaving** but preservation of each process order)

- What is the result?
  - provides a general model independent of scheduling

    (**asynchronous** model of execution)

parallel composition - action interleaving

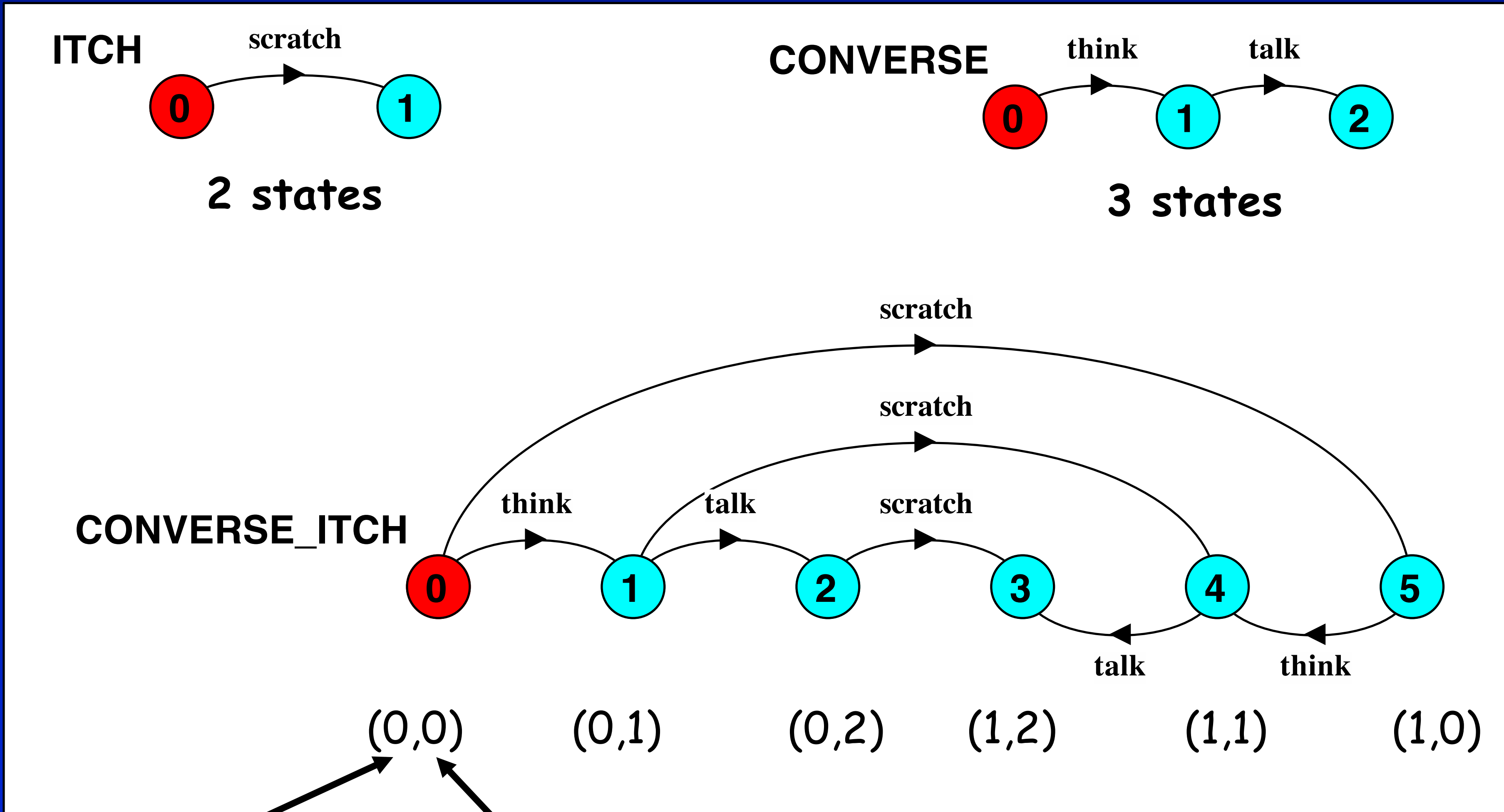
If P and Q are processes then (P||Q) represents the concurrent execution of P and Q. The operator || is the parallel composition operator.

```
ITCH   = (scratch->STOP).
CONVERSE = (think->talk->STOP).

||CONVERSE_ITCH = (ITCH || CONVERSE).
```

think→talk→scratch
think→scratch→talk
scratch→think→talk

Possible traces as a result of action interleaving.

parallel composition - action interleaving



from ITCH from CONVERSE 2 x 3 states

parallel composition - algebraic laws

Commutative: `(P||Q) = (Q||P)`

Associative: `(P||(Q||R)) = ((P||Q)||R)`
`= (P||Q||R).`

Clock radio example:

```
CLOCK = (tick->CLOCK).
RADIO = (on->off->RADIO).

||CLOCK_RADIO = (CLOCK || RADIO).
```

LTS? Traces? Number of states?

modeling interaction - shared actions

If processes in a composition have actions in common, these actions are said to be ***shared***. Shared actions are the way that process interaction is modeled. While unshared actions may be arbitrarily interleaved, a shared action must be executed at the same time by all processes that participate in the shared action.

```
MAKER = (make->ready->MAKER).
USER  = (ready->use->USER).

||MAKER_USER = (MAKER || USER).
```

MAKER synchronizes with **USER** when **ready**.

Non-disjoint alphabets

LTS? *Traces?* *Number of states?*

modeling interaction - handshake

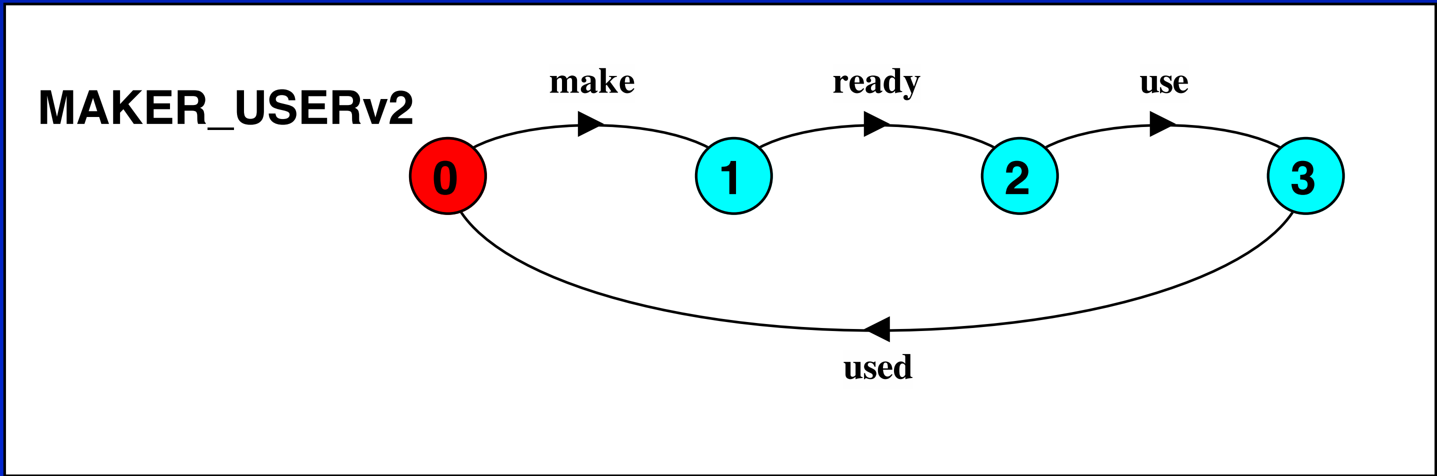
A handshake is an action acknowledged by another:

```
MAKERv2 = (make->ready->used->MAKERv2).
USERv2  = (ready->use->used ->USERv2).

||MAKER_USERv2 = (MAKERv2 || USERv2).
```

3 states

3 states

3 x 3 states?

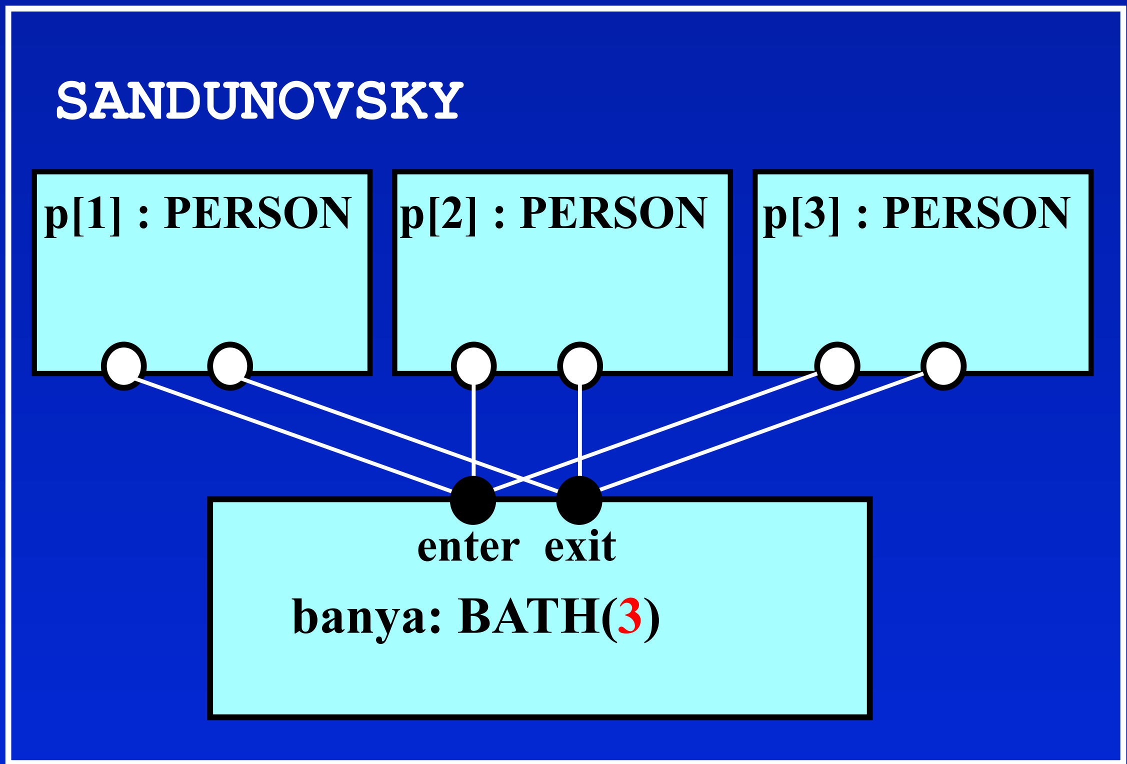


4 states

Interaction constrains the overall behaviour.

Composite component behaviour

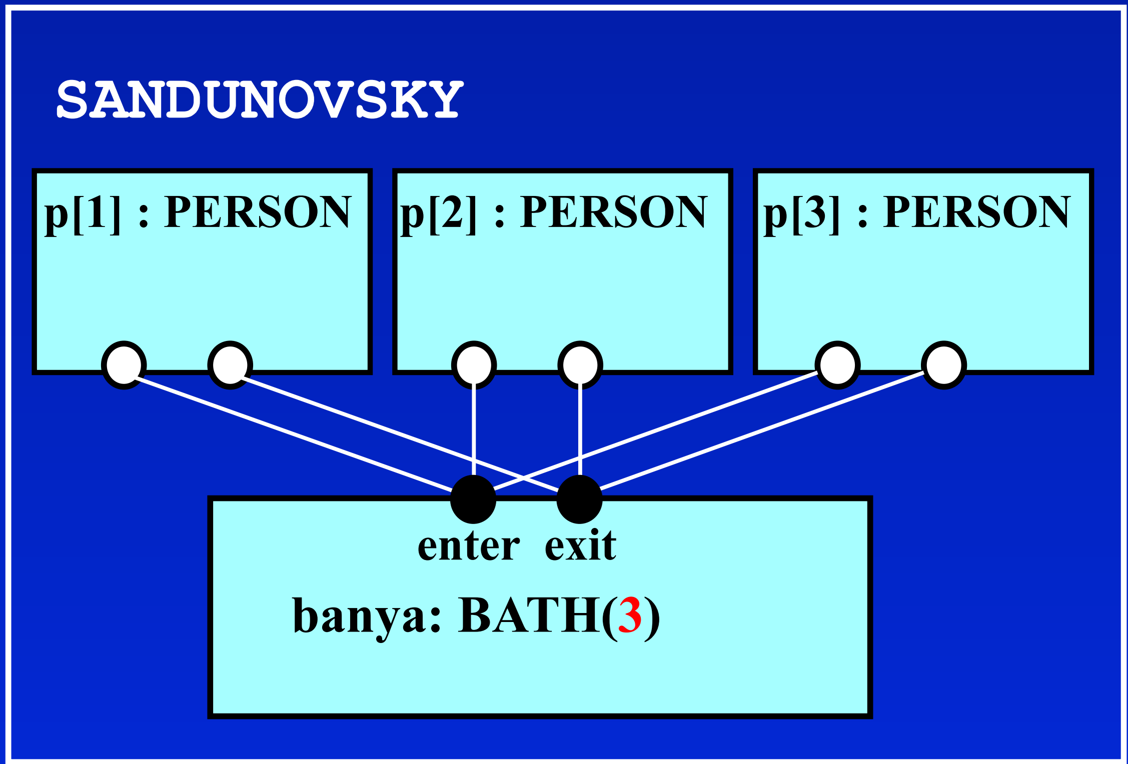
```
component SANDUNOVSKY
        {inst    p[1..3]  : PERSON;
                 banya: BATH(3);
         bind p[1..3].enter -- banya.enter;
         bind p[1..3].exit  -- banya.exit; }
```



Three persons `p[1..3]` use a shared Russian bath, **`banya`**.

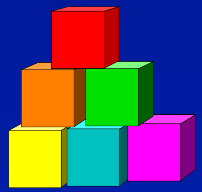
Composite component behaviour - FSP

```
||SANDUNOVSKY = (  p[1..Max]:PERSON
                 || banya:BATH(3)
                  )/{p[1..Max].enter/ banya.enter,
                     p[1..Max].exit/ banya.exit}.
```



: instantiation
|| composition
/ relabelling

Composite Component – summary of FSP static operators



- Component composition is modelled as parallel composition ||.

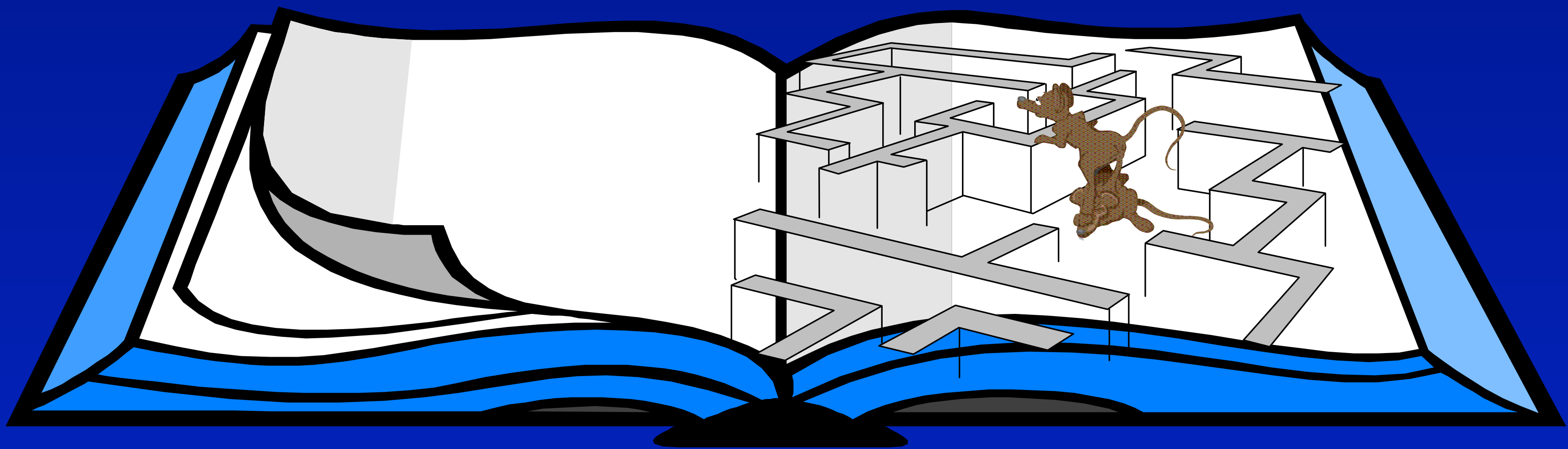
  (**Interleaving** of all the actions)

- Binding is modelled by relabelling /.

  (Processes synchronise on **shared** actions)

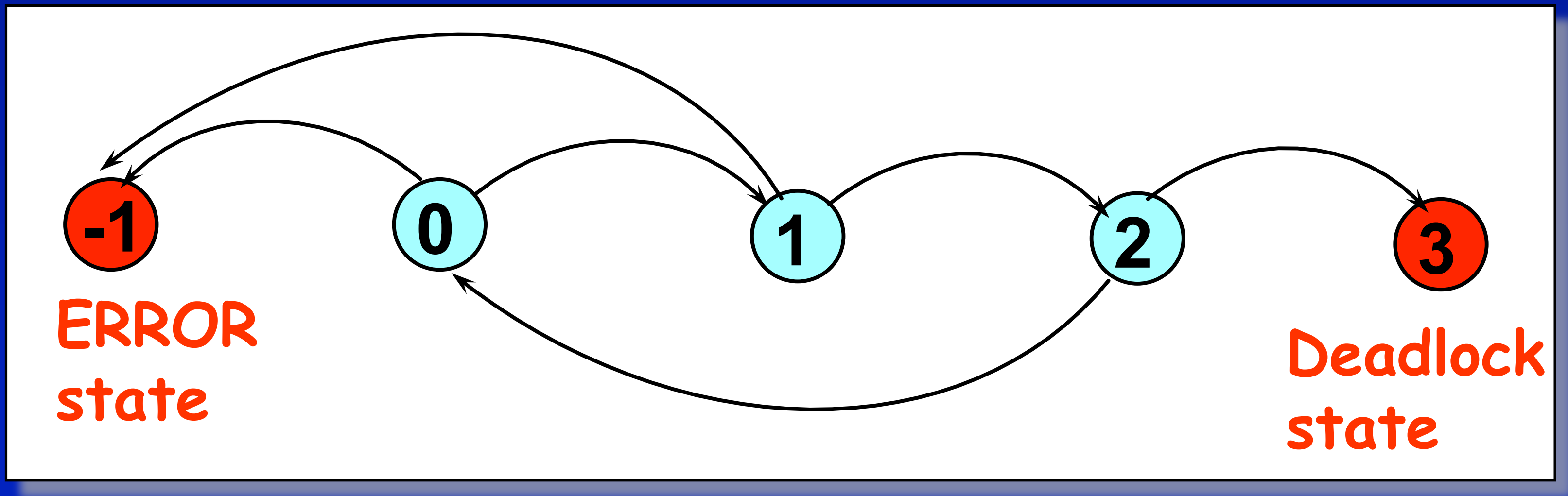
- Composition expressions are **direct** translations from architecture descriptions.

Chapter 4. Behaviour analysis



Reachability analysis for checking models

Searches the *entire* system state space for **deadlock** states and **ERROR** states arising from property violations.



Deadlock - state with no outgoing transitions.

ERROR (π) state -1 is a trap state. Undefined transitions are automatically mapped to the **ERROR** state.

Safety - property automata

Safety properties are specified by deterministic finite state processes called property automata. These generate an image automata which is *transparent* for valid behaviour, but transitions to an **ERROR** state otherwise.

```
property EXCLUSION =( p[i:1..3].enter
                     -> p[i].exit
                     -> EXCLUSION ).
```

```
||CHECK = (SANDUNOVSKY || EXCLUSION).
```

Safety properties are composed with the (sub)systems to which they apply, then check if ***ERROR*** is reachable in the composed system.

…if the number of spaces in the bath is 1 ? …or 0?

Liveness - progress properties

To avoid the need to know LTL (Linear Temporal Logic), we directly support a limited class of liveness properties, called progress, which can be checked efficiently :

$$[]\Diamond a$$

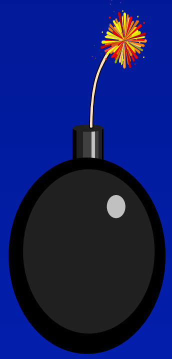
i.e. Progress properties check that, in an infinite execution, particular actions occur infinitely often.

For example:

```
progress OKtoBATH[i:1..3] = {p[i].enter}
```

…if we give priority to two of the bathers?

Scalability



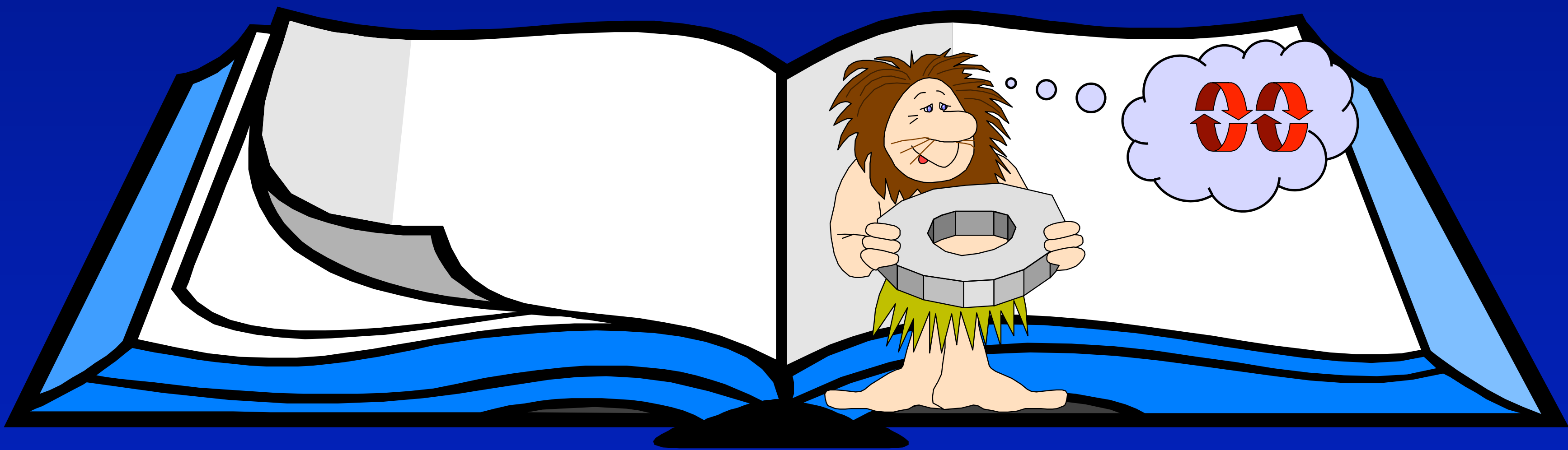
The problem with reachability analysis is that the state space "explodes" exponentially with increasing problem size.

How do we hope to alleviate this problem?

- **Compositional Reachability Analysis**
- **Partial Order Reduction**

As in SPIN, we employ on-the-fly analysis, exploring only that part of the state space which affects *visible actions* (cf. *properties* in SPIN).
This can be done while *preserving observational equivalence.*

Chapter 5. Implementation in Java



Translation to Java

Identify active components (threads) & passive components (monitors): **person** **bath**

```
FSP:    when cond act -> NEWSTAT
```

```
Java:  public synchronized void act()
                throws InterruptedException
       {
        while (!cond) wait();
        // modify monitor data
        notifyAll()
       }
```

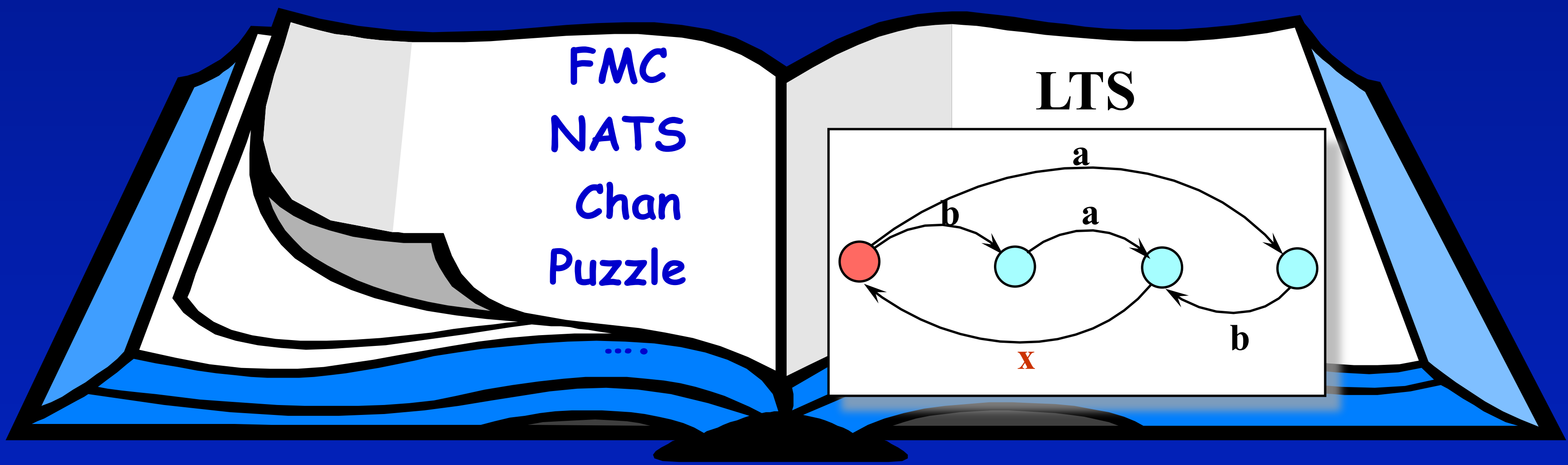
class Bath

```
class Bath {
  protected int spaces;
  protected int max;

  Bath(int n)
    {max = spaces = n;}

  synchronized void enter() throws InterruptedException {
    while (spaces==0) wait();
    --spaces;
    notifyAll();                                   //omit?
  }

  synchronized void exit() throws InterruptedException {
    while (spaces==n) wait();                      //omit?
    ++spaces;
    notifyAll();
  }
}
```

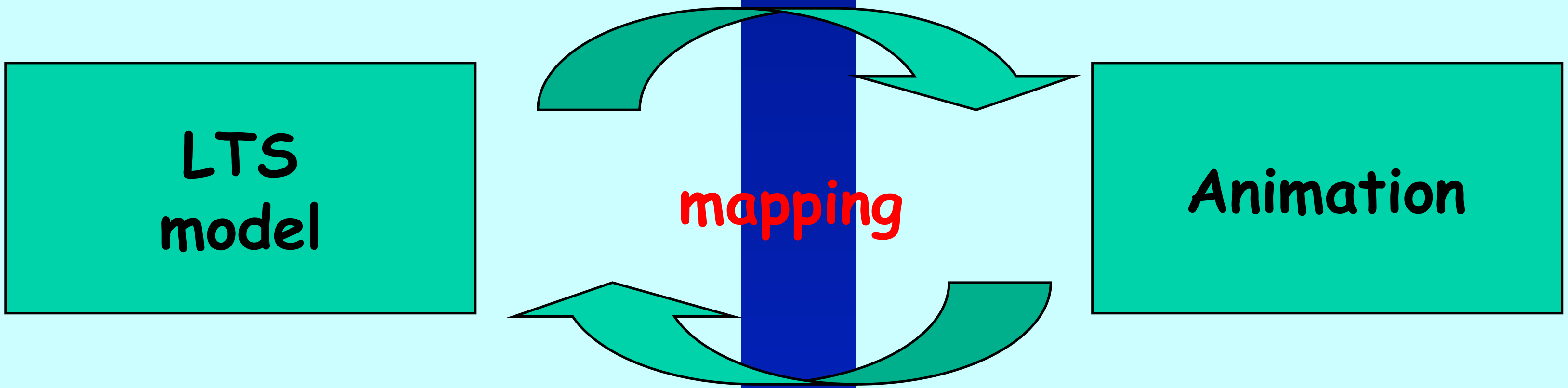
Person threads

```
class Person implements Runnable {
  Bath bath;

  Person(Bath b) {bath = b;}

  public void run() {
    try {
      while(true) {
        …
        bath.enter();
        <bathe actions>
        bath.exit();
        …
      }
    } catch (InterruptedException e){}
  }
}
```

Chapter 6. Graphical Animation – some examples



Model analysis & animation

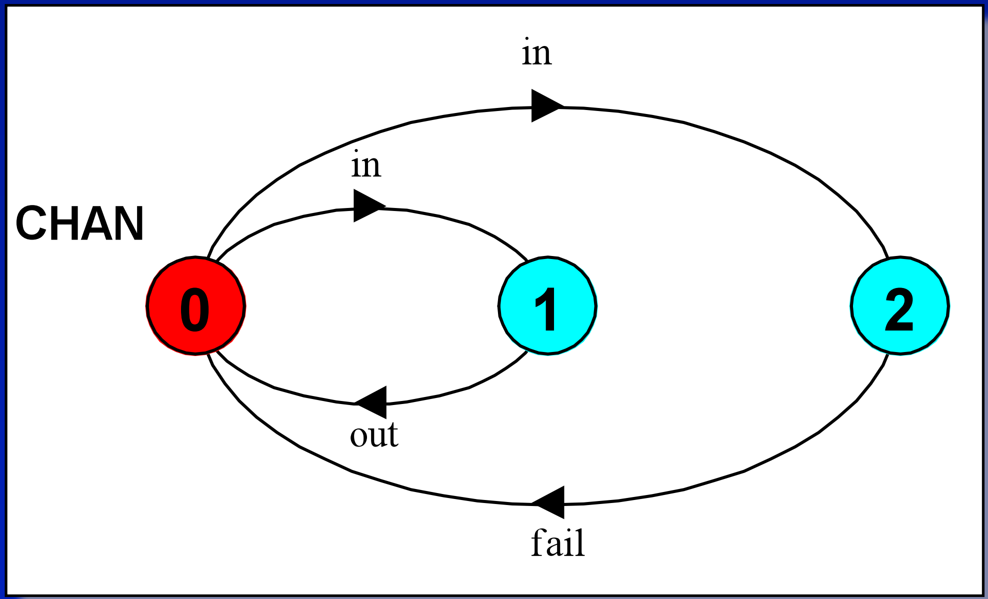


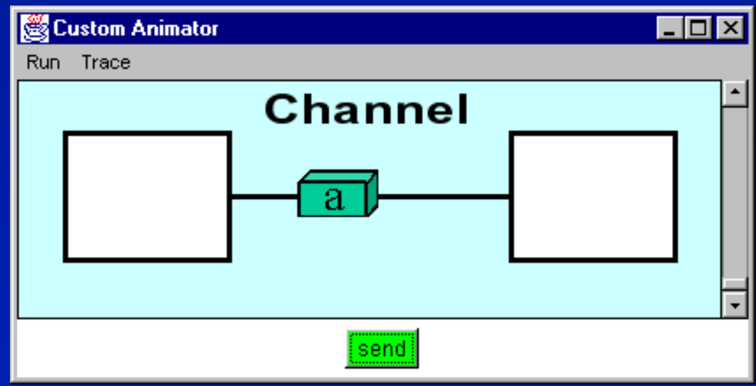
LTS Model checking

- safety properties
- progress properties
- compositional reachability
- abstraction & minimisation

Separate graphic animation model which preserves the behaviour of the model and has sound semantics based on Timed Automata.

A simple example - CHAN






```
CHAN = (in -> out  -> CHAN
       |in -> fail -> CHAN
       ).
```

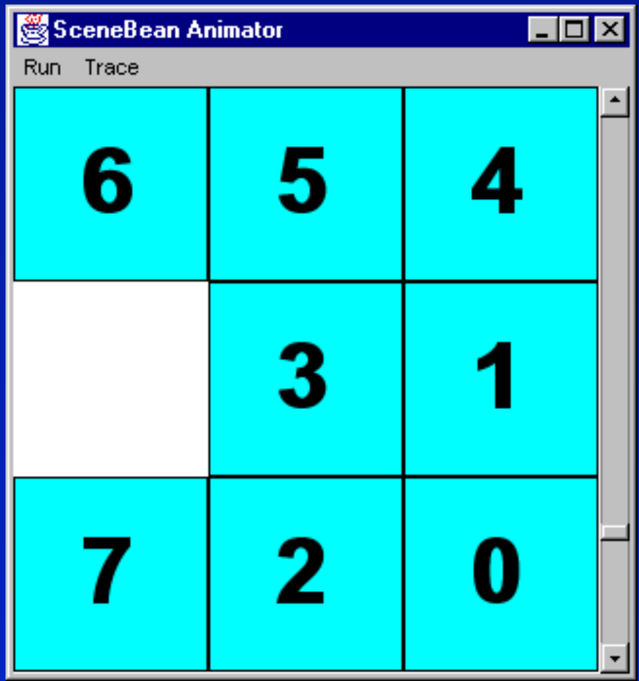
Models & Annotated models

Safety Properties

The annotated model cannot exhibit behavior that is not contained in the base model:

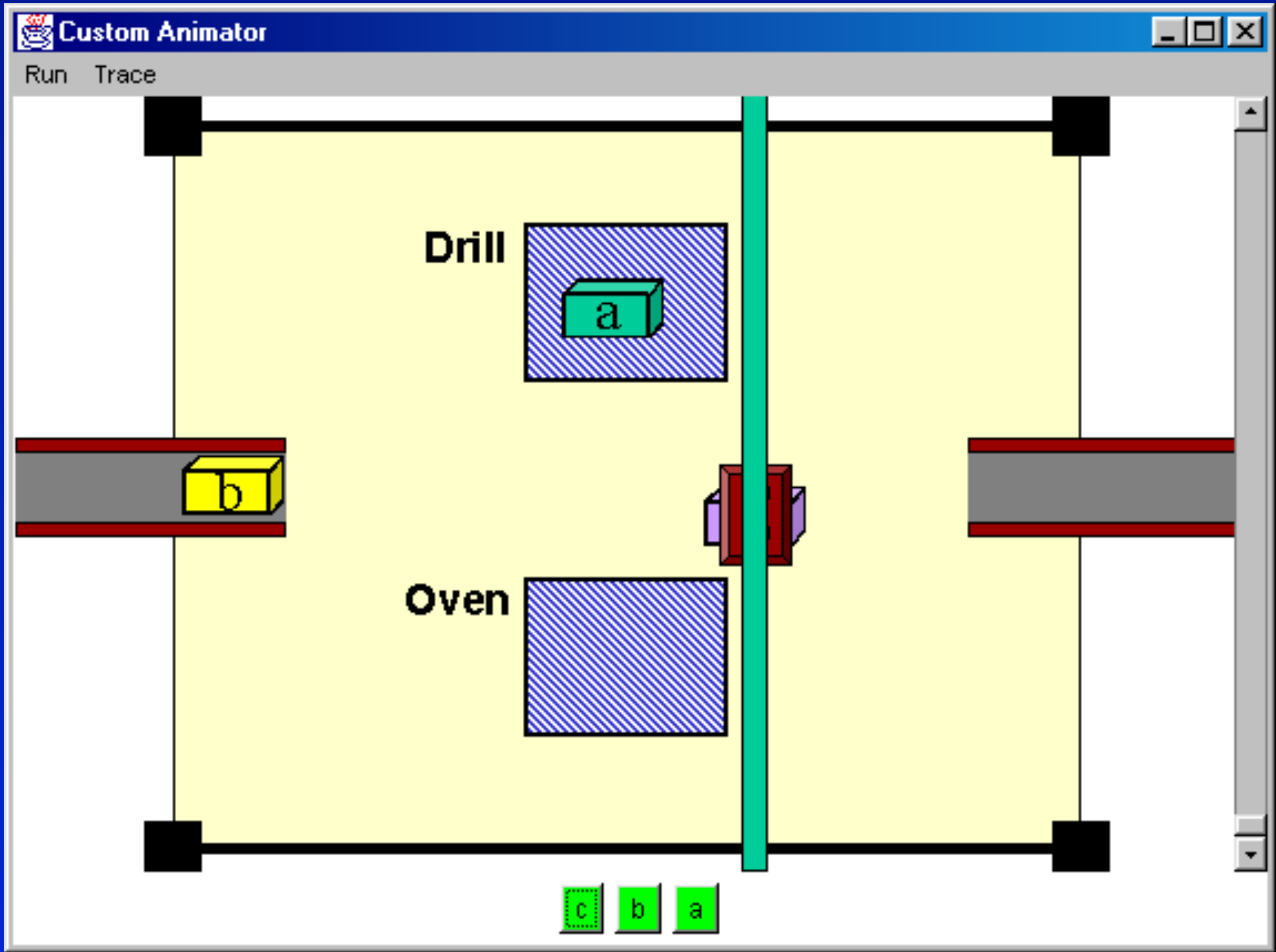
Any safety property that holds for the base model also holds for the animated model.

Puzzle



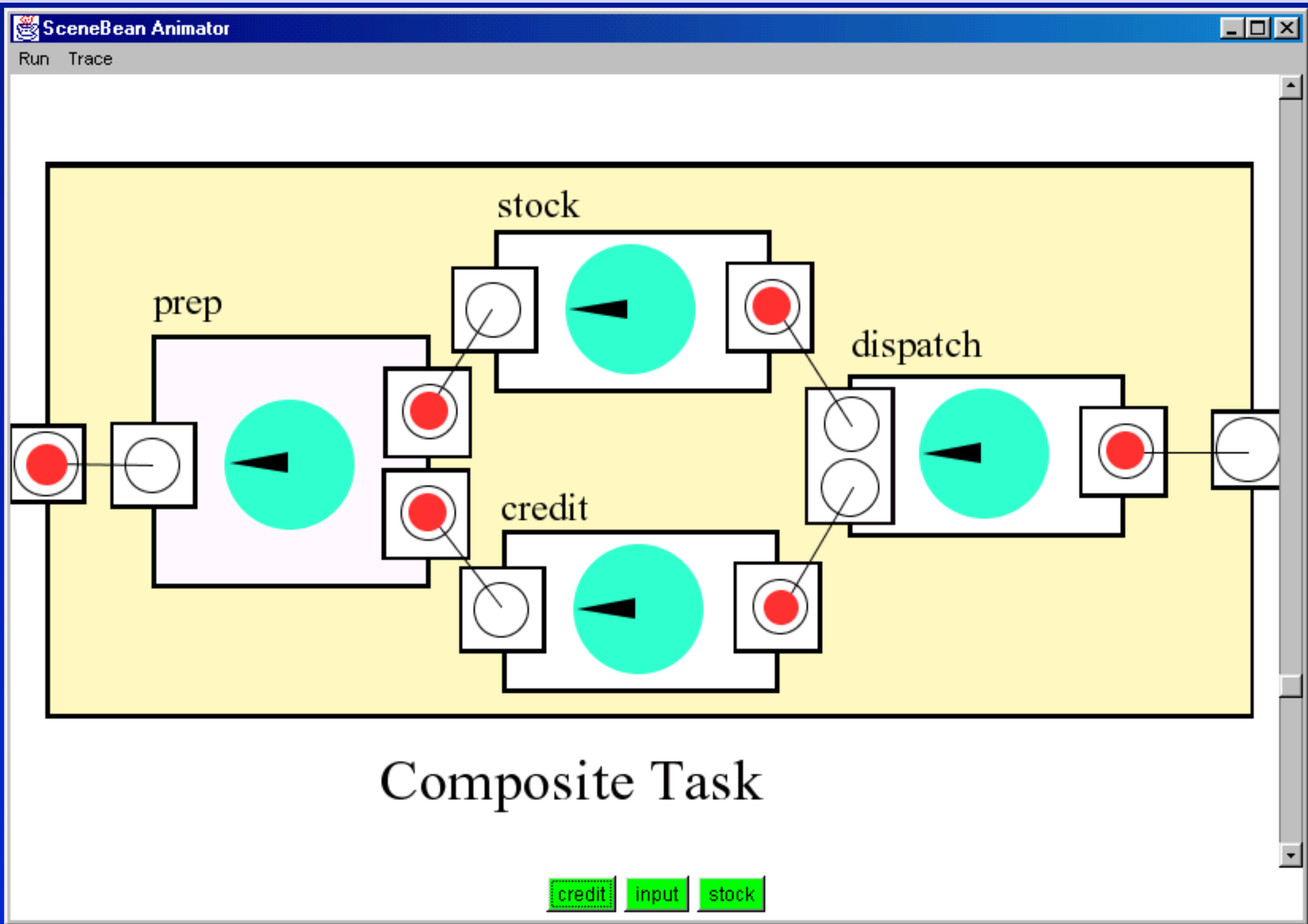
The animated model can thus be used to help understand the meaning of **counterexamples**.

Flexible Manufacturing Cell

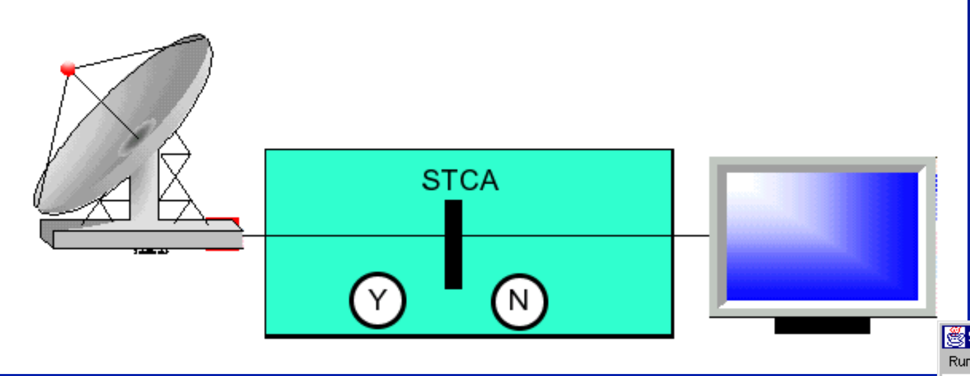


Animated models can be composed to form complex models.

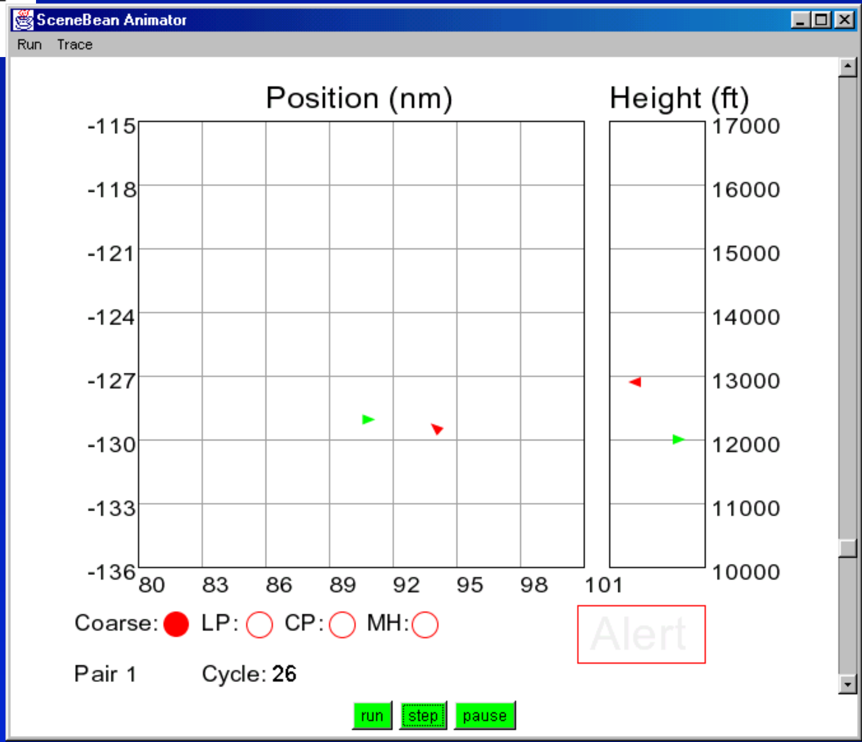
A simple workflow system – *OpenFlow*



NATS – short term conflict alert (STCA)

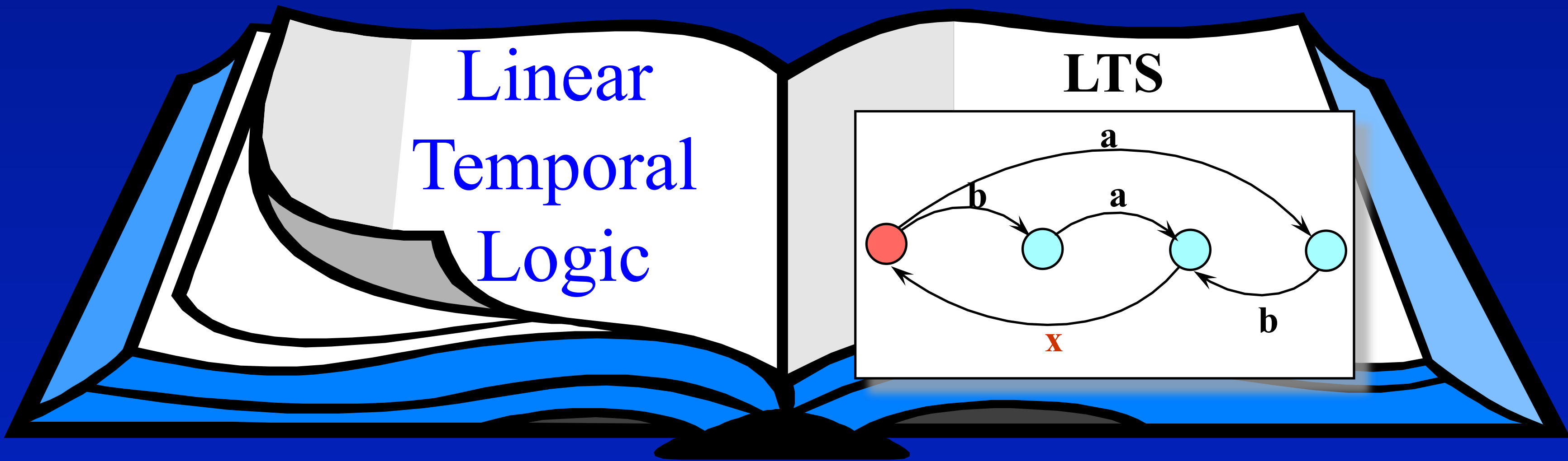


For each pair of aircraft determine potential conflict.



We can construct **hybrid models** that combine the discrete behavioural model with a real valued data stream.

Chapter 7. Logical Properties - states Vs events



Properties – some deficiencies

- For simple models, safety properties are very similar to the model itself.

-Cannot specify some common liveness properties directly

e.g. *Response* [](request -> <> reply)

Use the Fluent Linear Temporal Logic model checker in LTSA tool:-

Defining Abstract States over Sequences of Events

- Fluents - from the Event Calculus

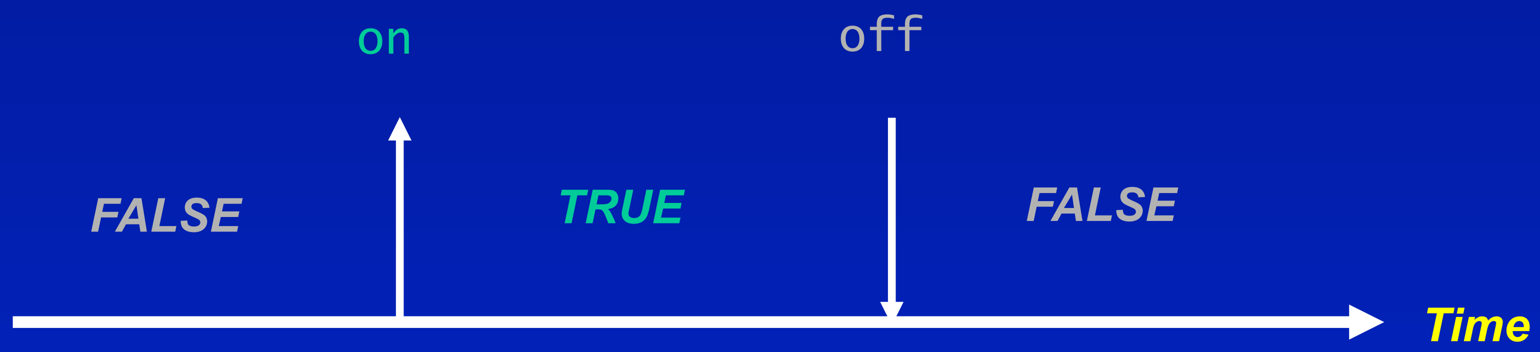
"Fluents - time varying properties of the world

Fluents are true at particular time-points if they have been initiated by an action occurrence at some earlier time-point and not terminated by another action occurrence in the meantime. "

Miller & Shanahan

Fluent Propositions

Defined in terms of sets actions




```
fluent
  LIGHT = <{on},{power_cut,off}> initially False
```

[Magee & Giannakopoulou]

Fluents and the LTSA

- LTSA supports model checking of Fluent Linear Temporal Logic (FLTL)
  - Fluents
  - and (&&) , or (||) , implies (->), not (!)
  - always ([]), eventually (<>), until (U),
  - weak until (W), next (X),

Using Fluents in SANDUNOVSKY

```
fluent BATHING[i:1..Max]
                  = <p[i].enter,p[i].exit>
```

//safety property

```
assert EXCLUSIONf  = []!(exists[i:1..Max-1]
           (BATHING[i] && BATHING [i+1..Max]))
```

//liveness property

```
assert OKtoBATHf = forall[i:1..Max]
                      []<>p[i].enter
```

Chapter 8. Dynamic and Adaptive Systems