Synchronous Modelling of Complex Systems

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joint work with
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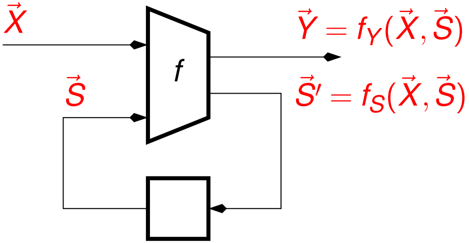
and D. Lesens — *Astrium Space Transportation*

The Synchronous Paradigm (1/8)

Synchronous machines

Basic components: generalized Mealy machines


$\vec{X}$
$\vec{S}$
f
$\vec{Y} = f_Y(\vec{X}, \vec{S})$
$\vec{S'} = f_S(\vec{X}, \vec{S})$

Behaviour: $(\vec{S}_0, \vec{X}_0, \vec{Y}_0), (\vec{S}_1, \vec{X}_1, \vec{Y}_1), \ldots, (\vec{S}_n, \vec{X}_n, \vec{Y}_n), \ldots,$

with $Y_n = f_Y(\vec{X}_n, \vec{S}_n)$ and $\vec{S}_{n+1} = f_S(\vec{X}_n, \vec{S}_n)$

Deterministic!

The Synchronous Paradigm (2/8)

Basic components, simple examples

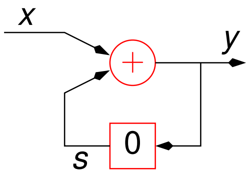
- unit delay δ: outputs the value received at the previous reaction
$$f_O(\vec{X},\vec{S}) = \vec{S} \quad , \quad f_S(\vec{X},\vec{S}) = \vec{X}$$
- sampler $\beta(b)$: outputs the current input if b is true, the previous output otherwise
$$f_O(b,\vec{X},\vec{S}) = f_S(b,\vec{X},\vec{S}) = \text{if } b \text{ then } \vec{X} \text{ else } \vec{S}$$

The Synchronous Paradigm (3/8)

Example: an integrator

Outputs the sum of inputs received so far

$$f_Y(x,s) = f_S(x,s) = s + x$$



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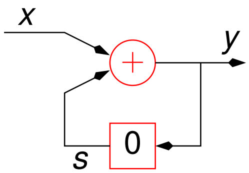

In Lustre:

```
y = x+s ;
s = 0 ->pre(y) ;
```

The Synchronous Paradigm (3/8)

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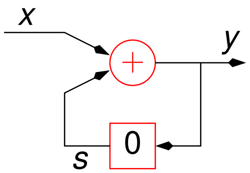

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or

```
y = x + (0 ->pre(y)) ;
```

The Synchronous Paradigm (3/8)

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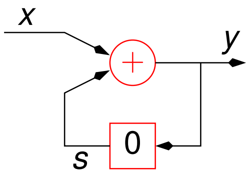

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step	0	1	2	3	...
x	x_0	x_1	x_2	x_3	...

The Synchronous Paradigm (3/8)

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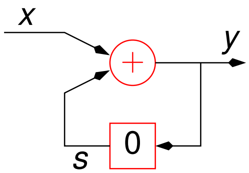

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step	0	1	2	3	...
x	x_0	x_1	x_2	x_3	...
y	x_0	x_0+x_1	$x_0+x_1+x_2$	$x_0+x_1+x_2+x_3$	...

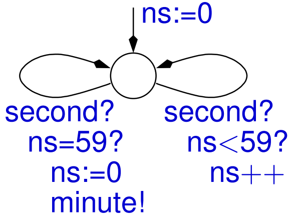
The Synchronous Paradigm (4/8)

Example: a counter of events

Detect a “minute” every 60 “second”

In Lustre:

```
ns = 0 ->   if second then
                     if pre(ns) < 59
                     then pre(ns)+1 else 0
            else pre(ns) ;
minute = (second and ns=0) ;
```



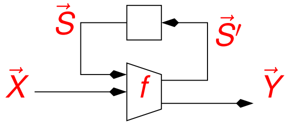
In Esterel

```
every 60 second do emit minute ;
```

The Synchronous Paradigm (5/8)

Synchronous machines

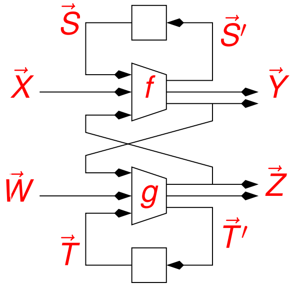
Parallel composition:



The Synchronous Paradigm (5/8)

Synchronous machines

Parallel composition:



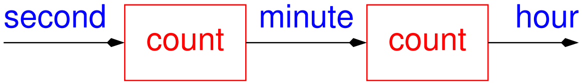
$$(\vec{S}', \vec{Y}) = f(\vec{X}, \vec{S}, \vec{Z})$$
$$(\vec{T}', \vec{Z}) = g(\vec{W}, \vec{T}, \vec{Y})$$

(deterministic, provided there is no combinational loop)

The Synchronous Paradigm (6/8)

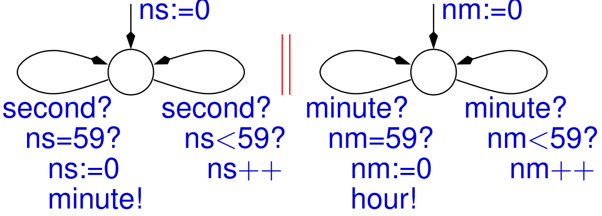
Parallel composition, example

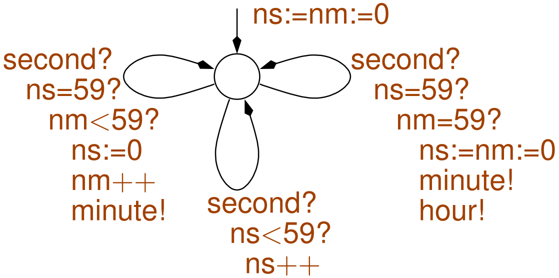
```
        every 60 second do emit minute ;
    ||
        every 60 second do emit minute ;
```



The Synchronous Paradigm (7/8)

Parallel composition, example





The Synchronous Paradigm (8/8)

Synchronous languages are well accepted as description formalisms

- precise, formally defined
- match the way of thinking of users
- various, complementary, compatible paradigms (imperative/data-flow, textual/graphical)

Powerful associated tools

- efficient code generation (for centralized, statically scheduled applications)
- precise and inexpensive modelling, no overhead in analysis and verification
- can be used for expressing properties (observers)

Industrial environments:

Esterel Studio, Lustre-Scade, Signal-Sildex

Synchrony and Asynchrony (1/3)

Synchronous languages and associated tools are well-established for centralized, statically scheduled applications

What about more complex situations?

- Need for dynamic scheduling:
  urgent sporadic events, multiple periods
- Need for distribution:
  redundancy, performances, physical constraints

Synchrony and Asynchrony (2/3)

First remark: In real-time systems, purely asynchronous situations are rare

Partial synchrony, or strongly constrained asynchrony: e.g.,

- known periods
- known clock drift
- quite precise WCET

Synchrony and Asynchrony (3/3)

Related works:

Synchrony and Asynchrony (3/3)

Related works:

- extend the synchronous model
  CRP [Berry-Shyamasundar-Ramesh],
  Multiclock-Esterel [Berry-Sentovitch],
  n-synchrony [Cohen-Duranton-Eisenbeis-Pagetti-Plateau-Pouzet],
  GALS [Metropolis], [Polychrony],
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- less synchronous implementations
  Multi-task implementations [SYNDEX], [Caspi-Scaife],
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- less synchronous implementations
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- model asynchrony within the synchronous framework
  SafeAir, SafeAir-II projects [Baufreton et-al],
  Polychrony [Le Guernic-Talpin-Le Lann], [Gamatié-Gautier],
  this talk (same approach, in the ctxt of the Assert project)

The ASSERT Project (1/2)

European “Integrated Project” (2005-08) on model-driven design of embbedded systems

Main application domain: aerospace applications

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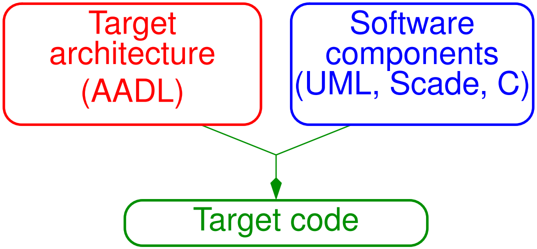
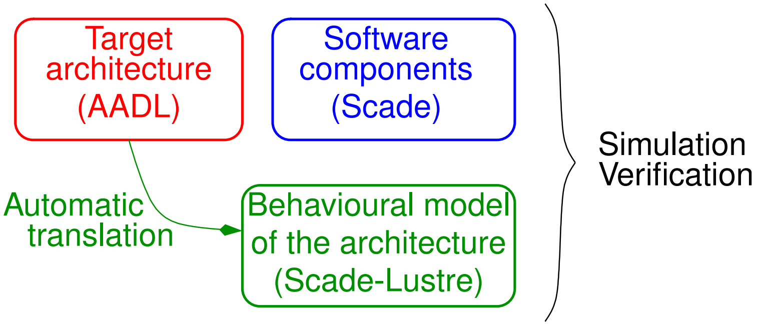

Target architecture (AADL)
Software components (UML, Scade, C)
Target code

The ASSERT Project (2/2)

What this talk is about:


Target architecture (AADL)
Software components (Scade)
Automatic translation
Behavioural model of the architecture (Scade-Lustre)
Simulation
Verification

Synchronous Modelling of Asynchrony (1/5)

Need to

- prevent a component from reacting (sporadic reactions)
- non-determinism
- model execution time

Synchronous Modelling of Asynchrony (2/5)

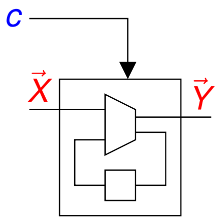
Prevent a component from reacting

- available in all synchronous languages:
  - clocks in Lustre and Signal
  - activation conditions in Scade
  - suspend statement in Esterel

Synchronous Modelling of Asynchrony (3/5)

Activation condition in Scade

A distinguished Boolean input, say c, decides if the component must react.



Synchronous Modelling of Asynchrony (3/5)

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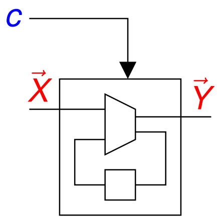

Synchronous Modelling of Asynchrony (3/5)

Activation condition in Scade

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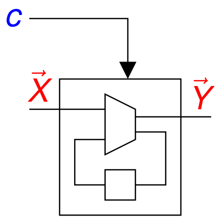
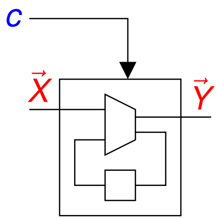


Synchronous Modelling of Asynchrony (3/5)

Activation condition in Scade

A distinguished Boolean input, say c, decides if the component must react.

- when $c = 1$ the normal reaction occurs
- when $c = 0$
  - the state does not change
  - the output keeps its previous value

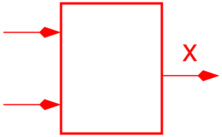


Synchronous Modelling of Asynchrony(4/5)

Non determinism

- Just by adding auxiliary inputs (oracles)
- Restriction of non-determinism:
  - constraints/assumptions on oracles ensured by “assertions” or transducer (scheduler)

A task in the synchronous world



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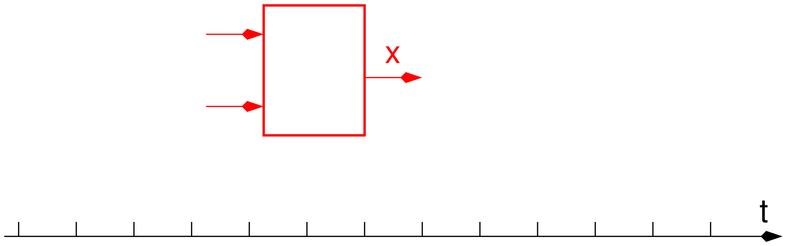

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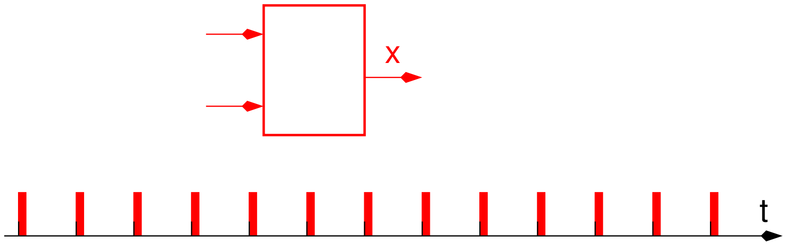

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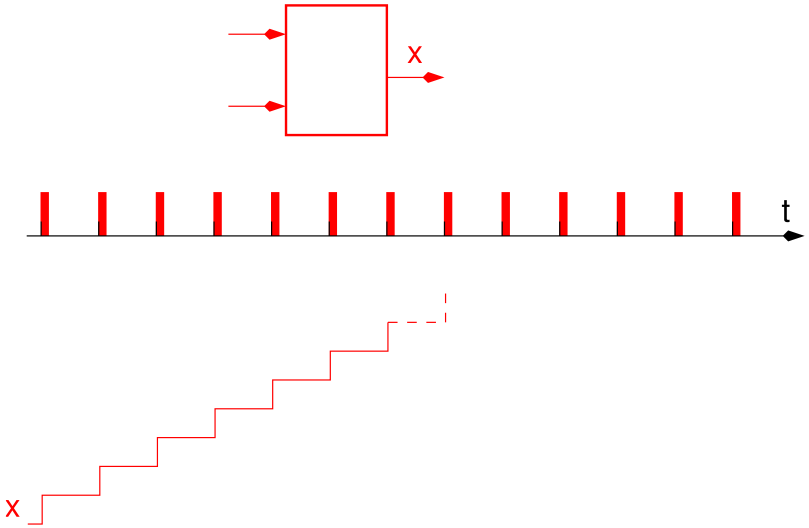
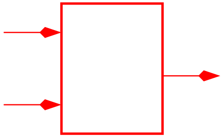


A sporadic or periodic task



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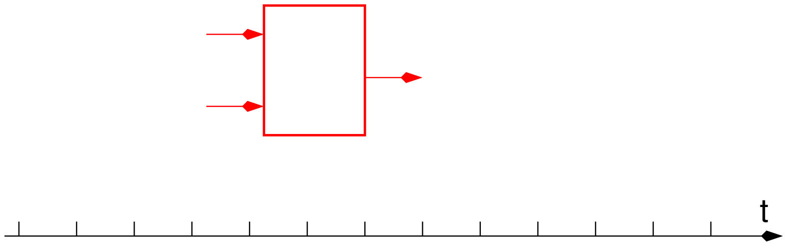

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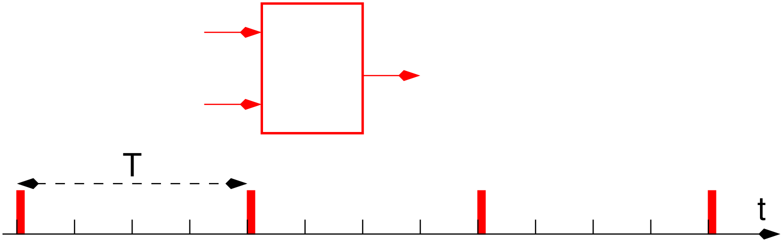

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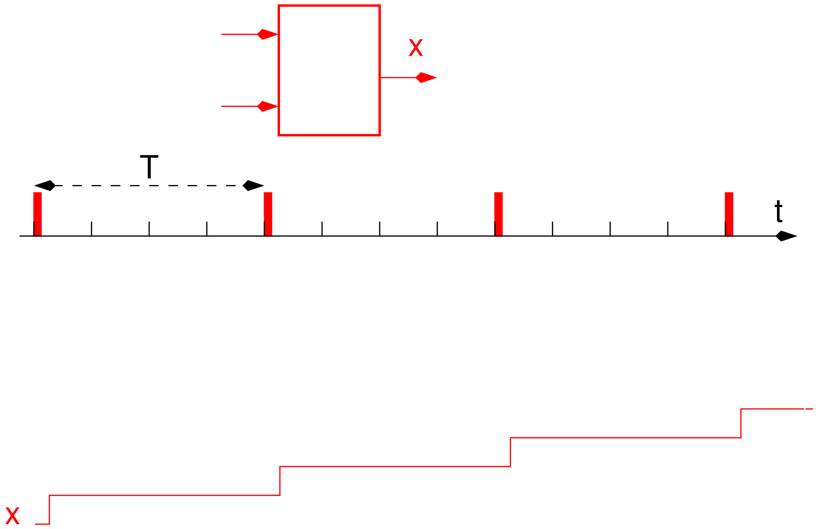

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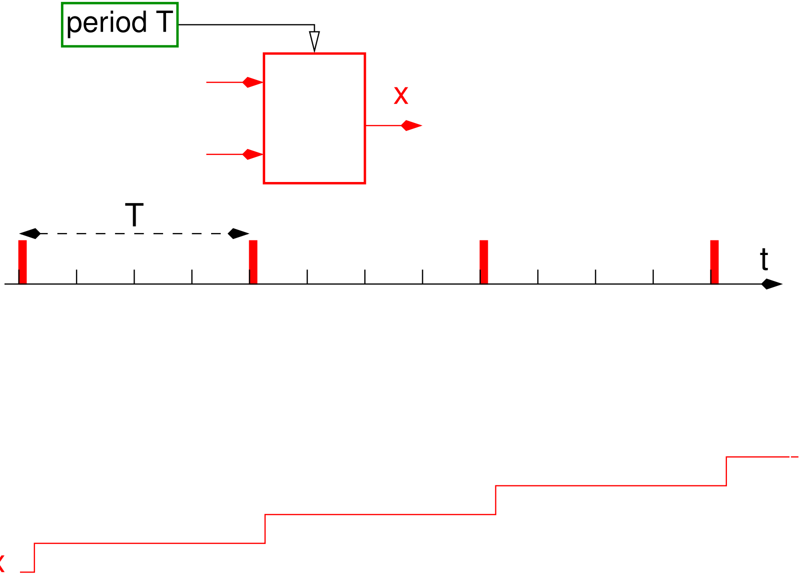
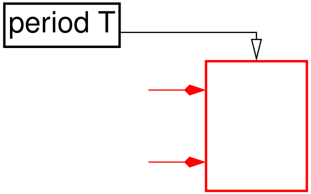


Execution time



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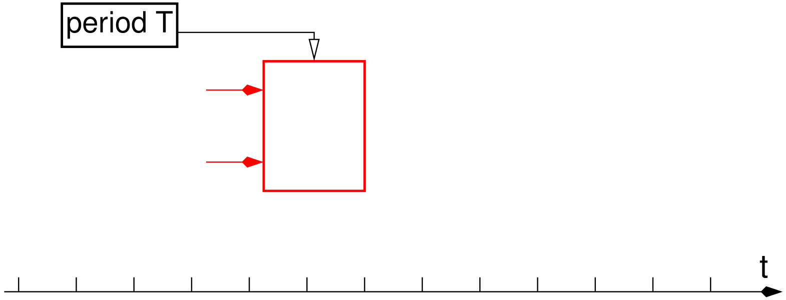

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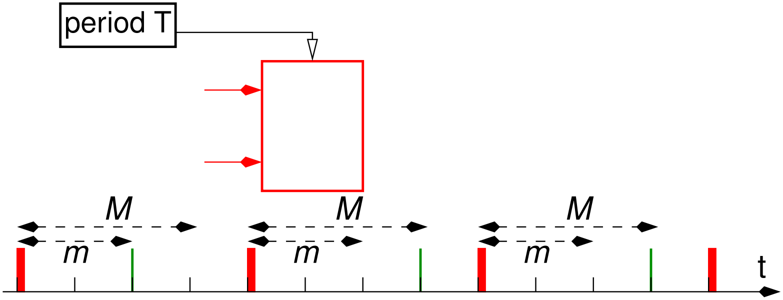

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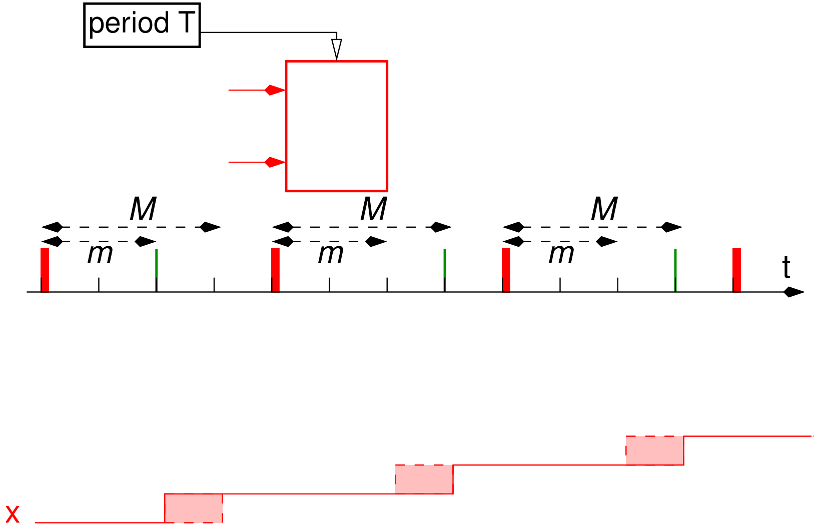

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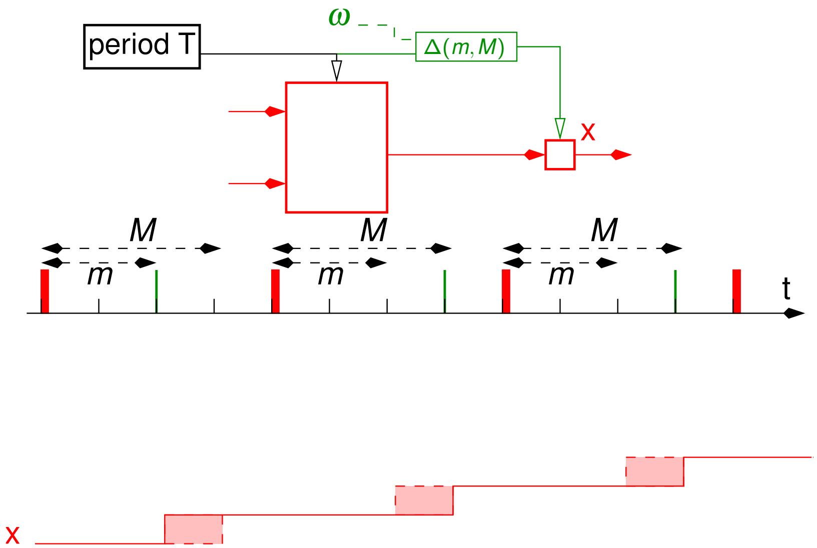
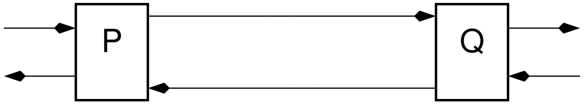


Synchronous Modelling of Asynchrony (5/5)

A quite general structure:



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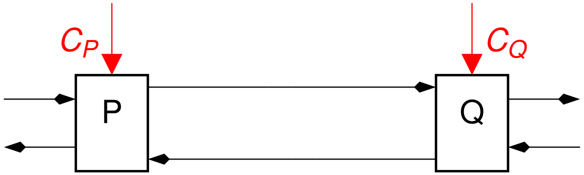

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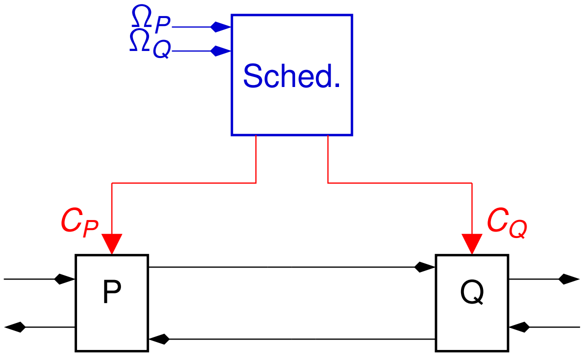

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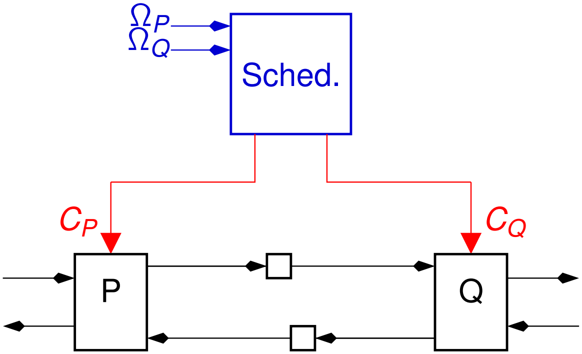

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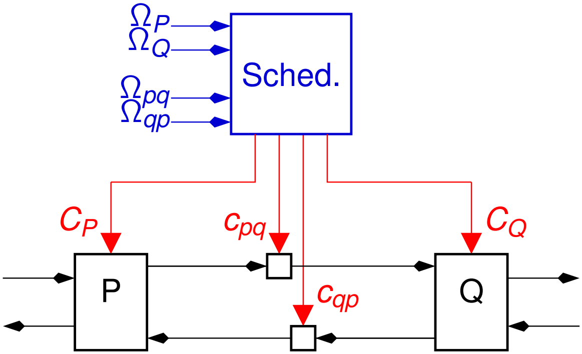
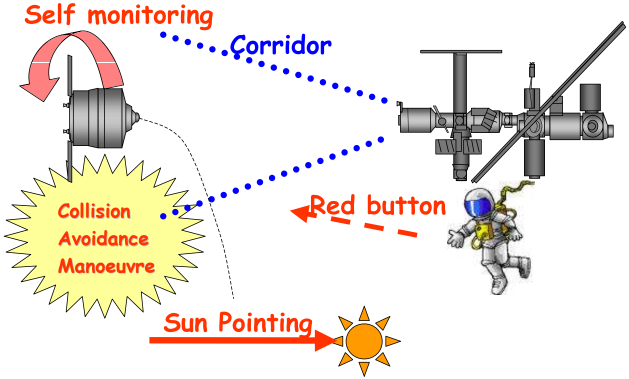


The PFS case study (1/5)

- Proximity Flight Safety (PFS), part of the Automatic Transfer Vehicule (ATV), spacecraft in charge of supplying the International Space Station (ISS) ESA, Astrium-ST
- Ensures the safety of the approach of the ATV to the ISS (most safety critical part of the mission)



When anything goes wrong, the PFS is in charge of safely moving the ATV apart from the ISS, and to orient it towards the sun (“Collision Avoidance Manoeuvre”, CAM)

The PFS case study (3/5)

The system is made of two redundant “Monitoring and Safety Units” (MSU): one master, one backup

Each MSU:

- detects anomalies: failures of the main computer, abnormal state of the bus, erroneous position or speed of the ATV, “red button” pressed from inside the ISS
- detects its own failures (master change)
- is able to perform a CAM

The PFS case study (4/5)

At each instant, one of the MSU is the master. If the master detects its own failure, it transmits its mastership to the other MSU.

However,

- such a master change can only occur once in a mission
- master change is forbidden during a CAM

The PFS case study (5/5)

Distribution: Two computers (one for each MSU) running in quasi-synchrony

Multitasking: Each MSU consists of two periodic tasks (one fast, one slow). Each task specified in Scade

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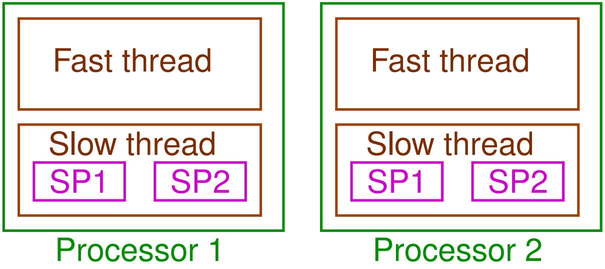
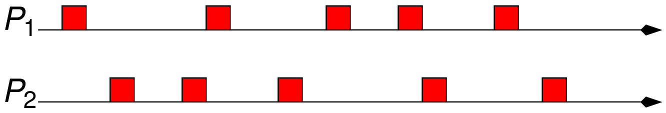


Quasi-synchrony (1/2)

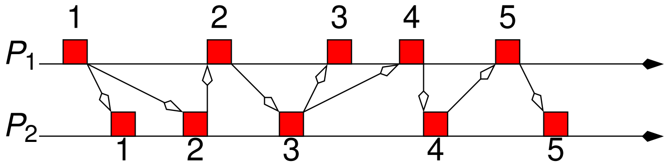
[Caspi et al, FTRTFT'00, Safecomp'01]
Several periodic processes on different computers Supposed to run with the same clock Small clock drift, under which the following assumption can be made:

Between two successive activations of one periodic process, each other process is activated either 0, or 1, or at most 2 times



Quasi-synchrony (2/2)

In case of simple communication (e.g., by shared memory), each process can only miss or duplicate at most one output in a row from any other process:



Modeling quasi-synchrony (1/2)

2 processes P and Q, activated by conditions C_P, C_Q

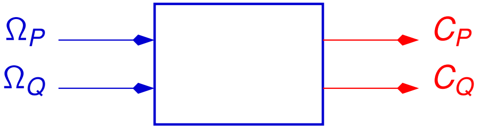
Assumption: between 2 occurrences of C_i there are at most 2 occurrences of C_j

Ambiguous, because of simultaneity...

Precise assumption: Each condition cannot be true alone more than twice in a row. If a condition occurs alone twice in a row, the other condition must follow alone

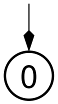
Modeling quasi-synchrony (2/2)

Non-deterministic quasi-synchronous scheduler



Quasi-synchronous scheduler

$\Omega_P, \Omega_Q / C_P, C_Q$



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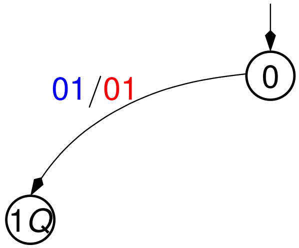

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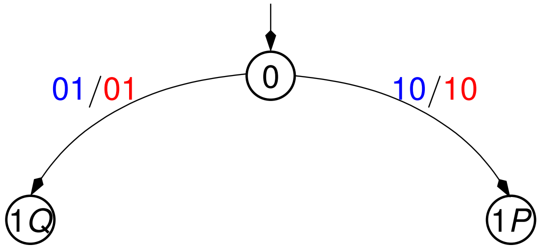
$$\begin{tikzcd}
 & \arrow[d] & \\
 & 0 \arrow[dl, bend right, "01/01"'] \arrow[dr, bend left, "10/10"] & \\
1Q & & 1P
\end{tikzcd}$$

Quasi-synchronous scheduler

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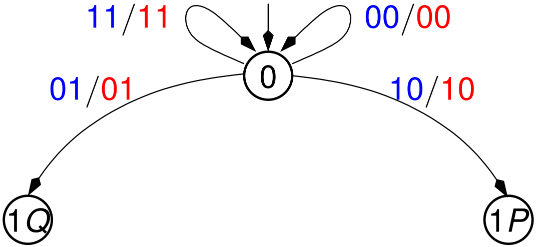

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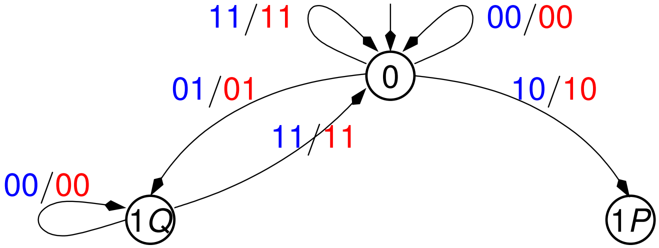

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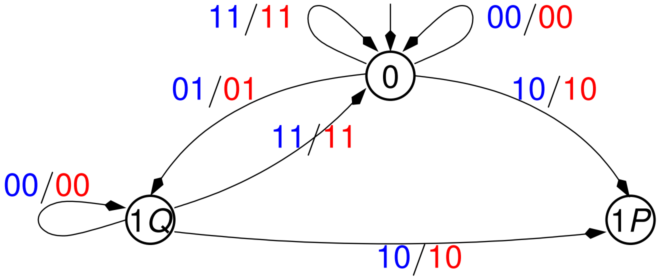

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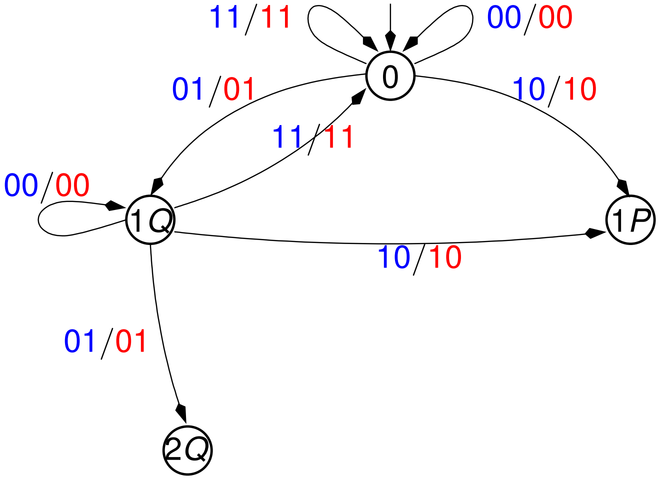

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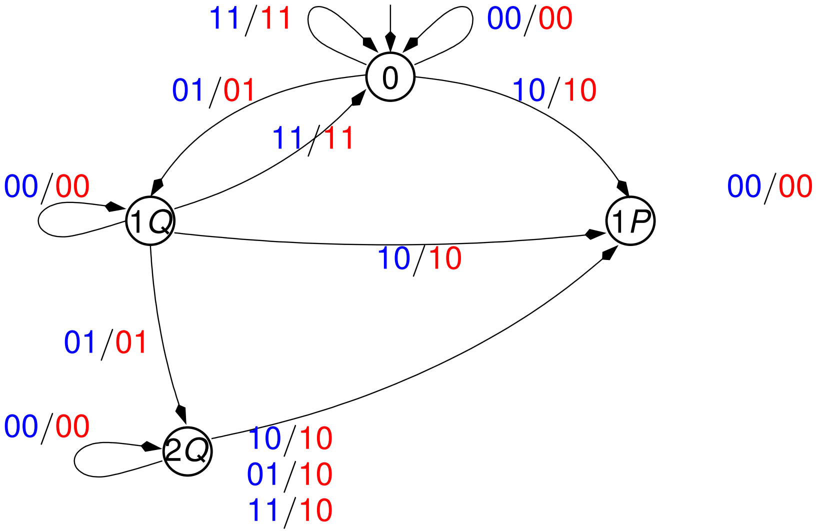

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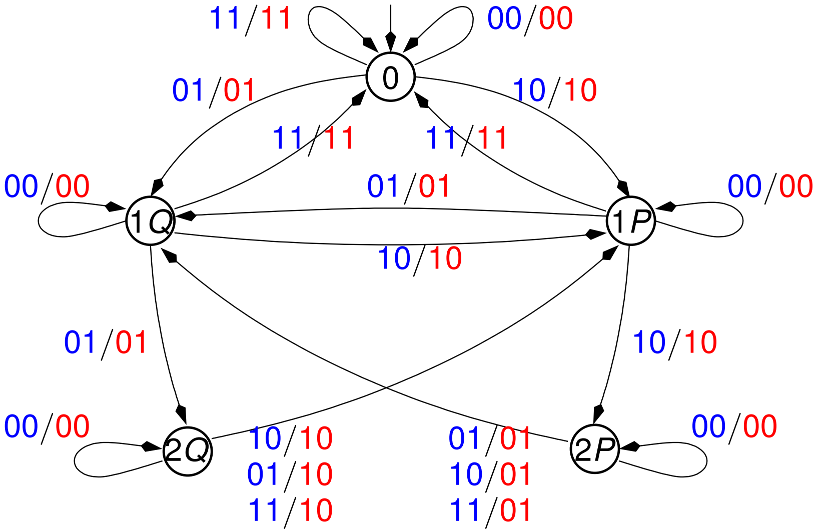
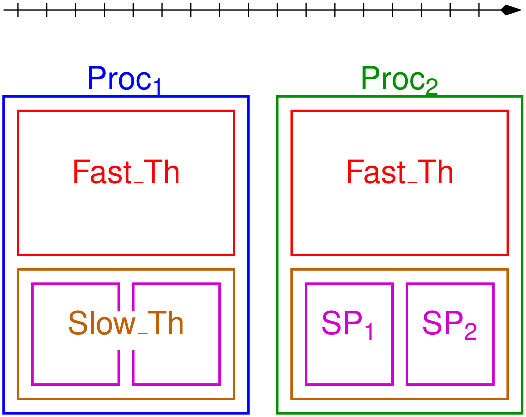


Processes: actual clocks



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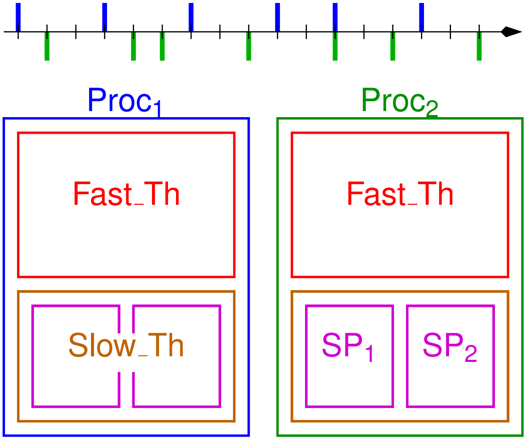
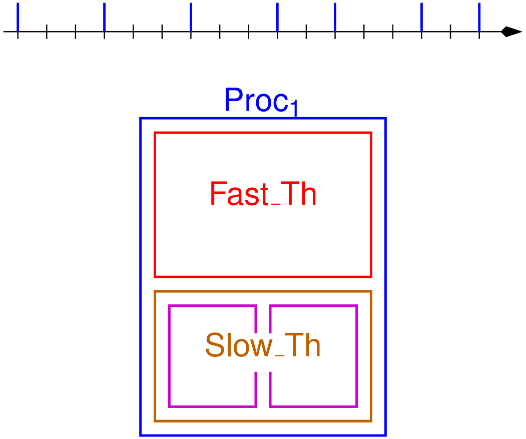


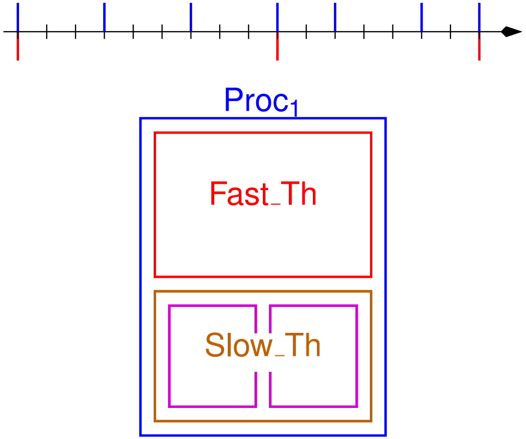
“Quasi-synchronous” clocks

used to count periods and deadlines

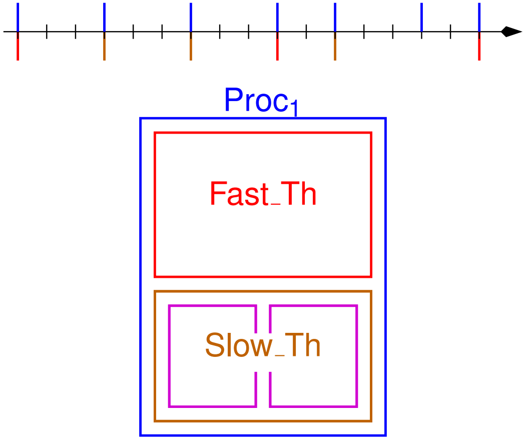
Threads: sharing the processor



Threads: sharing the processor

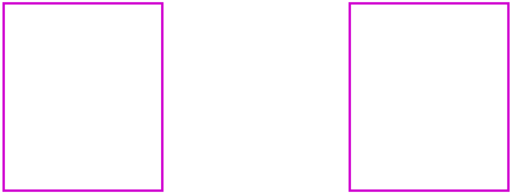


Threads: sharing the processor

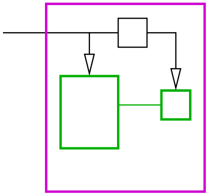


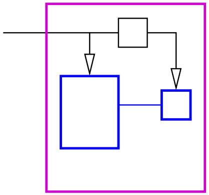
Activity clocks, used to count execution times

Subprograms: sequencing

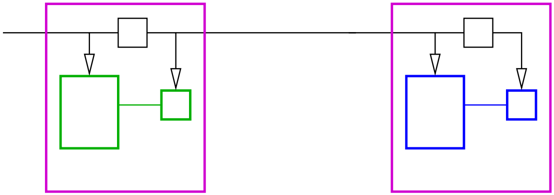


Subprograms: sequencing

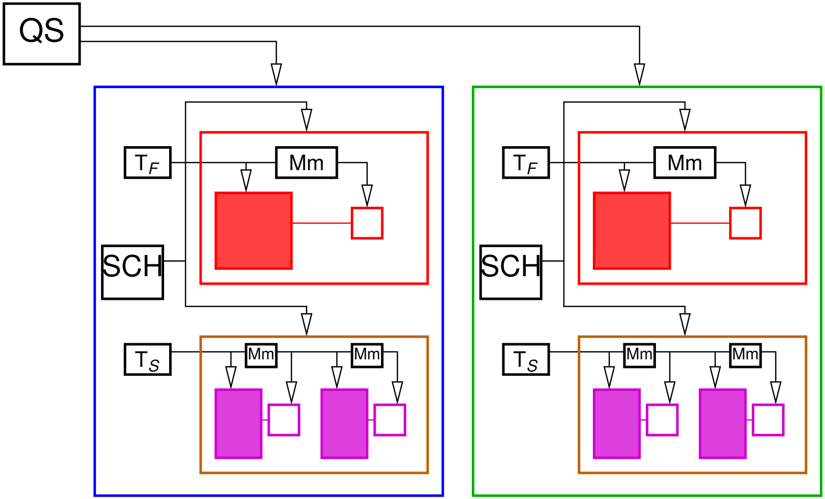




Subprograms: sequencing



Final model



Applications

- extensive simulation
  (using the tool LURETTE to generate oracles automatically)
- automatic verification
  - Example of property of the PFS:
    "at each instant, one and only one MSU is the master"

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  (using the tool LURETTE to generate oracles automatically)
- automatic verification
  - Example of property of the PFS:
    “at each instant, one and only one MSU is the master”
    Wrong, because of asynchrony.
    Right property:
    “at each instant, there is at most one master”
    “there are at most two clock cycles without master”

Other works

- deterministic communication [ACSD2006]
- scheduling policies and resource management [FASE2009]

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Conclusion

- Gives precise semantics to AADL
- Makes it executable (early simulation/validation)
- One more non-synchronous application of synchrony