Embedded Control:

From Asynchrony to Synchrony and Back

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Crisys Esprit Project

http://borneo.gmd.de/~ap/crisys/

A historical perspective based on the observation of several real-world systems during the Crisys Esprit project:

- **The Airbus "fly-by-wire" system.**
- **Schneider's safety control and monitoring systems for nuclear plants.**
- **Siemens' letter sorting machine control,**

and many other distributed safety-critical control systems.

Overview

- Real-time asynchronous languages.
- Synchronous practices.
- The formalisation of these practices.
- Real-time and distribution: the need for robustness.
- Asynchronous synchronous programming.

Basic Needs of the Domain

- **Parallelism:**
  - **between the controller and the controlled device**
  - **between the several degrees of freedom to be controlled at the same time**
- **Guaranteed bounds :**
  - **on memory**
  - **on execution times**
- **Distribution**

The Computer Science Answer:

Real-Time Kernels and Languages

Based on the concurrency tradition of operating systems:

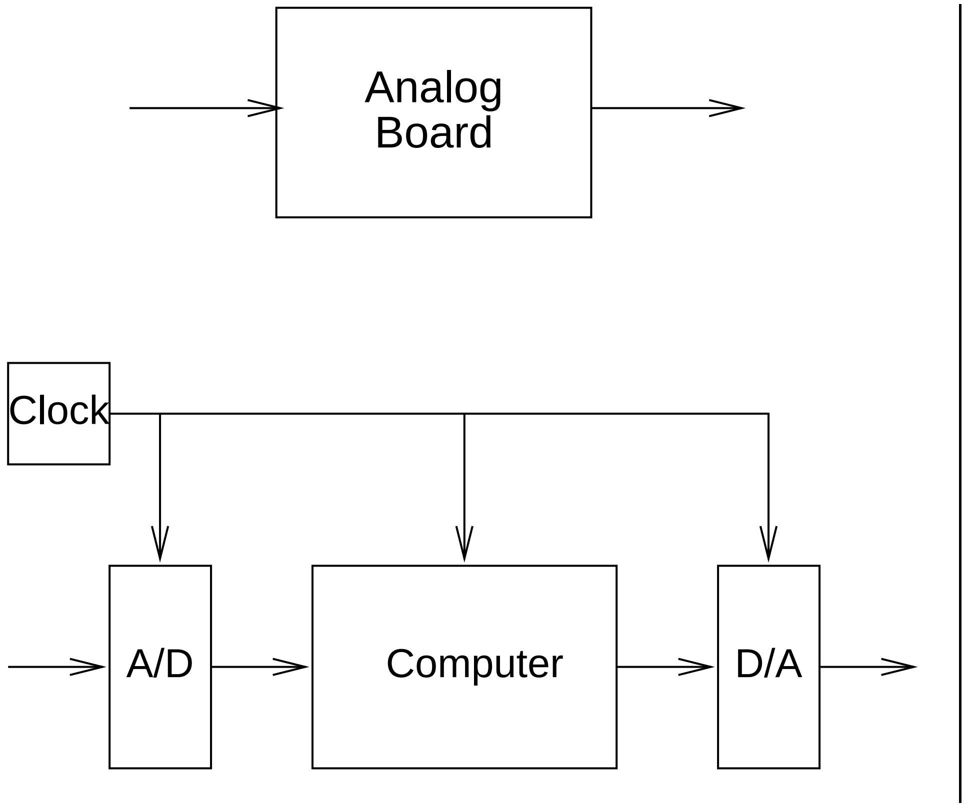
- Synchronisation: semaphores, monitors, sequential processes,
- Communication: shared memory, messages,
- Synchronisation + communication: queues, rendez-vous.

Examples:

- CSP, OCCAM,
- ADA tasking
- real-time OS

The Evolution of Practices

From analog boards to computers:



periodic clocks

synchronous programs

Periodic Synchronous Programming

```
initialize state;

loop each clock tick

   read other inputs;
   compute outputs and state;
   emit outputs

 end loop
```

Practical Interest

- **Perfectly matches:**
  - **the need for real-time integration of differential equations: forward, fixed step methods,**
  - **the mathematical theory of sampled control systems,**
  - **the theory of switching systems.**
- **Safety, simplicity and efficiency:**
  - **no OS, a single interrupt (the real-time clock), no context saving (the interrupt should occur at idle time)**
  - **bounded memory, bounded execution time.**

$\Rightarrow$ **Easy validation, certification**

Generalisation: Synchronous Languages

```
initialize state;

loop each input event

   read other inputs;
   compute outputs and state;
   emit outputs

 end loop
```

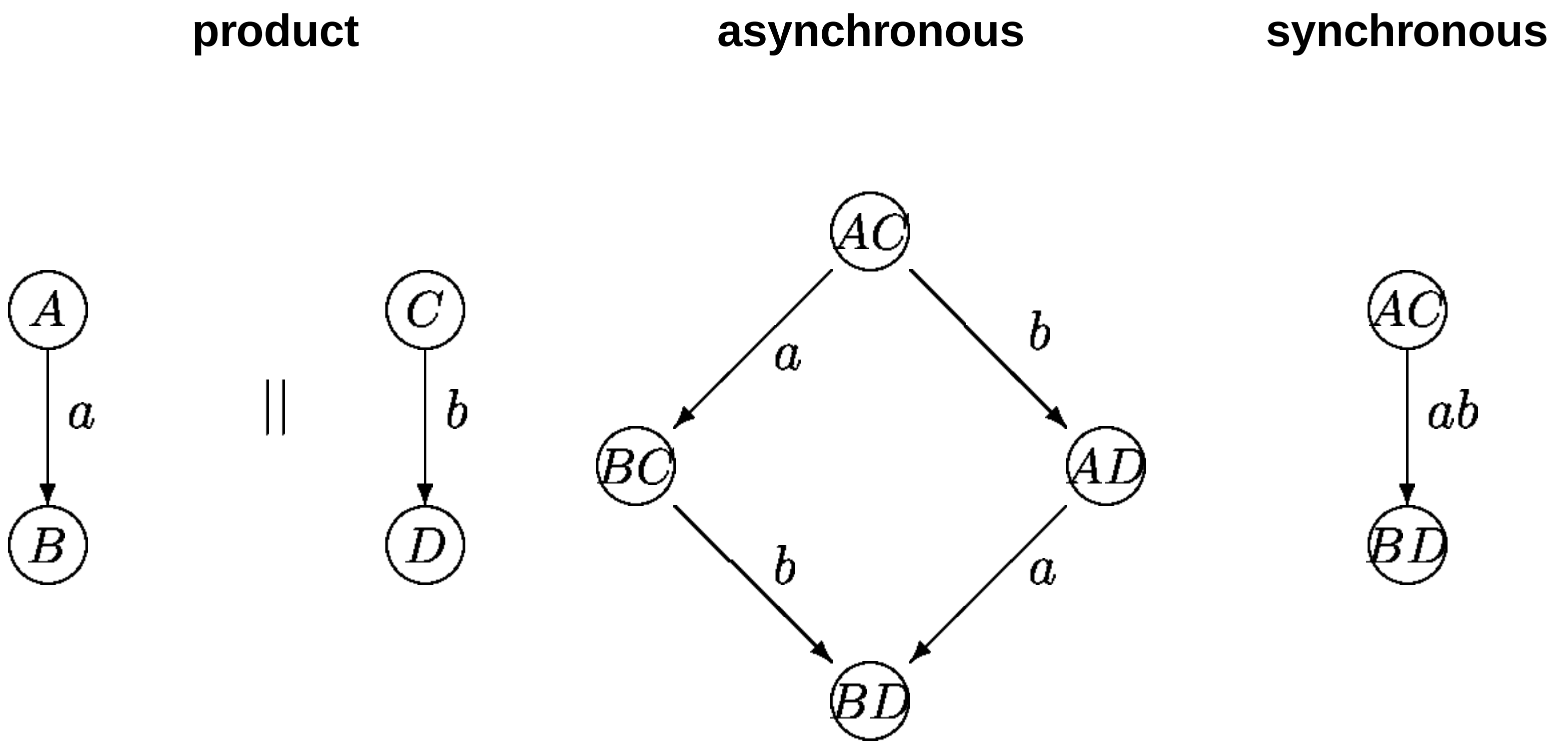
Several styles (imperative, data-flow,...)

Compiled parallelism (instead of concurrent

most applications of synchronous programming are actually periodic ones.

Theory: SCCS (Milner)

Based on the synchronous product of automata:



CCS (asynchronous) is a sub-theory of SCCS

Provides a theoretical justification of practice:

Synchronous primitives are stronger, programming is easier

Further Justifications (Berry)

- **No added non determinism:**
  - **easier debugging and test**
  - **less state explosion in formal verification**
- **Easier temporal reasoning:**
  - **synchronous steps provide a "natural" notion of logical time:**

    in a concurrency framework `delay 5 seconds` **means "a least 5 seconds" and is priority dependent.**
  - **Easier roll-back and recovery**

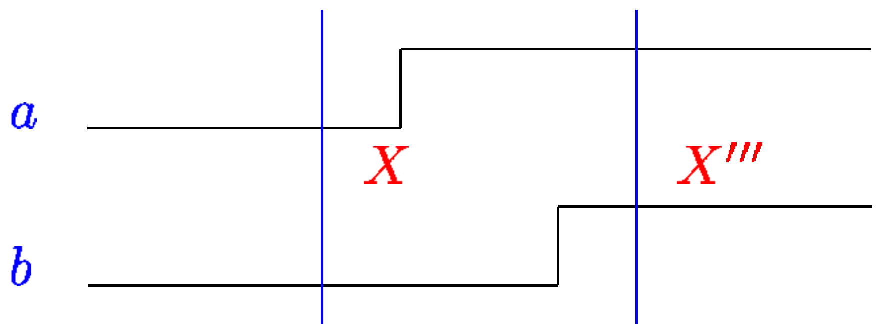
Provisional Conclusion 1:

These advantages seem conclusive and justify the practices.

But . . .

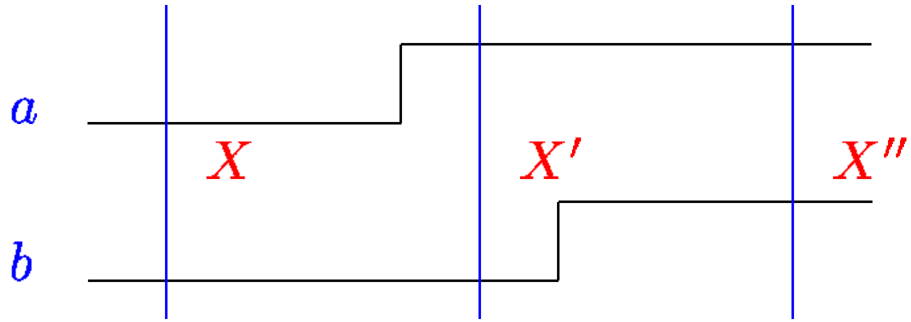
. . . Real-Time is not Logical Time: Sampling Tuples

A possible sampling



. . . Real-Time is not Logical Time: Sampling Tuples

Another possible sampling



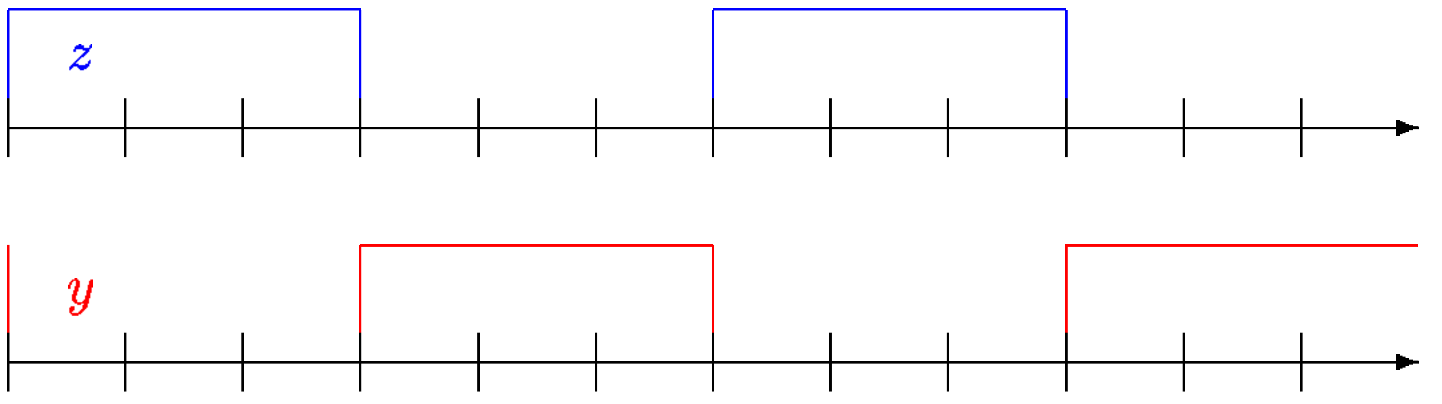
Non determinism, possible race

This was considered a side effect, but practitioners must take it into account.

. . . Real-Time is not Logical Time: Outputs

example : **mutual exclusion** `always not (y and z)`

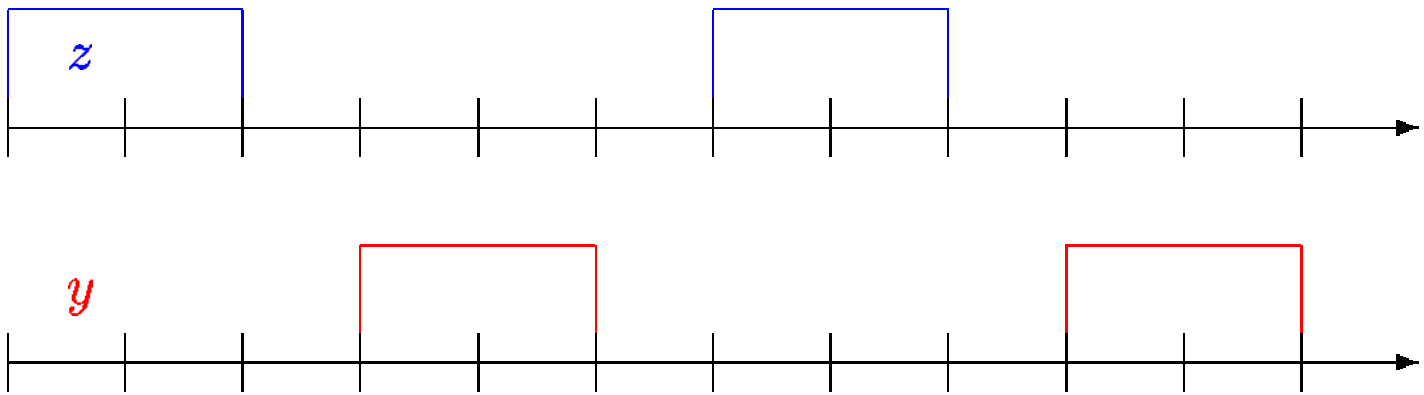
a non robust solution :



. . . Real-Time is not Logical Time: Outputs

example : mutual exclusion `always not (y and z)`

a robust solution :

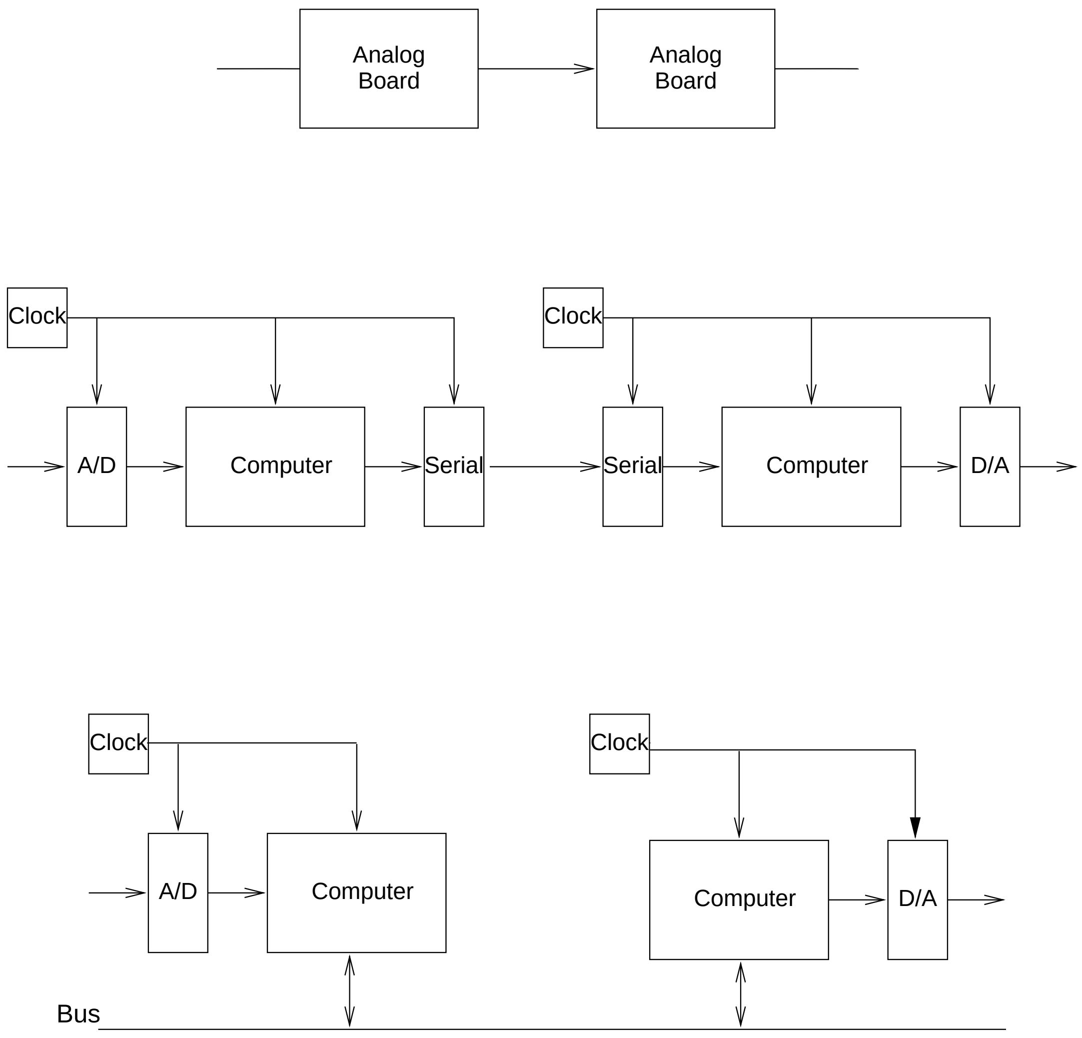


z **waits for** y **to go down before going up and conversely.**

no race !

. . . Distribution

From networks of analog boards to local area networks



independent periodic clocks

synchronous programs

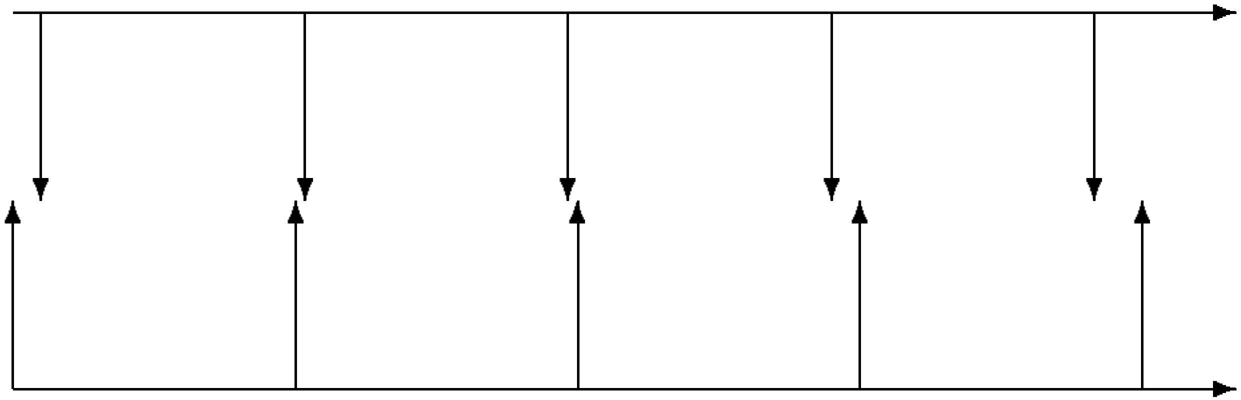
Interest

Autonomy, robustness

- Each computer is a complete one, including its own clock and even possibly its own power supply.

- Communication between computers is non-blocking, based on periodic reads and writes, akin to periodic sampling.

Some Consequences of Quasi Periodicity



Worst situation: reads occur just before writes $\Rightarrow$ Bounded communication delays

Absolute time is lost: time-outs better than time ???

Sampling errors: data loss or duplication from time to time

Bounded Fairness

Provisional Conclusion 2

Real-time and distribution require accommodating some asynchrony within the synchronous programming paradigm.

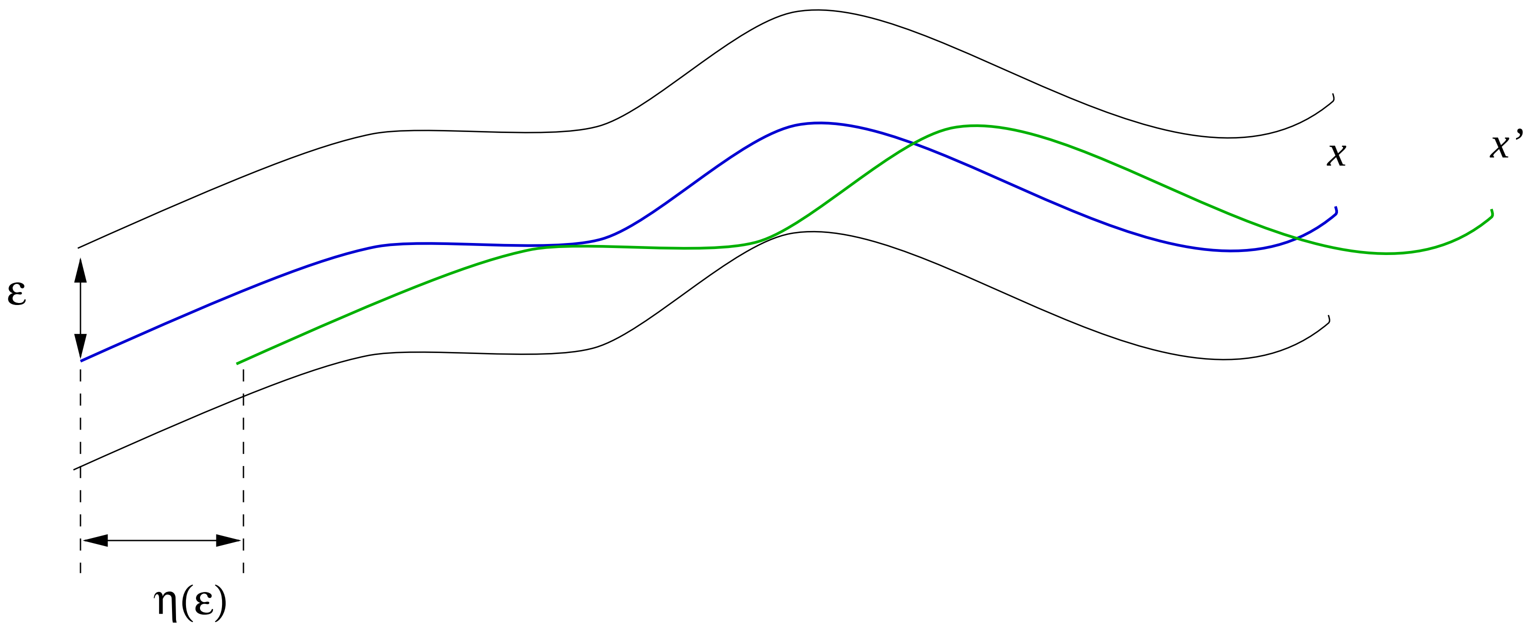
In the sequel we investigate some tracks taken by practioners in this purpose.

Asynchronous-Synchronous Programming:

How to understand it ?

- **Continuous Systems**
- **Non Continuous Systems**
- **(Mixed Systems)**

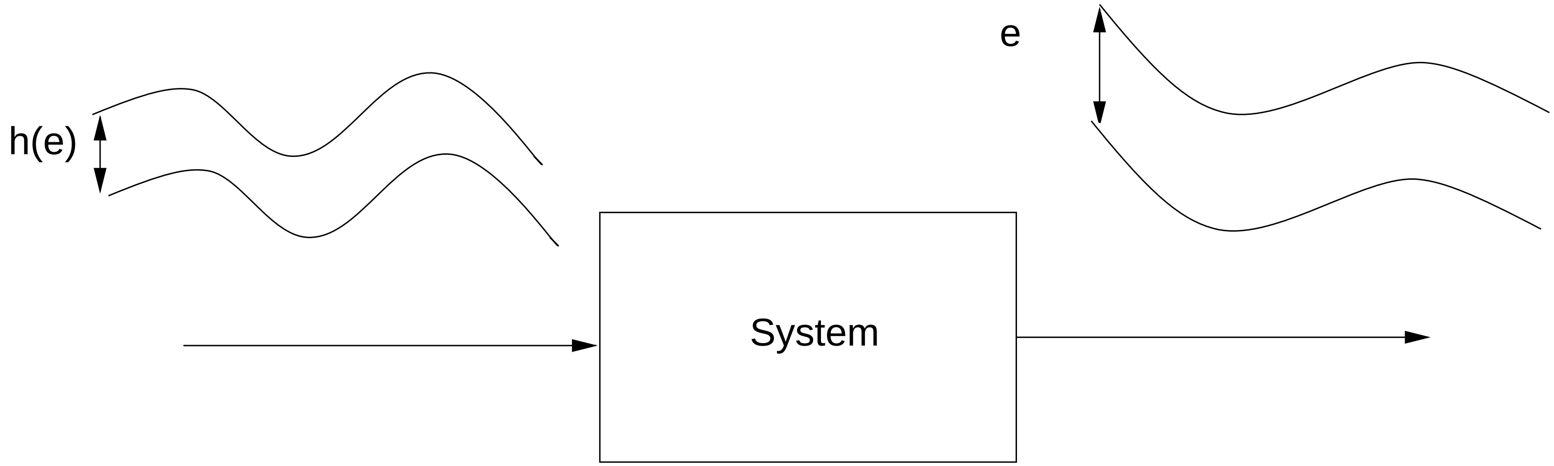
Uniformly Continuous Signals



$$\forall \epsilon > 0, \exists \eta > 0, \forall t, t', |t - t'| \leq \eta_x \Rightarrow |x(t) - x(t')| \leq \epsilon$$

Bounded delays yield bounded errors

Uniformly Continuous Systems



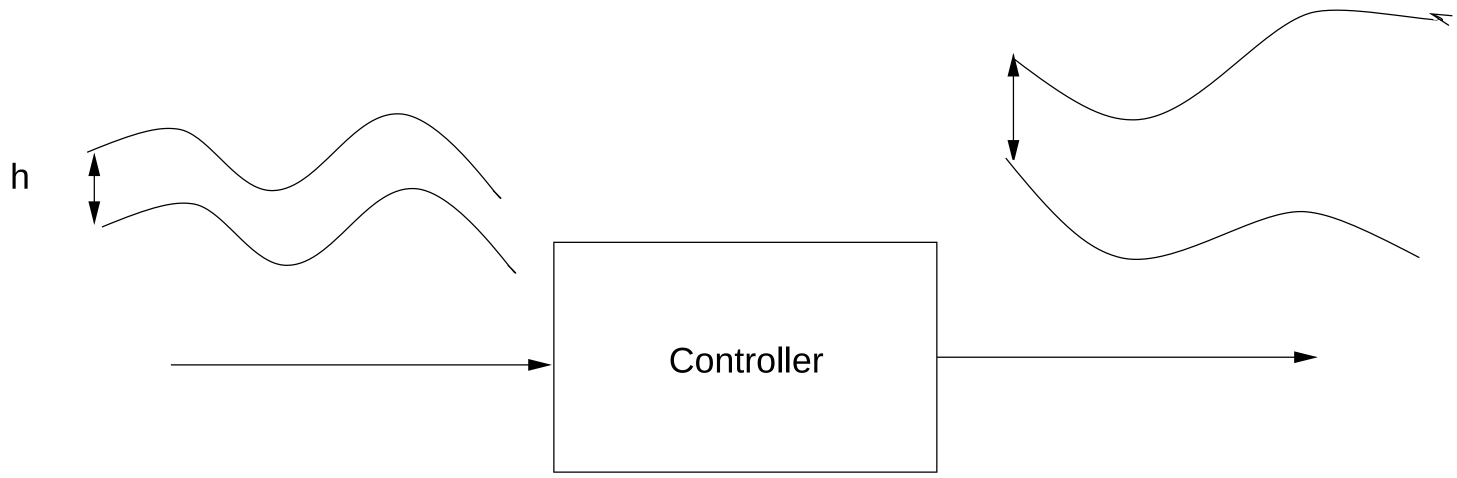
$$\forall \epsilon > 0, \exists \eta > 0, \forall x, x', ||x - x'||_\infty \leq \eta \Rightarrow ||f(x) - f(x')||_\infty \leq \epsilon$$

Bounded errors yield bounded errors

But . . .

Even very simple controllers are not uniformly continuous.

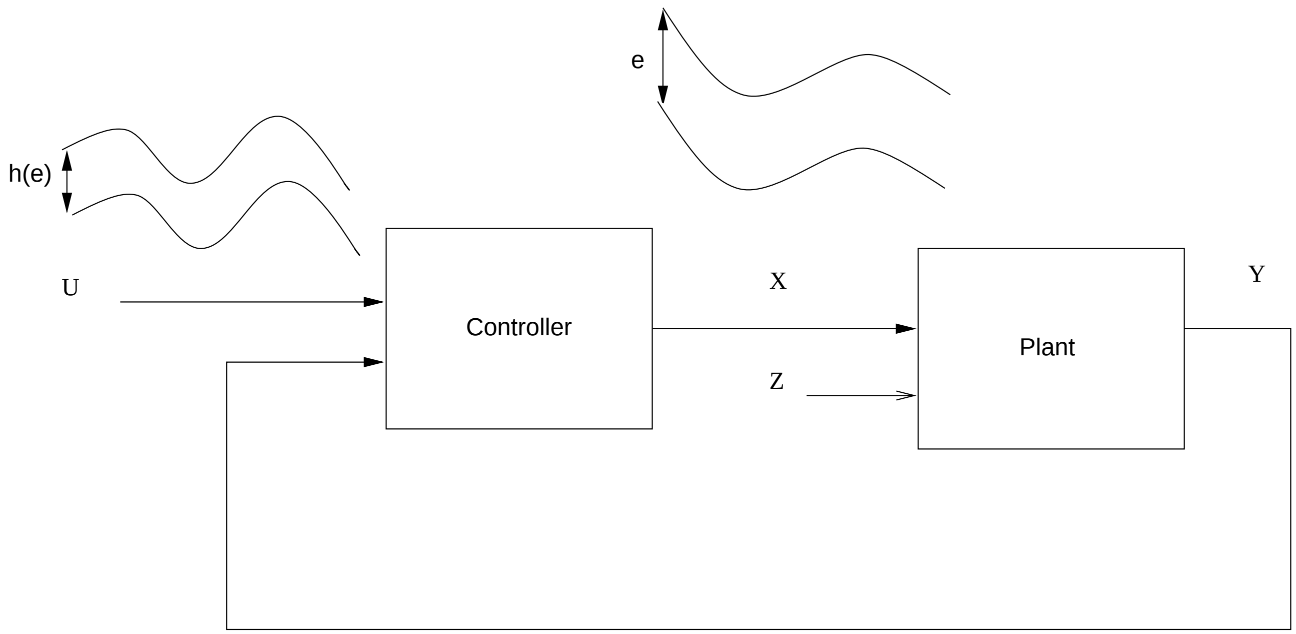
PID for instance



Bounded errors do not yield bounded errors

Stabilized Systems

The closed-loop system computes uniformly continuous signals



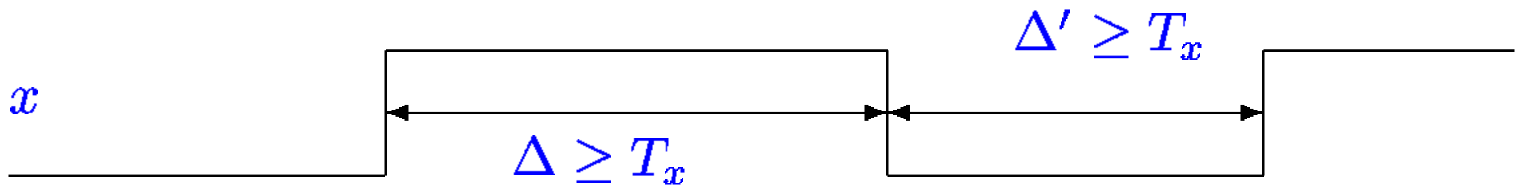
Bounded delays yield bounded errors

Non Continuous Systems

- **Combinational Systems**
- **Robust Sequential Systems**
- **Sequential Systems**

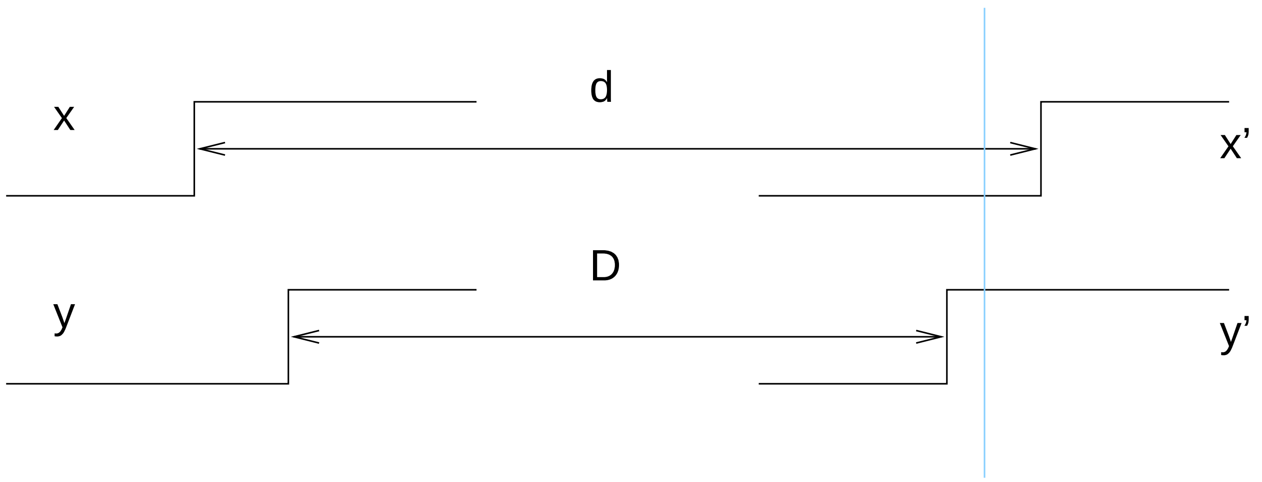
Uniform Bounded-Variability

There exists a minimum stable time T_x associated with a signal x.



But . . .

Delays on tuples do not yield delayed tuples



Solution : Confirmation functions

Confirmation Functions

When a component of a tuple changes, wait for some $\Delta_{max} - \Delta_{min}$ time before taking it into account.

If x', y' are $(\Delta_{min}, \Delta_{max})$ bounded images of x and y,

then $confirm(x', y')$ is a delayed image of (x, y)

allows to retrieve the continuous framework

Robust Sequential Systems

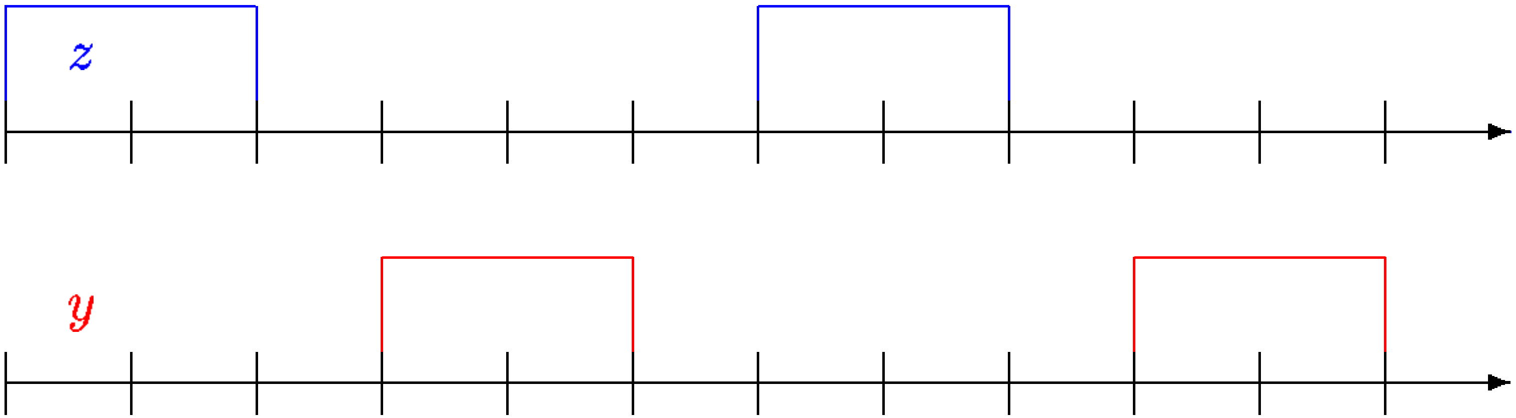
idea : avoid (critical) races

- between state variables : order insensitivity
- between inputs : confluence

Property checking

Asynchronous programming style

Asynchronous Programming Style



Insert causality chains disallowing races:

z waits for y to go down before going up and conversely.

$$\begin{array}{l} not\ y \\ not\ z \end{array} \quad ((\rightarrow y \rightarrow not\ y)^* (\rightarrow z \rightarrow not\ z)^*)^*$$

Provisional Conclusion 3

- Some insight on techniques used in practice.

- Maybe useful for designers and certification authorities

  (Crisys Esprit Project)

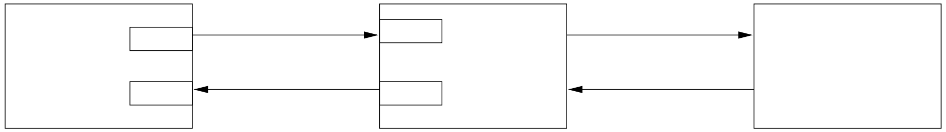
- An attempt to draw the attention of the Computer Science community on these important problems.

Questions

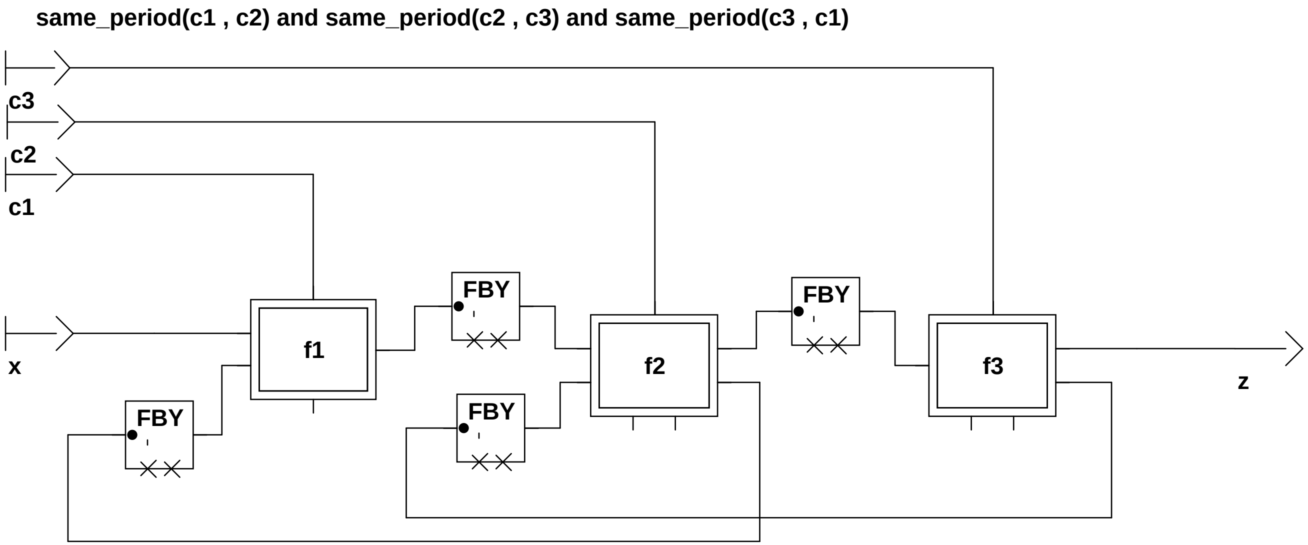
- **Are there linguistic ways to robustness (asynchronous-synchronous languages)?**
- **How to safely encompass some event-driven computations within the approach?**
- **Is there a common framework encompassing both theories?**

continuous	discrete
uniformly continuous signals	uniform bounded variability
uniformly continuous functions	robust systems
unstable systems	sequential non robust systems

How to formalize it



Net View on chain - eq_chain

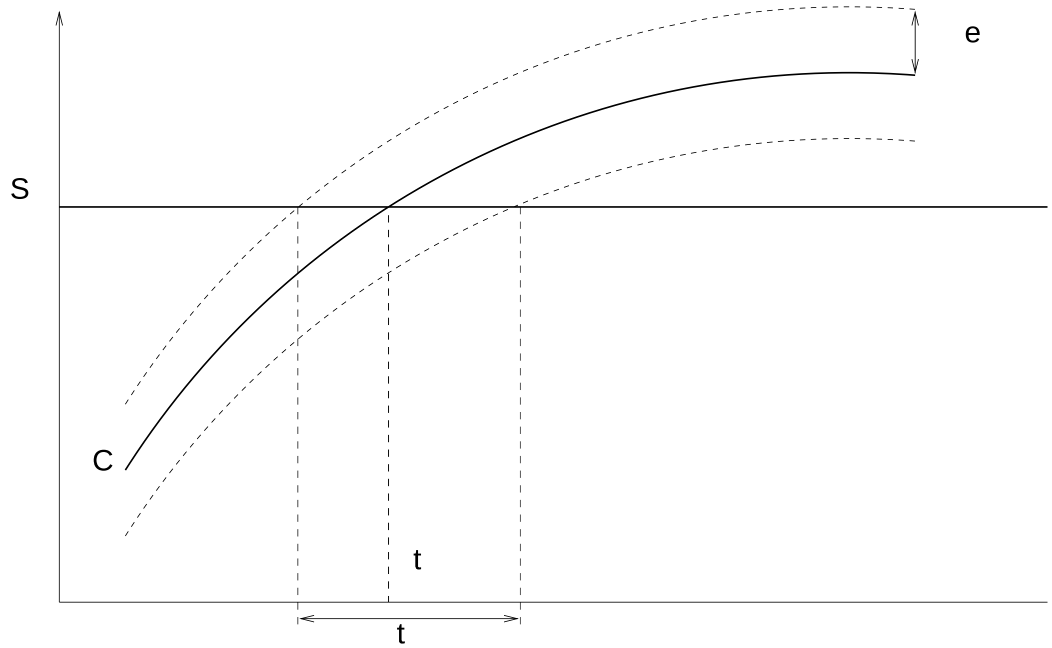


Synchronous simulation, test and verification tools apply

Efficiency issues ?

Mixed Systems

Example : **Threshold crossing**

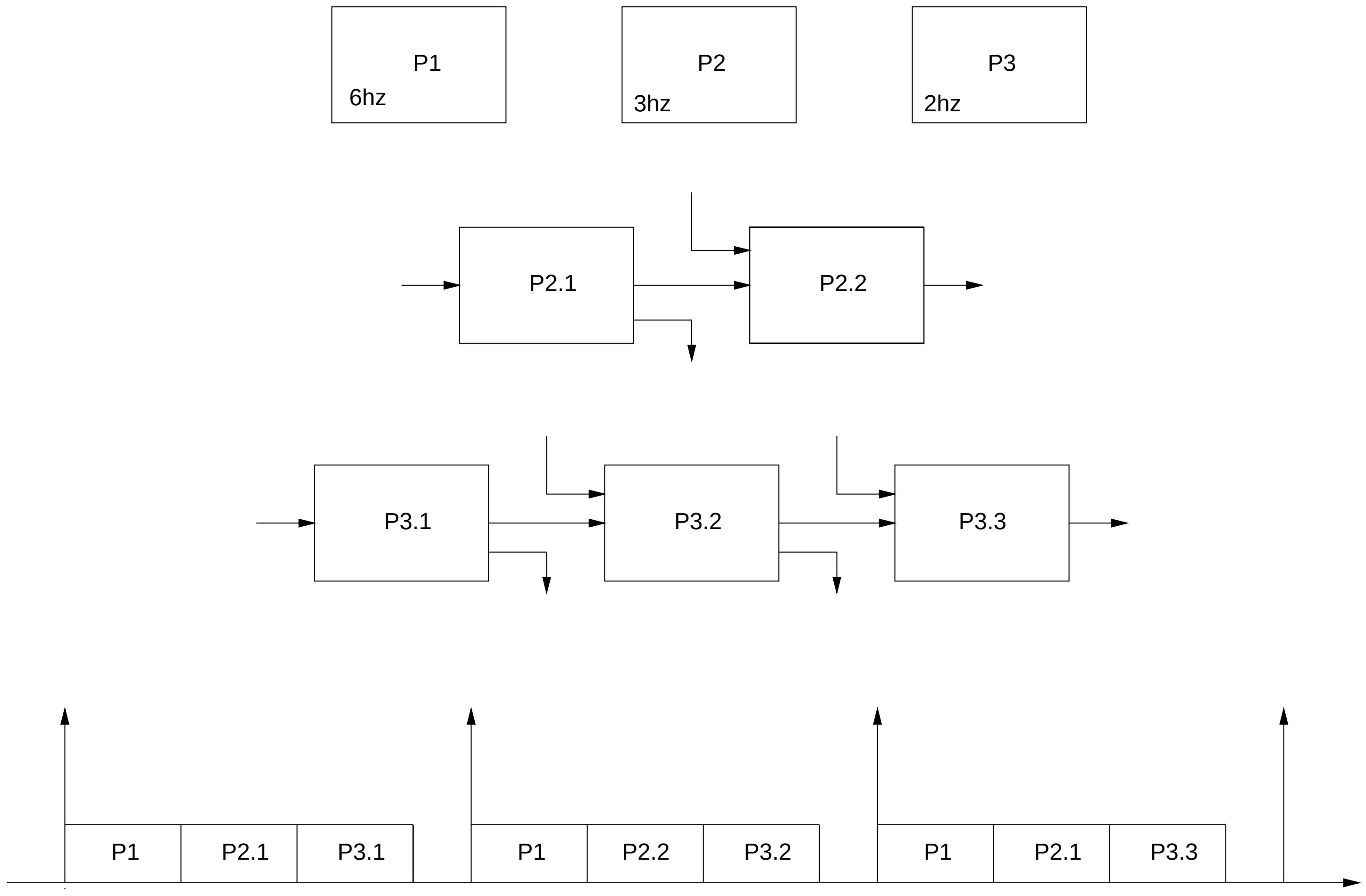


Relates errors and delays : $\tau = \dfrac{2\epsilon}{|C'(t)|}$

This analysis too should not be skipped

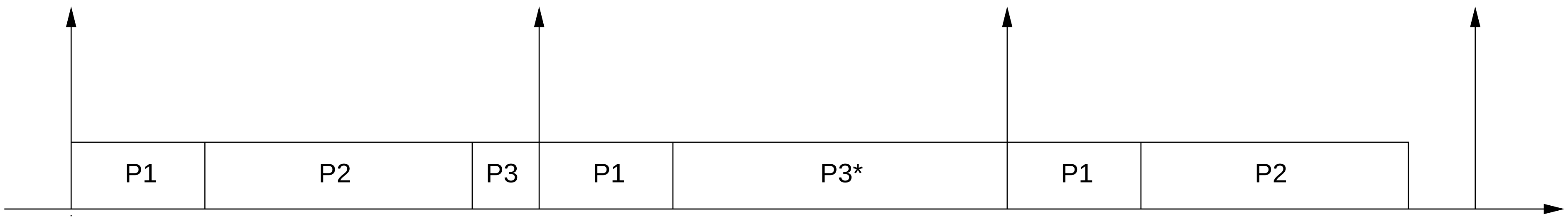
Concurrency

Actual Practices (Airbus)



Concurrency

A Crisys Proposal: earliest deadline preemptive scheduling



Schedulability condition

$$\sum_{i=1,n} \frac{WET_i}{T_i} < 1$$

Generalizes the synchronous program execution condition

$$WET < T$$

Concurrency

Exact functional semantics is guaranteed as soon as

Slow processes communicate with fast processes through a slow clock unit delay

c	t	f	t	f	t
x	x_0	x_1	x_2	x_3	x_4
$x \downarrow c$	x_0		x_2		x_4
$f(x \downarrow c)$	$f(x_0)$		$f(x_2)$		$f(x_4)$
$z = z_0 \Delta f(x \downarrow c)$	z_0		$f(x_0)$		$f(x_2)$
$(z_0, z) \uparrow c$	z_0	z_0	$f(x_0)$	$f(x_0)$	$f(x_2)$

Non Robust Sequential Systems

require either soft or hard synchronization.

`Time Triggered Architecture` **for instance.**