Hybrid Systems Modeling Challenges caused by CPS

CPS course for NIST executives, January 2012

Albert Benveniste
Timothy Bourke, Benoît Caillaud, Marc Pouzet

Virtual Engineering in CPS

Albert Benveniste

20 January 2012

Virtual engineering everywhere

Helping over 30 different teams and skills in the company work together

Linking over 40 different EE design representations throughout the entire development process

Ensuring that the EE design flow is integrated at the same level of quality and performance as the 3D CAD system

Model based design and executable specification in the OEM/supplier chain

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CAD models

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Dassault Systèmes Delmia and Catia
http://www.3ds.com/products

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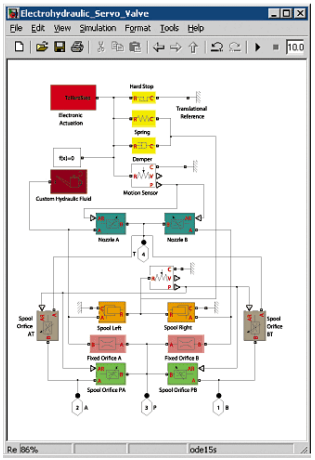

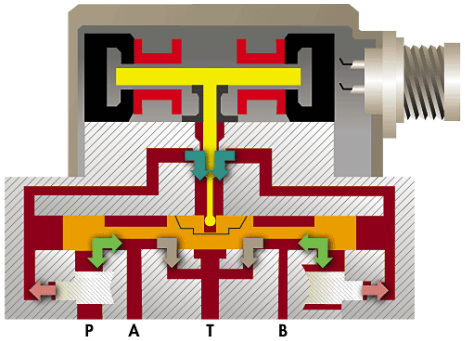

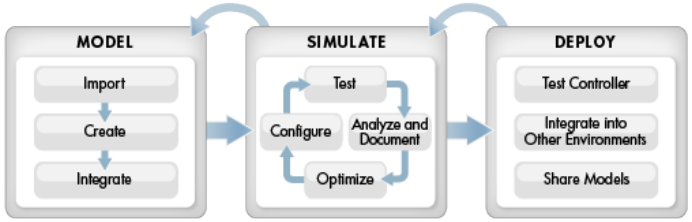

http://www.mathworks.fr/products/simscape/index.html

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Embedded Software

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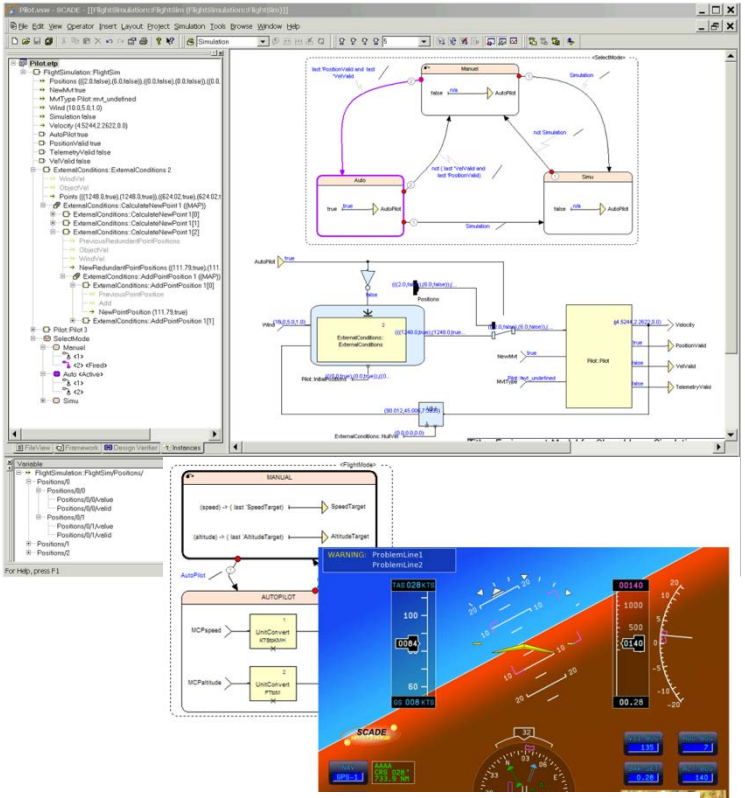

http://www.esterel-technologies.com/products/scade-suite/
http://www.esterel-technologies.com/products/scade-display/

Virtual engineering everywhere
Application+Architecture models

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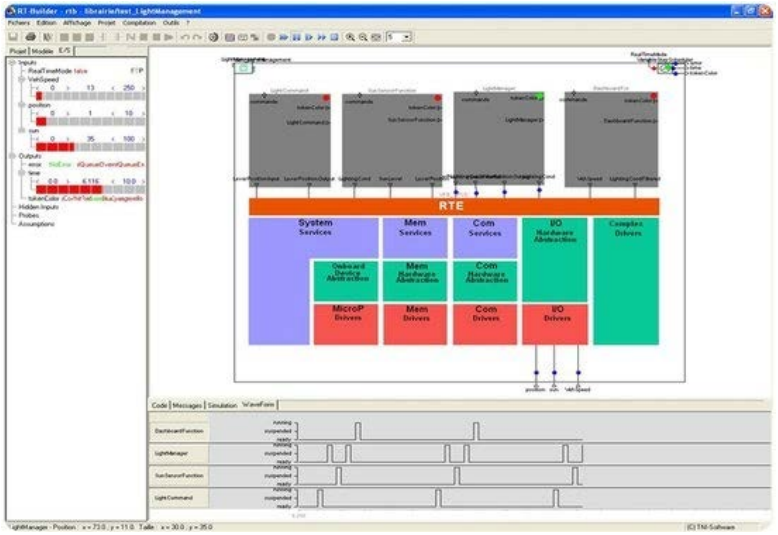

RT-Builder: modeling advanced RTOS and Bus libraries. ARINC653, CAN, OSEK, FlexRay standards. Can easily be customized or extended to provide a powerful support of customer's real-time design choices. Users can model: interactions between control and data functions, concurrency, multi-tasking, pre-emptive actions, shared resources, event routing and filtering, FIFO buffers, point-to-point data propagation time, etc...

Virtual engineering for CPS: the enablers

Seamless modeling

PLM/CAD

Multi-physics

CPS functions

Architecture

- ECU
- communications

Resources

- time,
- energy,
- memory,
- weight

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models from PLM

do *not* build models by hand!

Quality, certification

Executable models

- reproducible executions
- avoid unwanted non-determinism

Analyzable models

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Must reuse basic domains

- Discrete time
- Continuous, real, time
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Consequences for Hybrid Systems modeling in CPS

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Is the current situation good?

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Simulink® 7
User's Guide

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Is it the same discrete time everywhere?

- Discrete time

Simulink/Stateflow

- Simulation → development
- Two distinct engines
- Semantics & consistency: non-obvious

Two major difficulties

- Difficult to decide what is continuous/discrete (hard in Stateflow)
- Simulation is global

Is the current situation good?

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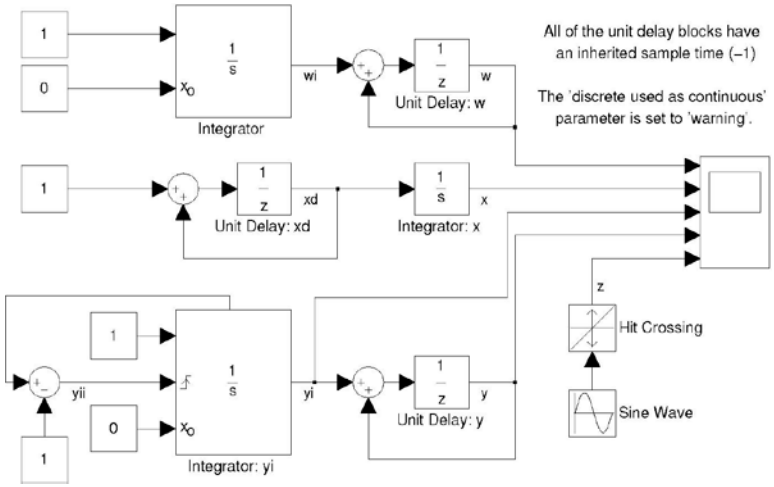

- It is allowed to construct diagrams in which "continuous" and "discrete" time blocks mix
- One (often) gets complaints and hints for parameter tuning

'Example4/Unit Delay: w' is discrete, yet is inheriting a continuous sample time; consider replacing unit delay with a memory block. When a unit delay block inherits continuous sample time, its behavior is the same as the memory block. Unit delay block's time delay will not be fixed and could change with each time step. This might be unexpected behavior. Normally, a unit delay block uses discrete sample time. *You can disable this diagnostic by setting the 'Discrete used as continuous' diagnostic to 'none' in the Sample Time group on the Diagnostics panel of the Configuration Parameters dialog box.*

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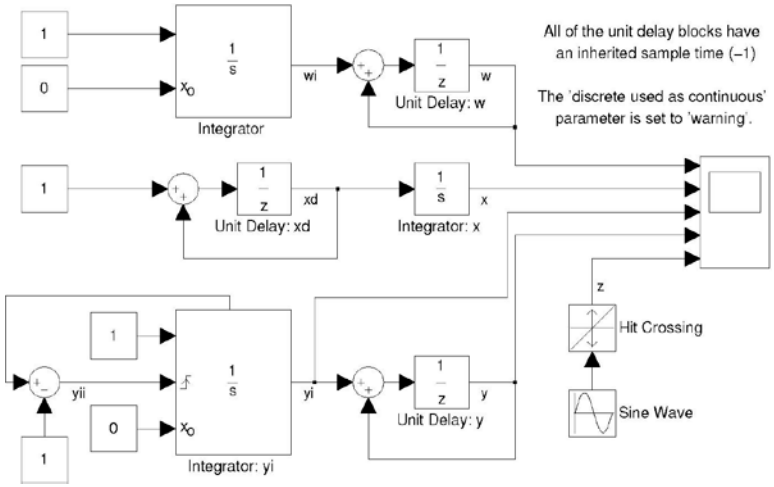

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Performing this yields: Warning: The configuration of the Unit Delay 'Example4/Unit Delay: w' is incorrect for handling a rate transition. Consider using the Rate Transition block to handle the data transfer between rates. Alternatively, you can control the diagnostic action for unspecified rate transitions on the Sample Time Diagnostics pane of the Configuration Parameters dialog box.

- Discrete time

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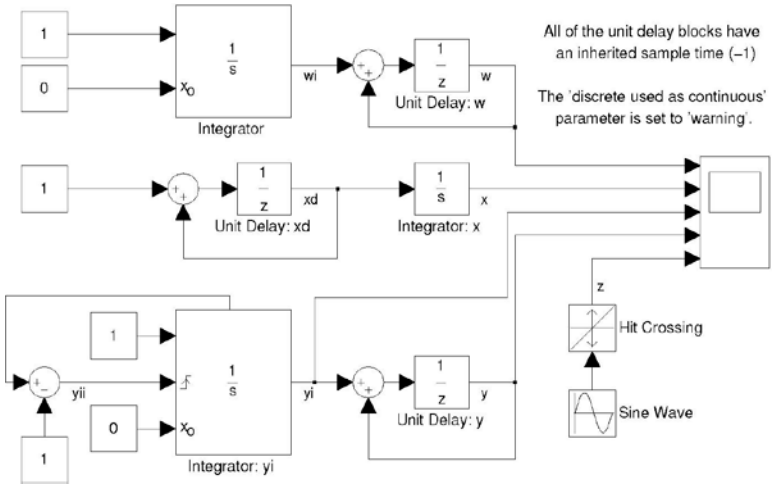

Disclaimer: this *not* a complaint against Simulink/Stateflow
The subject is difficult!

- It is allowed to construct diagrams in which "continuous" and "discrete" time blocks mix
- One (often) gets complaints and hints for parameter tuning
- Running this example results in unexpected couplings between the different outputs: changing the frequency of the sine change the other outputs, although there is no interaction other than sharing the simulator!

- Discrete time

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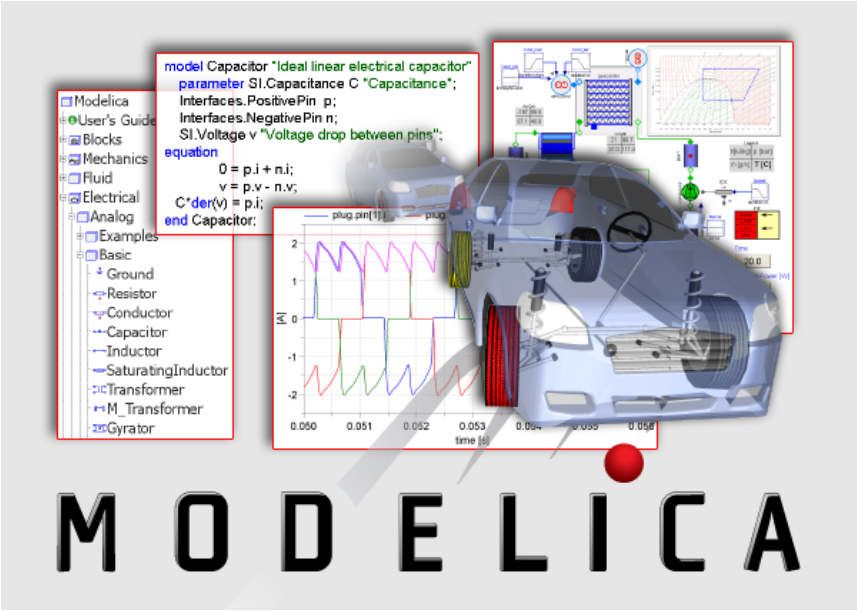

- Discrete time

Modelica group is currently working hard at separating

- Discrete reactions
- Continuous real-time
- Continuous dynamics

in the context of integrated virtual modeling

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Is it the same discrete time everywhere?

The Ptolemy Project has developed directors supporting process networks (PN), discrete-events (DE), dataflow (SDF), synchronous / reactive(SR), rendezvous-based models, 3-D visualization, and continuous-time models

- Discrete time

Ptolemy II delegates the blending of the different models to *directors*

When continuous-time models are involved, then the numerical solvers act as directors

Nice simulation examples of difficult hybrid systems

The physics can be difficult

Some difficulties from the physics

Non-determinism

- which side of the corner is hit first?

Cascades of hits

- in billiards
- in circuit breakers

Non-determinism in cascades of hits

French billiard

American billiard

Circuit breaker

Some difficulties from the physics

ABS brakes

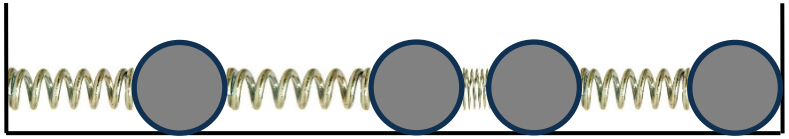
Chattering

- infinitely fast stop-and-go

The sticky masses (Ptolemy II)

three modes:

- free
- hitting
- sticking



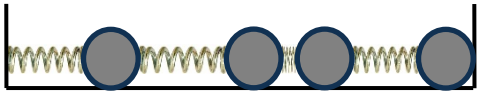
Some difficulties from the physics

Discrete time is subtle:

- Continuous dynamics and discrete events
- Cascades of causally related events
- Non-determinism in discrete events
- Non-determinism in cascades of events

How discrete is discrete?

- Chattering
- Looks discrete but time progresses



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Control interferes with

- Cascades of events
- Continuous dynamics (sampling)

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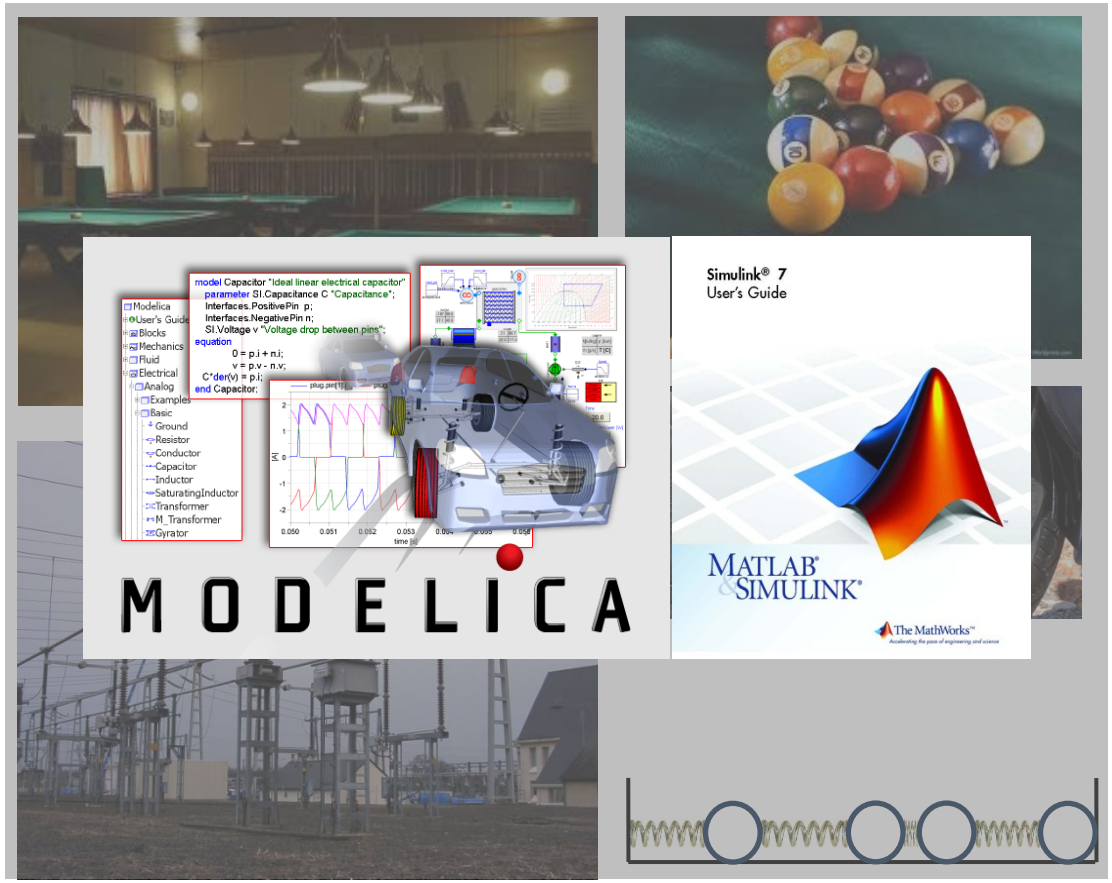
Unwanted couplings due to solvers

- Fast/Slow dynamics
- Zero-crossings, hot/cold restart



The problem with continuous/discrete

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20 January 2012

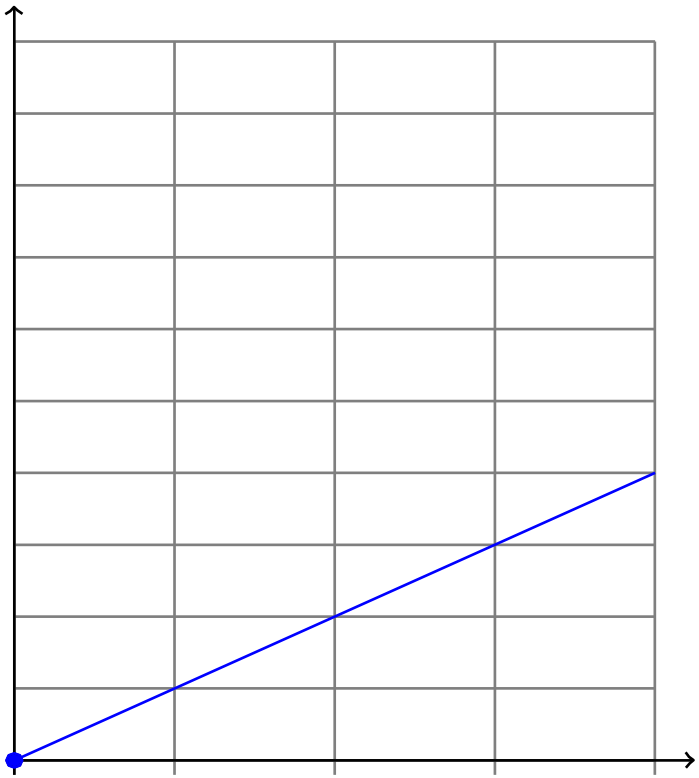
Which model makes sense?

Example

```
let node sum(x) = Cpt where
Cpt_n = Cpt_n-1 + x
```

Evaluate:

```
der  time = 1.0 init  0.0
y = sum( time )
```



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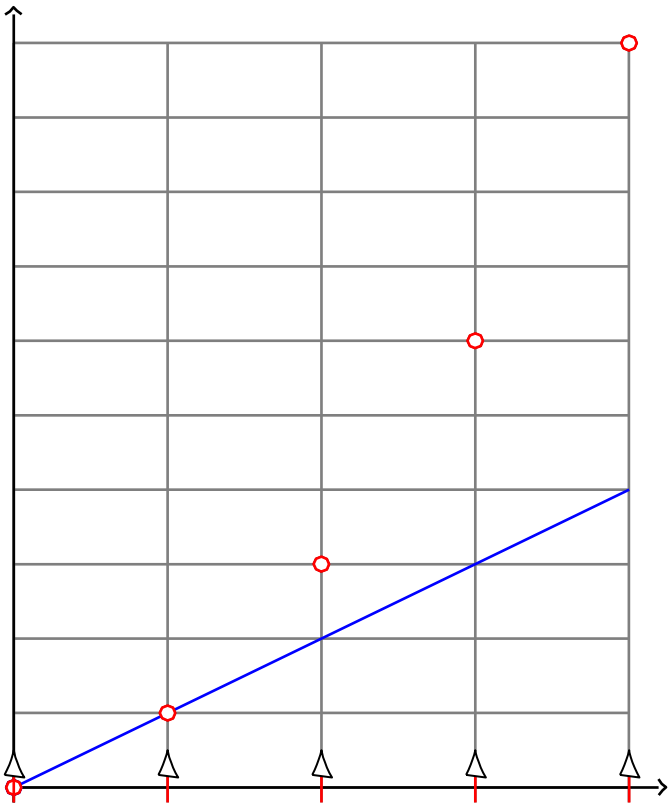
Interpretations

1. $N \subseteq R$



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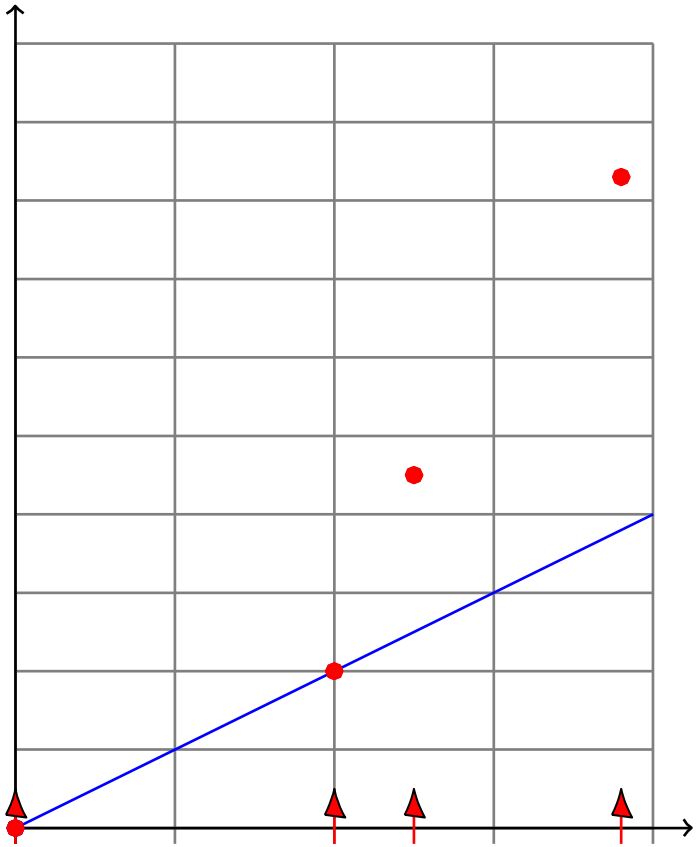

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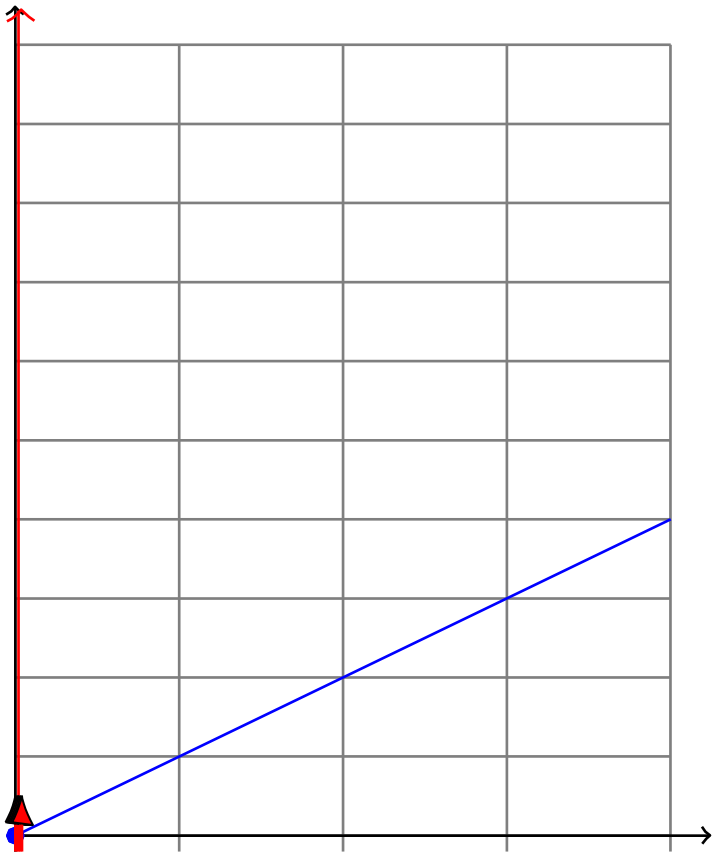
3. Infinitesimal discrete steps



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4. Reject the example

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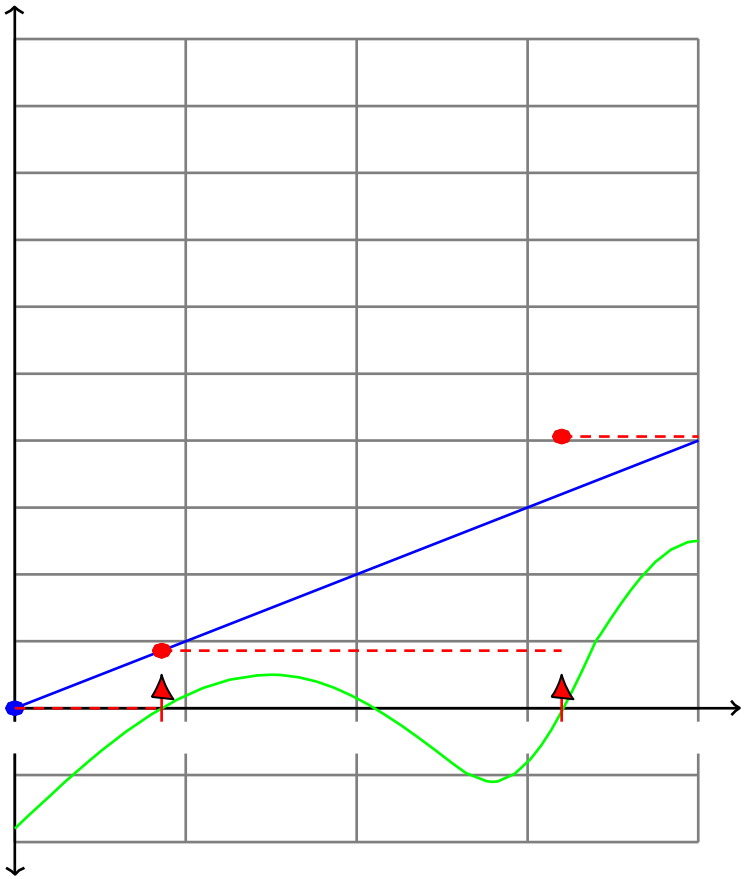
```

Evaluate:

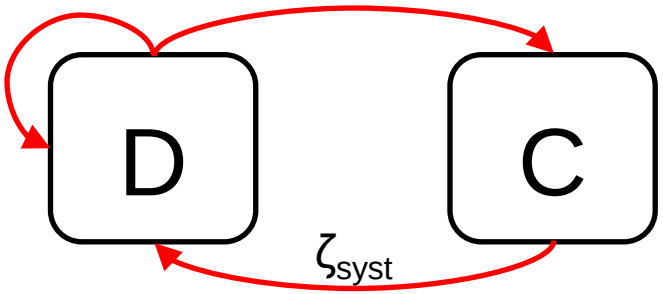
```
der  time = 1.0 init  0.0
y = sum( time ) every up(z)
```

Interpretations

1. $N \subseteq R$
2. Depends on the solver
3. Infinitesimal discrete steps
4. Reject the example
5. Explicit the missing synchro



Slicing Continuous/Discrete



- D: handled by the Discrete Engine (e.g., your favorite synchronous language)
- C: delegated to the solver
- C→D: zero-crossing detection (includes periodic sampling clocks)
- D→C: upon detecting end of cascade of events
- Slicing allows importing off-the-shelf
  - discrete-time modelers
  - continuous dynamics solvers

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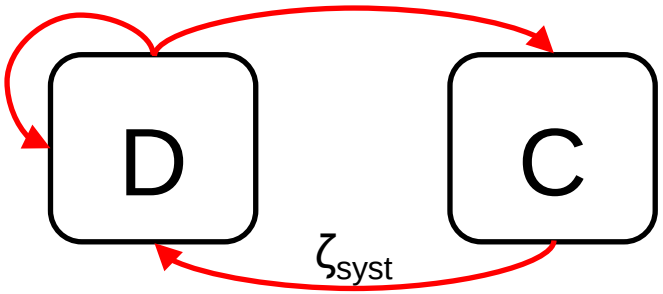

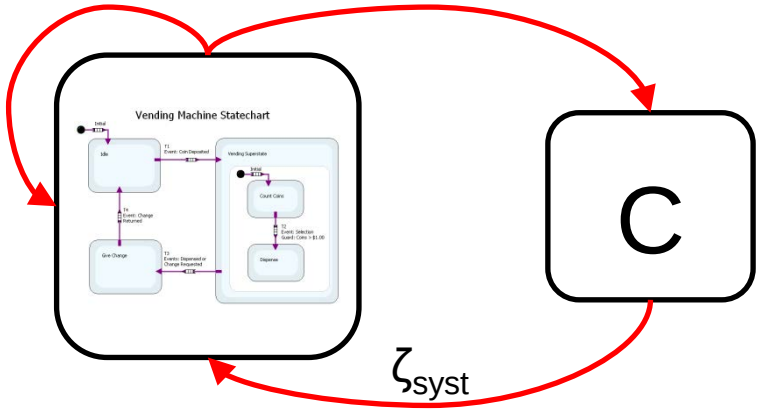

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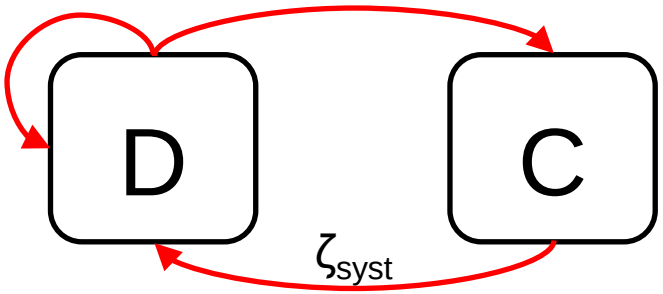
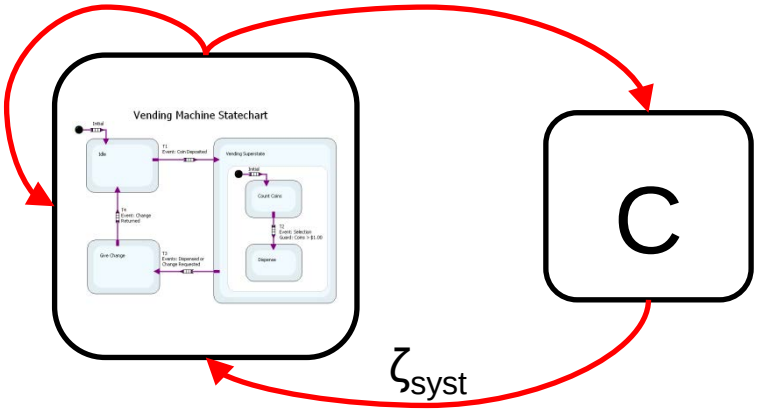
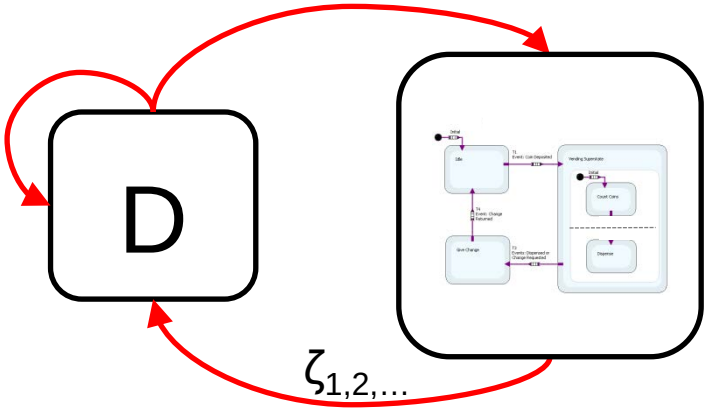
- Discrete time models of your choice
- Structured, multi-solver, simulation of continuous dynamics
  - to reduce unwanted coupling







Slicing is possible only if the language is well designed

statement	Assigned to D	Assigned to C
y = f (x)	on ζ_{syst} : y = f (x)	outside ζ_{syst} : y = f (x)
y = last (x)	on ζ_{syst} : y = last (x)	outside ζ_{syst} : y = last (x)
ζ = up(x)		ζ = up(x)
der(y) = x init y_0 reset z		der(y) = x init y_0 reset z
z = x every ζ init y_0	z = x every ζ init y_0	
z = pre (x) init y_0	z = pre (x) init y_0	

Slicing Continuous/Discrete

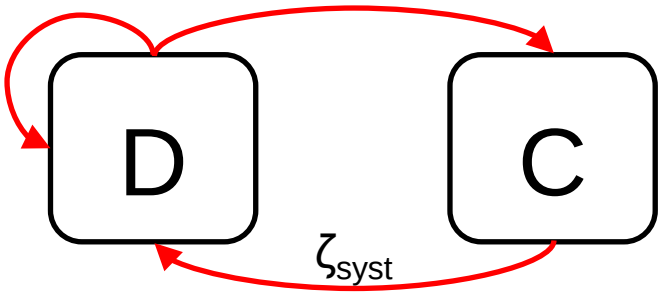
Slicing relies on typing A/C/D (A: any)

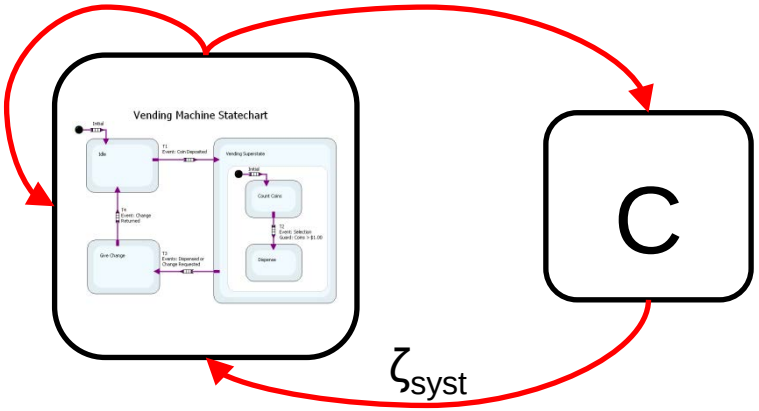
Key to good code generation

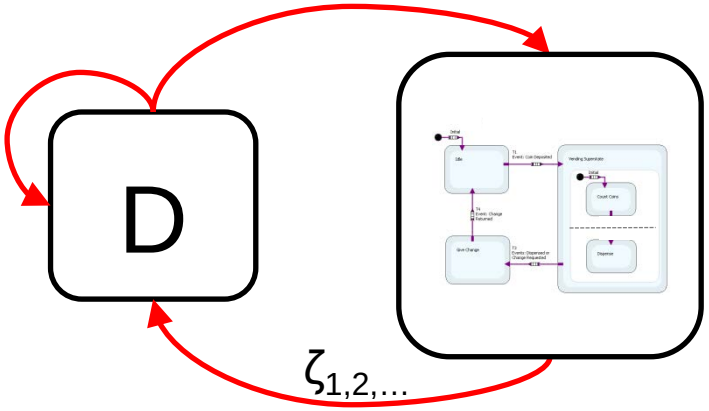
Typing A/C/D

- Variables and Wires
- Blocks (difficult)

How difficult is it on real languages?







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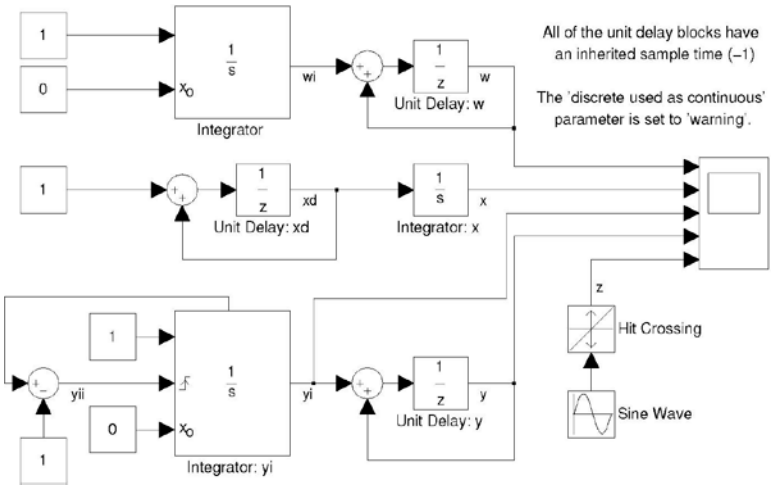
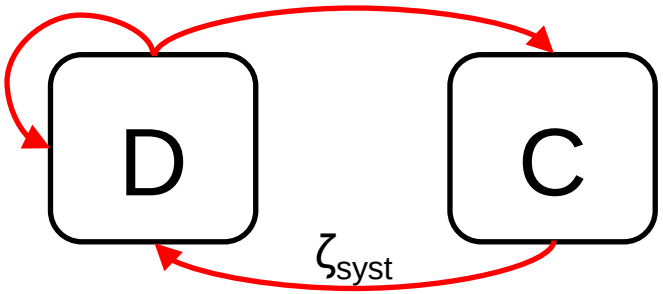
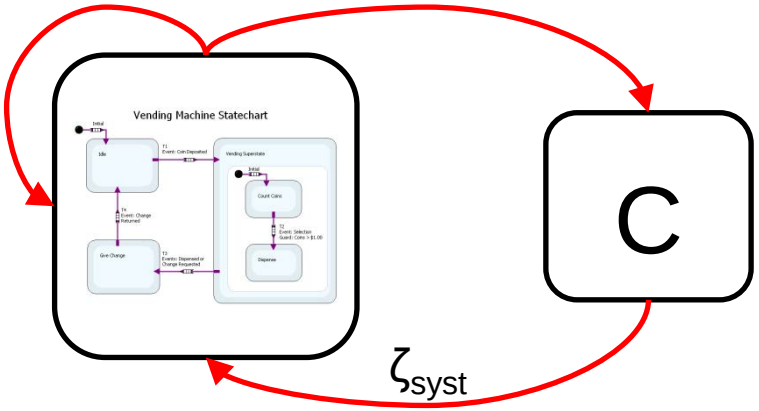
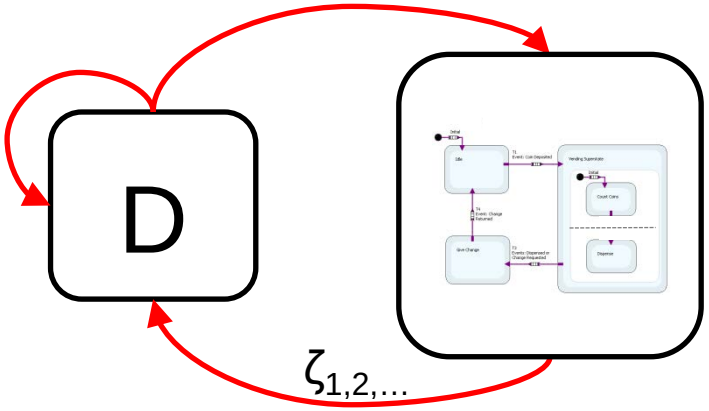
Doable in Simulink/Stateflow?









Slicing Continuous/Discrete

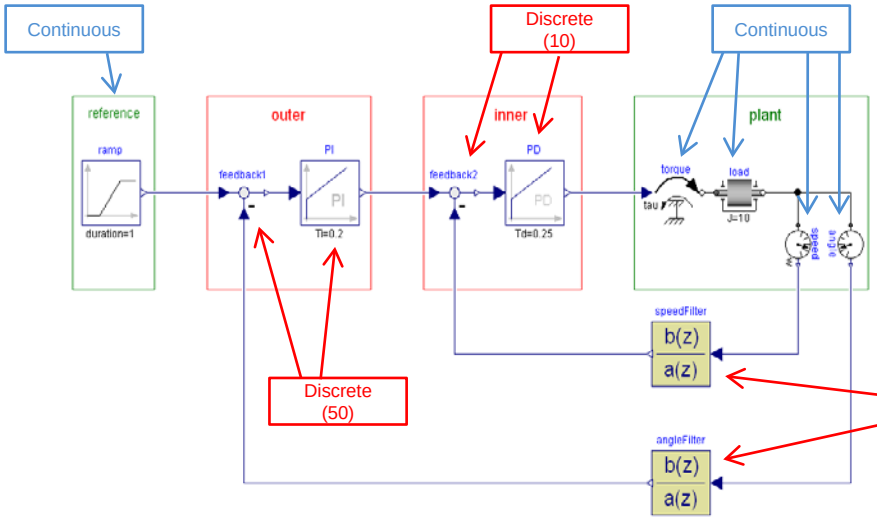
Slicing relies on typing A/C/D (A: any)

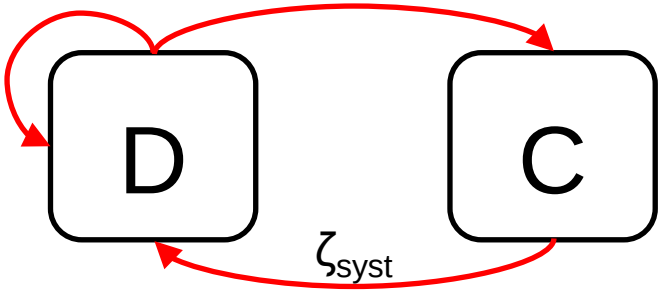
Key to good code generation

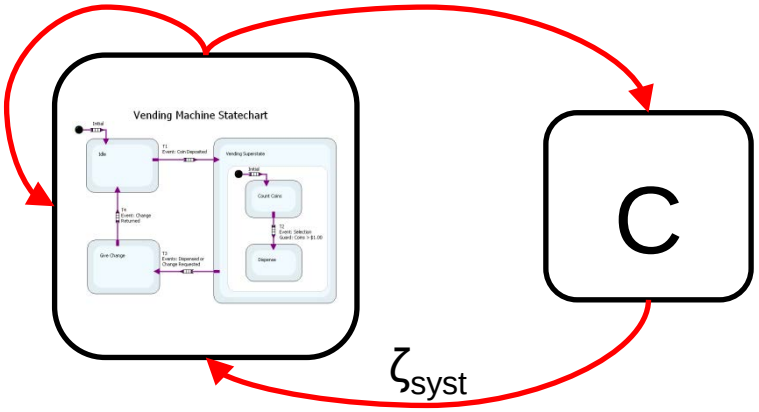
Typing A/C/D

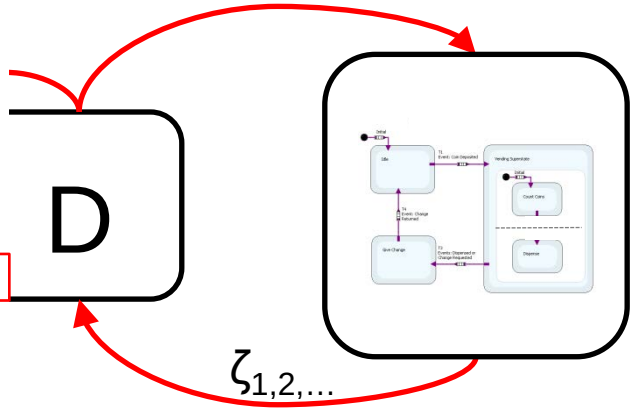
- Variables and Wires
- Blocks (difficult)

Ongoing effort in Modelica 3.X









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                        do
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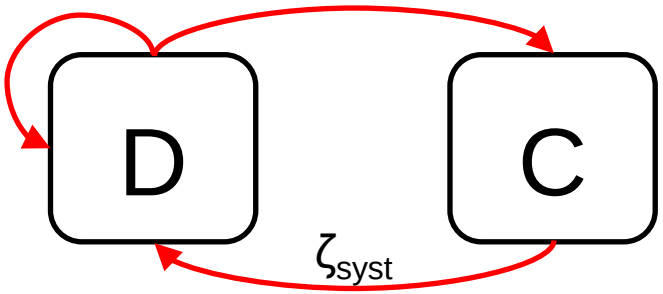
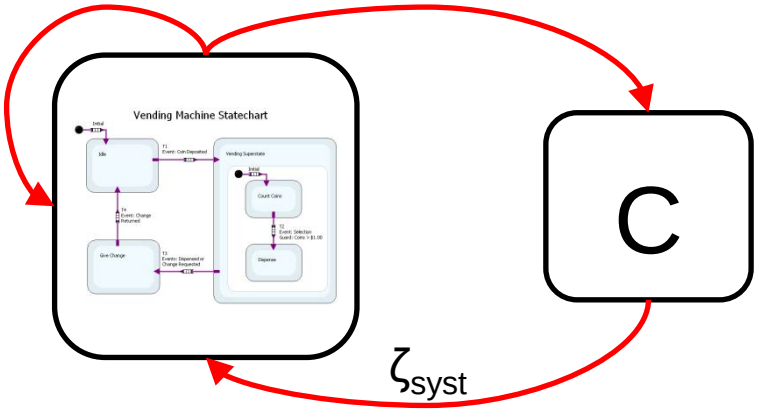
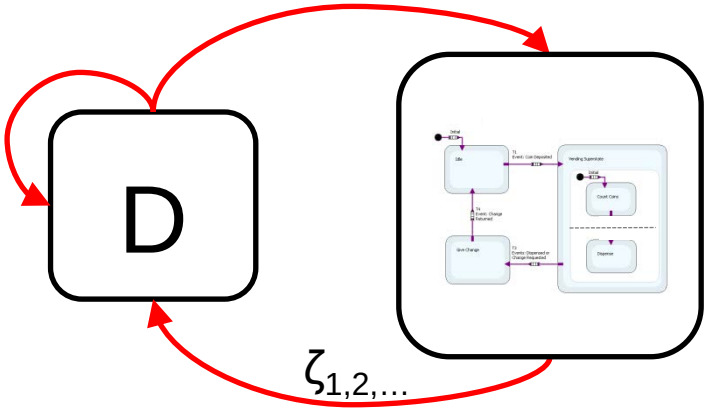
                        until start then Bounce (y'0)
                        done
                | Bounce (v) →
                        local c, y ' in
                        do
                        and der y' = −9.81 init v
                        and der y = y '
                        and c = up(–. y)
                        until c on ( y ' < eps ) then Await
                            | c then Bounce (−0.9 * . y ' )
                        done
                end
        in
        y
```







Any need for an effort on theory?

- time
- causality & dependencies

What is a good model of time?

Discrete time is subtle:

- Continuous dynamics and discrete events
- Cascades of causally related events
- Non-determinism in discrete events
- Non-determinism in cascades of events

How discrete is discrete?

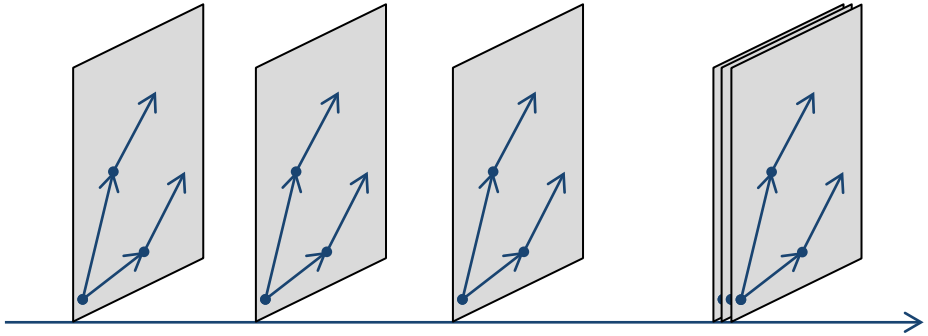
- Chattering
- Looks discrete but time progresses

Control interferes with

- Cascades of events
- Continuous dynamics (sampling)

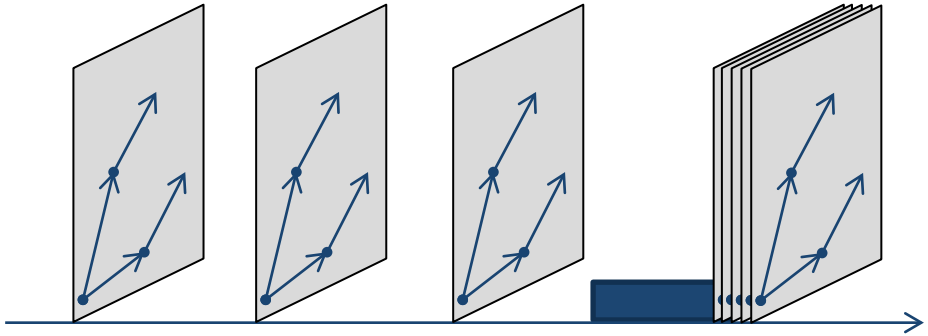
Unwanted couplings due to solvers

- Fast/Slow dynamics
- Zero-crossings, hot/cold restart



D: time is logical, not metric; events in a reaction are causally related; no date, no duration

C: time is metric; events are dated; actions have a duration



H: time can be logical or metric; events in a reaction are causally related; dates, durations

What is a good model of time?

Super-dense time R×N

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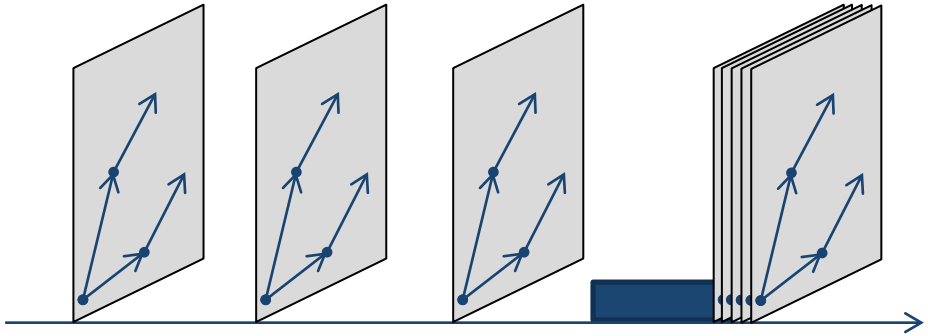

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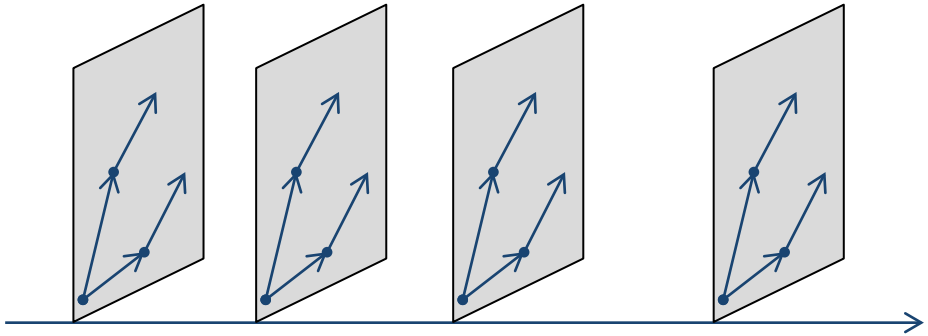

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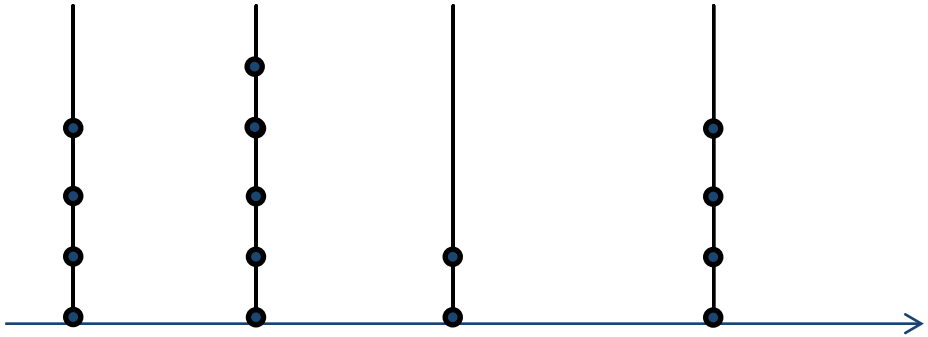

H: time can be logical or metric; events in a reaction are causally related; dates, durations; almost so…

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Non-standard time $T = \{n\partial \mid n \in N^*\}$

∂ : infinitesimal base step

N^* : non-standard integers

T is

- totally ordered like N, hence we can refer to $t-1$ and $t+1$
- dense in R_+

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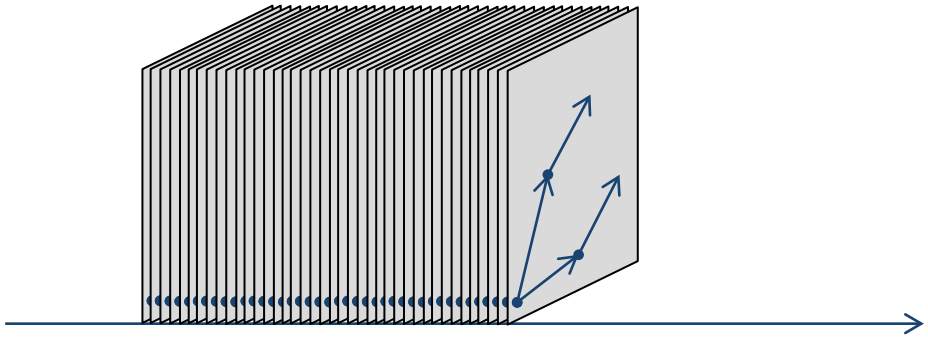

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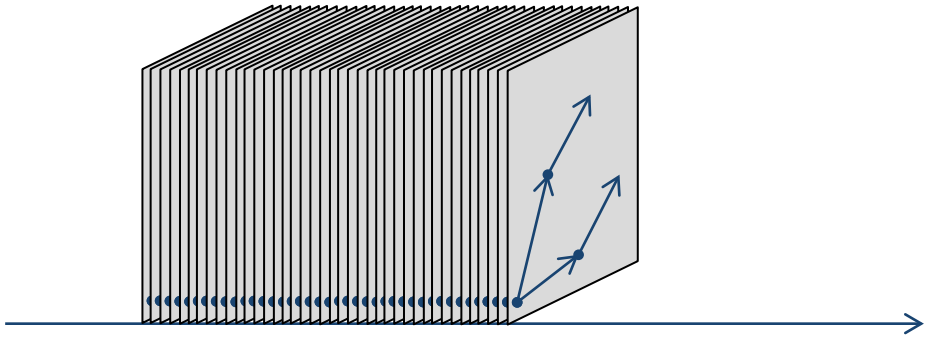
With the two we can write:

$$\dot{x} = f(x,t) \quad \Leftrightarrow \quad x_{t+1} = x_t + \partial \times f(x_t, t)$$

and we can study cascades of events as in usual discrete time formalisms; we can type continuous/discrete and implement slicing



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Further fundamental issues: Causality and dependencies

Avoiding unwanted coupling effects

- Seemingly unrelated sub-systems influence each other through their respective time-scales: due to adaptive step size and the use of a global solver
- Countermeasure: multi-solver

Physical modeling from first principles (Modelica, Simscape)

- Infer causality and direction of flows
- For DAE: index reduction

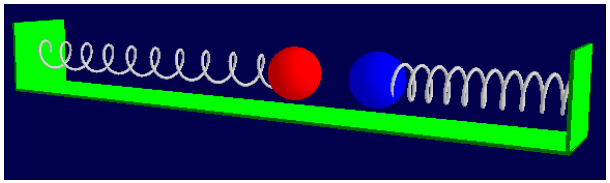
These are all issues related to causality

- State of the art: handled globally at system level: combinatorial explosion
- Need for a compositional processing

A proof of concept tool development: Zelus

By Timothy Bourke and Marc Pouzet

Zelus
(Zero-crossings for Lustre)
Objectives



Two steps

1. No support for DAE
2. With support for DAE (future)

Technical objectives

- Simple and consistent semantics
- Slicing Continuous/Discrete
- Elegant treatment of automata
- Certifiability


```
let hybrid ball ( y0, y'0, start ) =
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Principles

Slicing

- Compilation ensures that the discrete part of Zelus is compiled the usual way
- Off-the-shelf numerical solver (Sundials CVODE V2.6.0 from Lawrence Livermore)

Based on source-to-source transformations

- Helps for certification
- Automata transformed to data-flow constructs

Zelus
(Zero-crossings for Lustre)

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Status

Typing D/C: first version, still ongoing

Highlights difficulties related to solvers

- Hot/Cold restart
- What kind of solver for physical system modeling?

Future developments

- Multi-solver (to avoid unwanted coupling)
- Symbolic non-standard simulation (to avoid bothering solvers with ODE that stop immediately)

Recap

Virtual engineering for CPS: the enablers

Seamless modeling

PLM/CAD

Multi-physics

CPS functions

Architecture

- ECU
- communications

Resources

- time,
- energy,
- memory,
- weight

Quality, certification

Heterogeneity

Executable models

- reproducible executions
- avoid unwanted non-determinism

Analyzable models

Must reuse basic domains

- Discrete time
- Continuous, real, time
- Resource models

Slicing Continuous/Discrete

Typing A/C/D

- Variables and Wires
- Blocks (difficult)

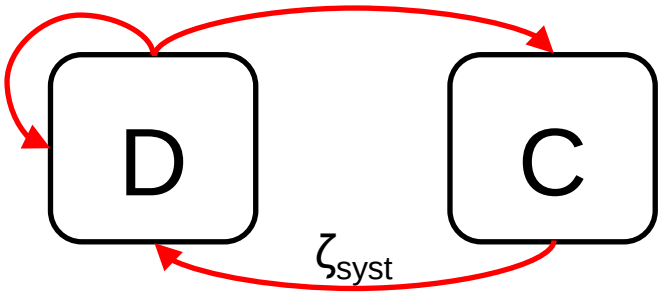
Slicing

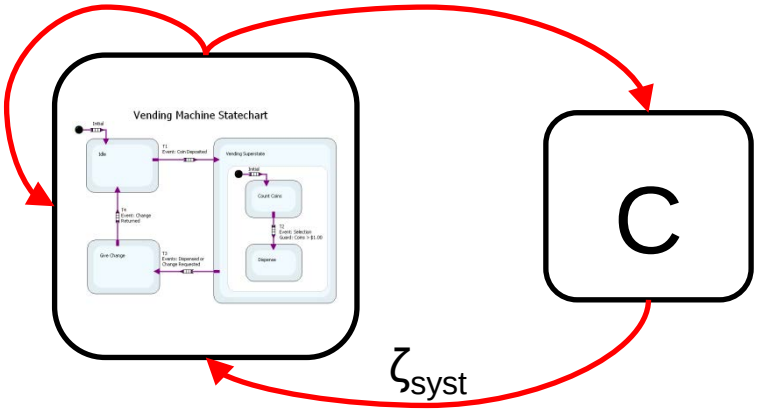
Rich structure in

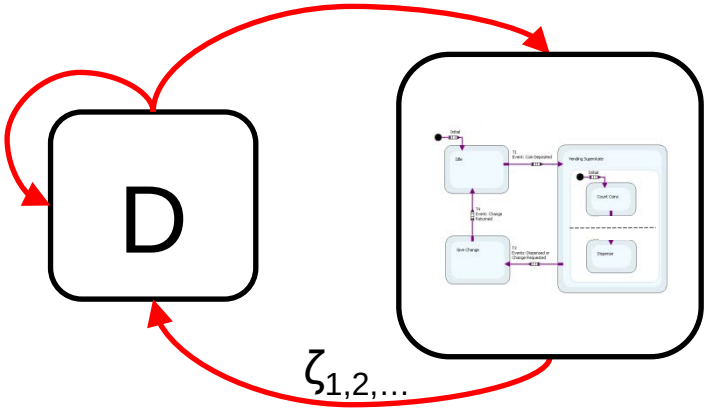
- D: hierarchical and concurrent automata
- C: multi-solver / distributed solvers

Causality

- Handling cascades of events
- Support for multi-solver
- Physical modeling from first principles







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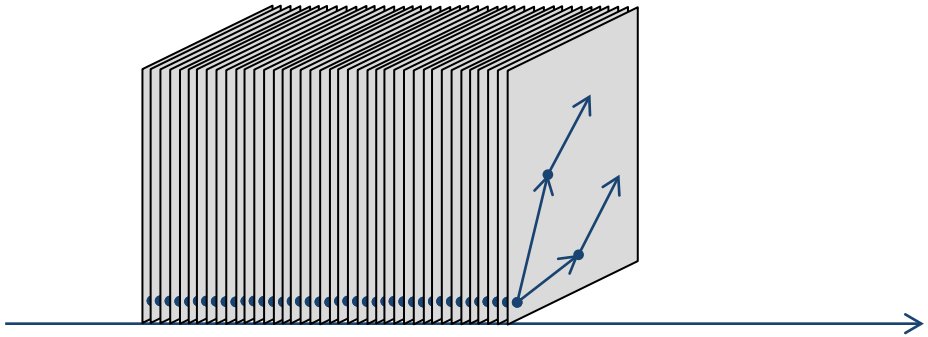

H: time can be logical or metric; events in a reaction are causally related; dates, durations

Modeling Physics in cPs is difficult

History has shown that developing theory for real-time programming of reactive systems was needed (Synchronous Languages…)

Multi-Physics modeling embedded in systems wide virtual models is needed and requires theoretical efforts too

Useful efforts toward supporting

- Reuse and imports of models
- Certification

Challenges for hybrid systems modeling research: a summary

Accurate modeling

Good language supporting D/C slicing and DAE (modeling from first principles)

Models of D/C time reusable across the different views of virtual modeling

Avoid unwanted coupling artifacts due to solvers

Reproducible simulations (determinism)

Large system modeling

Well structured D modeling

Well structured C modeling

- Distributed solvers

DAE index reduction

- Avoid combinatorial explosion

Efficient abstraction techniques

- Multi-scale
- Multiple time-scales

References related to the talk

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merci

INVENTEURS DU MONDE NUMÉRIQUE