

# Automated Verification of Cyber-Physical Systems

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Corso di Laurea Magistrale in Informatica

## Simulation of Systems

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# Simulation vs Model Checking

- In “standard” Model Checking, we are given
  - a non-deterministic Kripke Structure (KS)
  - an LTL or CTL property to be verified
- The output is either PASS or FAIL
  - if PASS, then *all* evolutions (paths) of the given model fulfill the given property
  - if FAIL, we also have a counterexample
- In probabilistic model checking, we consider probabilities of sets of evolutions
- *Simulation* of a system only considers *one* path



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# Murphi Simulation

```
void Make_a_run(NFSS  $\mathcal{N}$ , invariant  $\varphi$ )
{
    let  $\mathcal{N} = \langle S, I, \text{Post} \rangle$ ;
    s_curr = pick_a_state(I);
    if ( $\neg \varphi(s_{\text{curr}})$ )
        return with error message;
    while (1) { /* loop forever */
        if ( $\text{Post}(s_{\text{curr}}) = \emptyset$ )
            return with deadlock message;
        s_next = pick_a_state( $\text{Post}(s_{\text{curr}})$ );
        if ( $\neg \varphi(s_{\text{next}})$ )
            return with error message;
        s_curr = s_next;
    }
}
```



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# SPIN Simulation

```
void Make_a_run(NFSS  $\mathcal{N}$ )
{
    let  $\mathcal{N} = \langle S, \{s_0\}, \text{Post} \rangle$ ;
    s_curr =  $s_0$ ;
    if (some assertion fail in s_curr))
        return with error message;
    while (1) { /* loop forever */
        if ( $\text{Post}(s_{\text{curr}}) = \emptyset$ )
            return with deadlock message;
        s_next = pick_a_state( $\text{Post}(s_{\text{curr}})$ );
        if (some assertion fail in s_curr))
            return with error message;
        s_curr = s_next;
    }
}
```



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# Repeating a Simulation

- Simulations may be *deterministic* or *probabilistic*
  - both Murphi and SPIN simulations are probabilistic
  - at each step, a transition is chosen among the  $n$  possible ones with probability  $\frac{1}{n}$
  - of course,  $n$  may be different at each step
- Running multiple probabilistic simulations typically implies obtaining different paths
  - the longest the path, the more likely this is to happen



# Repeating a Simulation

- For deterministic simulations, all runs are the same
  - choice between successor states is fixed (e.g., always the first)
  - multiple simulations all result in the same path
- Deterministic simulation are however important when *inputs* from the environment are present
  - this is actually true for many systems
  - some inputs must be given at system startup, others must be given during the system evolution
  - for a given input tuple, there is only one possible successor
- Running multiple deterministic simulation results in different paths if we vary the inputs to be received
  - this is actually true for many systems



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# Simulation

- Similar to testing
- If an error is found, the system is bugged
  - or the model is not faithful
  - actually, simulation in standard model checking is also used to understand if the model itself contains errors
- If an error is not found, we cannot conclude anything
- The error state may lurk somewhere, out of reach for the random choice in `pick_a_state`



# Simulation vs Modeling

- However, for complex CPSs simulation is needed
- In fact, accurately modeling a complex CPS in a classical model checker is often too difficult or inconvenient
  - plant must be modeled by *real* variables: inherently infinite state systems
  - can be approximated, but accuracy may be low
- Simulators are often already available for testing, why can't we rely on them?
  - not "real" model checking, but something close to it
  - far better than "simple" testing
- May be either build from scratch, or implemented with dedicated tools
  - C/Java/Python dedicated programs vs. Simulink/Modelica



# Simulation-based Model Checking

- Too many states, we cannot store them in a hash table
  - transition relation defined by a complex simulator, translation in OBDDs cannot be done
- Two main workhorses:

**System Level Formal Verification** chooses system inputs so as to cover as much as possible

- mainly for safety, but also some sort of LTL may be used

**Statistical Model Checking** uses powerful statistical methods to perform model checking

- something like Monte-Carlo sampling
- i.e., we run the simulation several times, and we try to derive some guaranteed answer



# Simulation

- A simulation is an experiment on a model
  - we focus on simulations performed by a computer
- Simulation is very easy to implement in the case of classical model checkers
  - no problems with RAM or execution time
- This stems from the fact that classical model checking deals with finite state systems
  - one step at a time, time passing typically not important
  - state space is finite and described by discrete-typed variables
  - computing a transition from a state to another is straightforward



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# Simulation

- What if we need to simulate a cyber-physical system?
  - e.g., simulate the Apollo mission
  - many subsystem interacting with each other via continuous signals
  - some subsystems are described by ODEs (Ordinary Differential Equations)
- In some cases, system developers also builds a simulator from scratch, e.g., in the C language
  - directly experimenting on the physical object may be dangerous, expensive, or simply impossible (e.g., it still does not exist)
- Many tools are available to easily describe complex models to be simulated
  - e.g., able to approximate solutions for ODEs
- Here we will deal with the open-source Modelica
  - we will also have a look to Simulink

# Some Background: ODEs

- With some simplification, an ODE is an equation

$$F(x, y, y', y'', \dots, y^{(n)}) = 0$$

- The unknown  $y$  is a function  $y = f(x)$ , and  $y^{(n)}$  is the the  $n$ -th derivative of  $y$  w.r.t.  $x$
- In our context, the independent variable is time, denoted by  $t$ 
  - in simulations, we are interested in the system evolution over time...
- Thus, we have functions  $x = f(t)$  and  $n$ -th derivatives expressed in Newton's notation  $\dot{x}$
- Finally, our ODE is an equation

$$F(t, x, \dot{x}, \dots, \dot{x}^n) = 0$$



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# Some Background: ODEs

- We will consider *explicit* ODEs  $\dot{x} = F(t, x)$ 
  - $x$  usually is in some  $n$ -dimensional space, e.g.,  $x \in \mathbb{R}^n$
  - thus, this is a system of equations
  - note that, with explicit ODEs, derivatives higher than 1 are not needed
  - simply put  $x_1 = x, x_2 = \dot{x}_1 \dots$

# Example ODEs

- $\dot{x} = t + x$
- $(\dot{x}_1, \dot{x}_2) = (t + x_2 e^{x_1}, x_1 \log t)$
- Model of an infectious disease (HIV):  
 $(\dot{x}_1, \dot{x}_2) = (\lambda - dx_1 - \eta\beta x_1 x_2, -x_2(a + I) + \eta\beta x_1 x_2)$ 
  - $x_1, x_2$  are uninfected and infected cells,  $I$  is an action by the immune system
  - $a, d, \lambda, \beta, \eta$  are system parameters
  - this latter example is time-invariant (see next slide)



# ODEs: Euler Approximation

- Given the *time-invariant* ODE  $\dot{x} = F(x)$ , we may use the Euler approximation
  - for small  $\tau$ ,  $\dot{x} \approx \frac{x(t+\tau) - x(t)}{\tau}$
  - if we sample time with  $\tau$ , i.e., we only consider  $t \in \{0, \tau, 2\tau, \dots, k\tau, \dots\} \dots$
  - ... we have that  $F(x(k\tau)) = \frac{x(k\tau + \tau) - x(k\tau)}{\tau}$
  - thus by setting  $x_k = x(k\tau)$ , we have a discrete-time difference equation  $x_{k+1} = x_k + \tau F(x_k)$
- This only works for small  $\tau$  and small  $k$ 
  - it can be proved that  $\|x_k - x(k\tau)\| \leq \tau \psi(k)$ , where  $\psi$  is *not* bounded
  - at least, in the general case



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# Some Background: Systems

- A *system* is a mathematical concept used to study properties of physical objects
  - sometimes also called abstract system, or system model
- It is typically used to study evolutions as a function of *time*
- Virtually infinite examples:
  - population of rabbits
  - spread of diseases
  - physical objects: a fridge, an oven, a building, a car, ...
  - part of physical objects: a resistor, a brick, a wheel, ...
  - controllers for physical objects: ABS, autonomous driving, ...
- First distinction is among objects (what we want to model) and system (the mathematical model)
  - a system is defined through functions, sets, etc



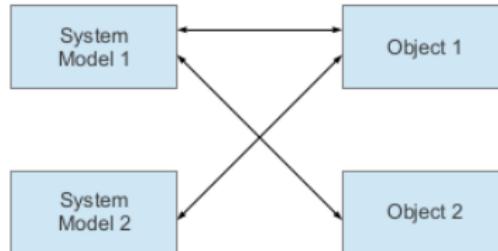
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# Some Background: Systems

- Given an object, one may devise different systems
  - as we may have different programs to solve the same problem
  - not only because of different people doing it: different properties on the same object may be investigated
- Given a system, it may be applied to different objects
  - spreading of different diseases may have a common model
  - wheel of a car and of a motorcycle



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# Some Background: Systems

- We start defining systems by looking at their *inputs and outputs*
  - keeping in mind that it is all as a function of time
- Deterministic systems: given an input sequence from some “start”, the output is the same
  - probabilistic systems also exist, we do not consider them here
- Black-box system: at first, we perform *experiments* on the system
  - we provide sequences of inputs and observe the sequence of outputs



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# Some Background: Systems

- We begin experiments at some time  $t_0 \in T$ , with  $T \subseteq \mathbb{R}$ 
  - for some systems,  $T \subseteq \mathbb{N}$
- We consider all input functions  $u : T \rightarrow U$  for our object
  - $U$  is some set on which inputs may vary
  - it may be multidimensional, e.g.  $U = \mathbb{N} \times \mathbb{Z} \times \mathbb{R}^2$
  - of course, such input functions are uncountably many, this is a conceptual experiment
- For each  $u$ , we have an output function  $y : T \rightarrow Y$  coming out of the object
  - $U$  and  $Y$  may be different
  - again,  $Y$  may be multidimensional
- We define the system  $\mathcal{S} = \{(u, y) \mid u \text{ is an input function and } y \text{ the corresponding output function}\}$ 
  - thus,  $\mathcal{S} \subset \mathcal{U} \times \mathcal{Y}$



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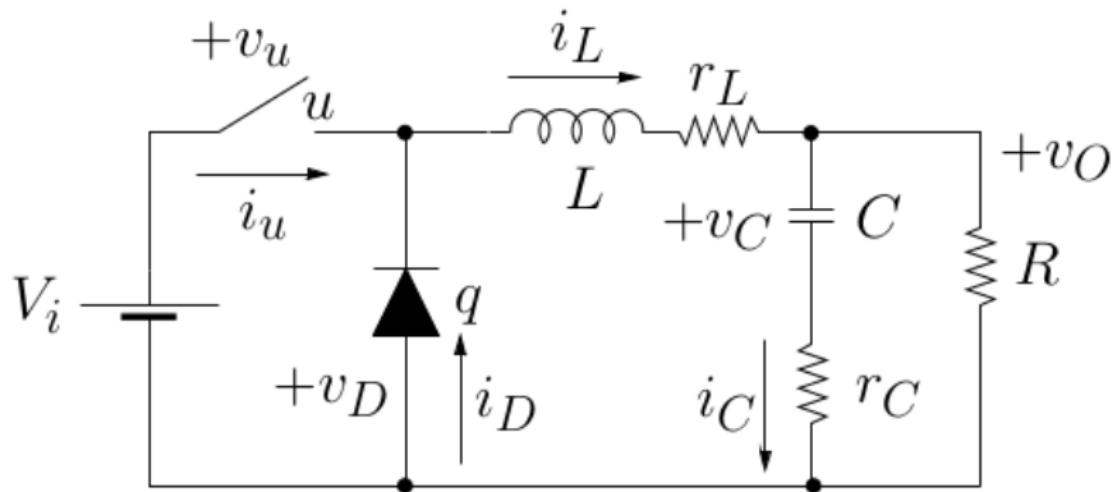
# Some Background: Systems

- Example: determine the number of students which graduate in same bachelor course
  - assumption: student enrolls once every year, thus  $T \subset \mathbb{N}$
  - $U \subset \mathbb{N}$ : number of students enrolling “from outside”
  - $Y \subset \mathbb{N}$ : number of graduated students
  - $\mathcal{U} = \{f \mid f : T \rightarrow U\}$ , analogous for  $\mathcal{Y}$
  - example of input-output:
    - $u_1(2020) = 200, u_1(2021) = 221, u_1(2022) = 198$ , and  
 $u_1(x) = 0$  for  $x \notin \{2020, 2021, 2022\}$ ...
    - ... and we observe  
 $y_1(2020) = 51, y_1(2021) = 51, y_1(2022) = 60$
    - $u_1(2020) = 136, u_2(2021) = 231, u_2(2022) = 90$ , and  
 $u_2(x) = 0$  for  $x \notin \{2020, 2021, 2022\}$ ...
    - ... and we observe  
 $y_2(2020) = 42, y_2(2021) = 37, y_2(2022) = 98$
- $u_1, u_2 \in \mathcal{U}, y_1, y_2 \in \mathcal{Y}, (u_1, y_1), (u_2, y_2) \in \mathcal{S}$



# Some Background: Systems

Example: determine the output voltage of a buck DC-DC converter



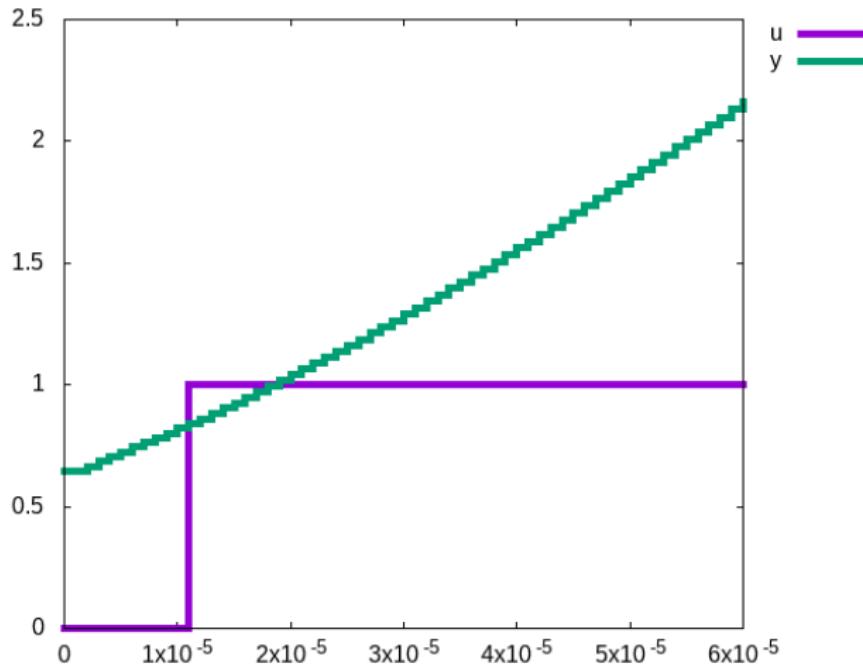
# Some Background: Systems

- Example: determine the output voltage of a buck DC-DC converter
  - $T \subset \mathbb{R}$
  - $U \subset \{0, 1\} \times \mathbb{R}$ 
    - $u$  may be closed (0) or open (1) at any time
    - $V_i$  may be any real number
  - $Y \subset \mathbb{R}$ : observed output voltage  $v_O$
  - example of input-output (times are in microseconds):
    - $u_1(t) = (0, 5)$  for all  $t \in [0, 10]$ ,  $u_1(t) = (1, 5)$  for all  $t \in [10, 100]$
    - $u_2(t) = (0, 15)$  for all  $t \in [0, 9]$ ,  $u_2(t) = (1, 10)$  for all  $t \in (9, 15]$ ,  $u_2(t) = (0, 7)$  for all  $t > 15$



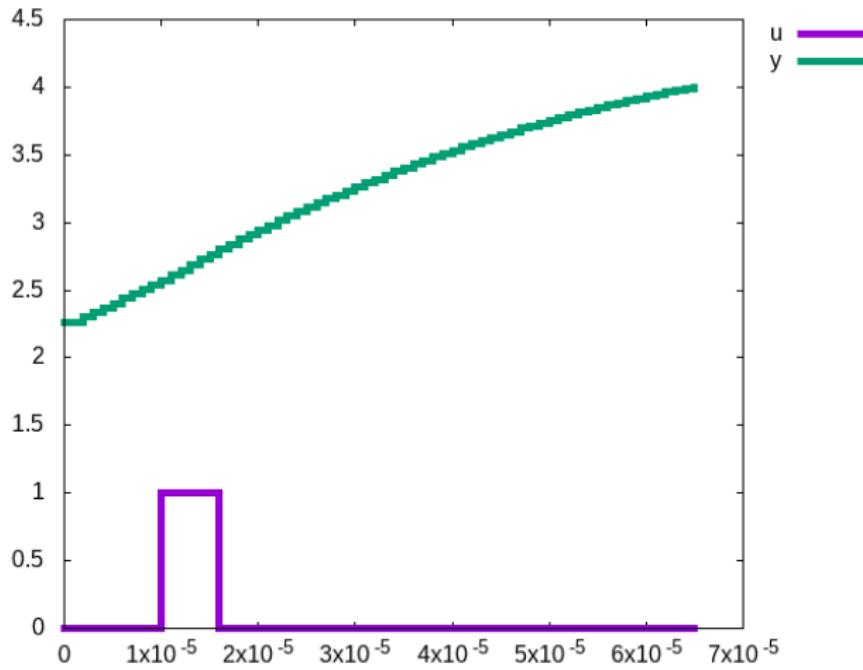
# Some Background: Systems

Result for  $u_1$



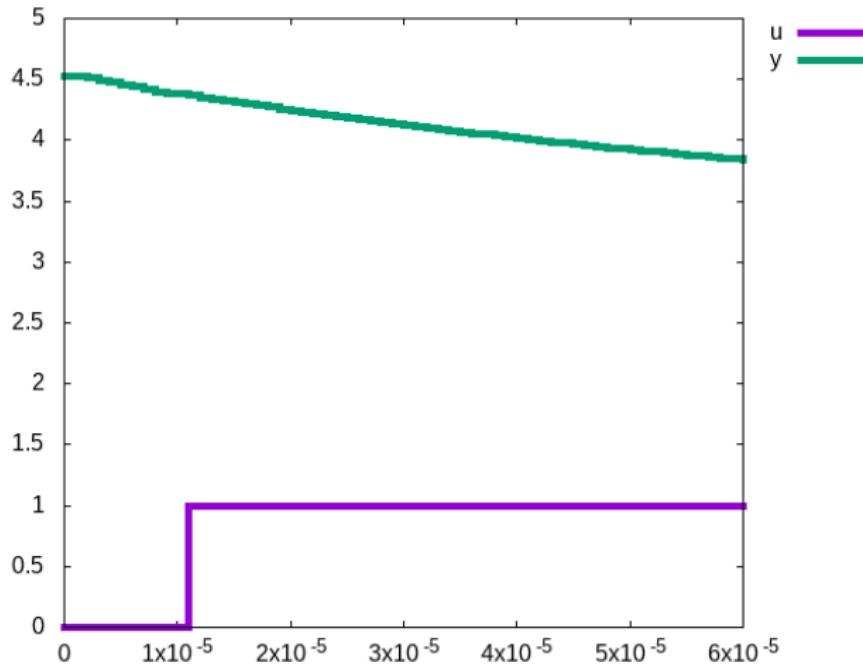
# Some Background: Systems

Result for  $u_2$



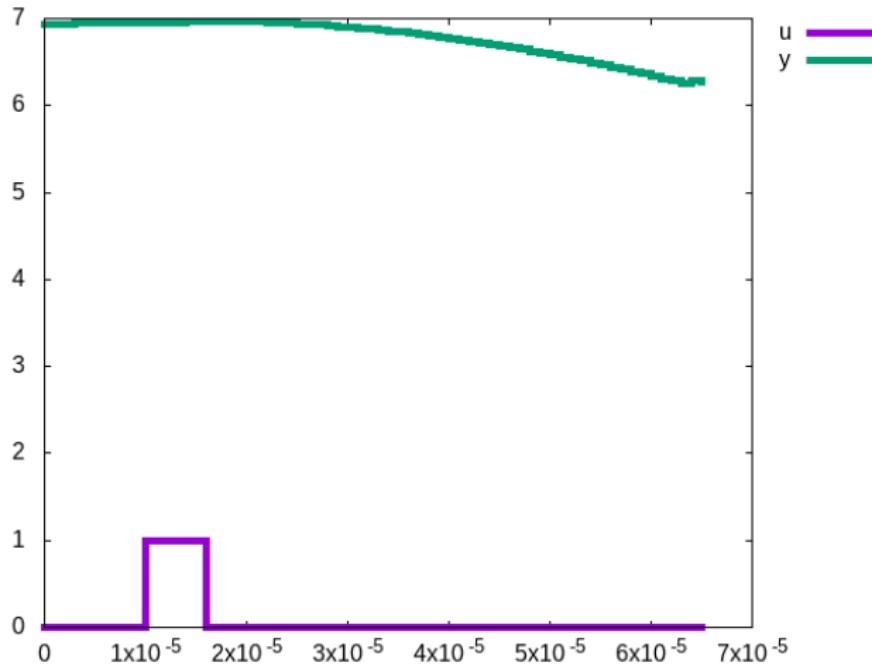
# Some Background: Systems

... but this is also a result for  $u_1$



# Some Background: Systems

... and this is also a result for  $u_2$



# Some Background: Systems

- Is this a non-deterministic system??? NO!
- The point is that output is not determined by input only
  - though for some systems this is the case: number of students above
- The missing element is the *state*
  - essentially, the input/output function has side effects...
- Thus, the output (for *deterministic* systems) is a function of both the input and the state
  - in the examples above, we made different choices for the starting state



# Some Background: Systems

- For our purposes, a system will be defined by a 6-tuple  $\mathcal{S} = \langle T, U, Y, X, \eta, \phi \rangle$ :
  - $U, Y$  are sets of possible input and output values, resp.
  - $T$  is a set of times
    - if  $T \subseteq \mathbb{R}$  then we have a *continuous-time* system
    - if  $T \subseteq \mathbb{N}$  then we have a *discrete-time* system
  - $X$  is a set of states
    - may be either finite or infinite
    - if  $T \subset \mathbb{N}$  and  $|X| < \infty$  then we essentially have a Kripke structure
  - $\eta : T \times X \times U \rightarrow Y$  defines the output function
  - $\phi : T \times T \times X \times \mathcal{U} \rightarrow X$  defines the state transition function
    - recall that  $\mathcal{U} = \{f \mid f : T \rightarrow U\}$



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# Some Background: Systems

- $\eta : T \times X \times U \rightarrow Y$  is as expected
  - given the current time, the current state, and the current input, we can compute the output
- $\phi : T \times T \times X \times U \rightarrow X$  is somewhat more complicated than expected
  - one would expect  $\phi : T \times X \times U \rightarrow X$
  - actually, this is enough for most systems
- For some systems, the state transition function depend on some sequence of inputs, not only the last one
  - so we need a function, defined at least on an interval  $[t_0, t)$
  - this is why  $\phi$  also takes two times instead of one
- 3 conditions must hold for  $\eta$  and  $\phi$ : *causality*, *consistency* and *separation*



# Some Background: Causal Systems

- $\forall t, t_0 \in T, x_0 \in X. (t \geq t_0 \wedge u|_{[t_0, t]} = u'|_{[t_0, t]}) \Rightarrow \phi(t, t_0, x_0, u|_{[t_0, t]}) = \phi(t, t_0, x_0, u'|_{[t_0, t]})$
- That is, if we fix the first 3 arguments  $t, t_0, x_0$  of  $\phi$ ...
- ... and we provide, as a fourth argument, two possible different functions  $u, u'$ ...
- ... which however output the same values in the interval  $[t_0, t]$ ...
- ... then the final value of  $\phi$  does not change
- Thus, what happens in the interval  $[t_0, t)$  causes the system to go to one single state



# Some Background: Consistent Systems

- $\forall t \in T, x_0 \in X, u \in \mathcal{U}. \phi(t, t, x_0, u) = x_0$
- Recall that, for a call  $\phi(t, t_0, x, u)$ ,  $u$  is considered in the interval  $[t_0, t)$
- Thus, in a call  $\phi(t, t, x_0, u)$ , we are considering the empty interval  $[t, t)$
- Hence, we have no input at all!
- Of course, without inputs, the system cannot change its current state



# Some Background: Separation Property of Systems

- $\forall t, t_0, t_1 \in T, x_0 \in X, u \in \mathcal{U}. (t > t_1 > t_0) \Rightarrow \phi(t, t_0, x_0, u|_{[t_0, t)}) = \phi(t, t_1, \phi(t_1, t_0, x_0, u|_{[t_0, t_1]}), u|_{[t_1, t]})$
- In few words: the state you obtain if you go straight from  $t_0$  to  $t$ , is the same state you would obtain if:
  - you first go from  $t_0$  to some intermediate  $t_1$ 
    - i.e.,  $x_1 = \phi(t_1, t_0, x_0, u|_{[t_0, t_1]})$
  - and then from  $t_1$  to  $t$ 
    - i.e.,  $\phi(t, t_1, x_1, u|_{[t_1, t]})$



# Some Background: Hybrid Systems

- Note that the set of states  $X$  may be multi-dimensional
  - e.g.,  $X = \mathbb{R}^3$ , or  $X = \{1, 2, 3\} \times \mathbb{Z}$
- Thus, also  $\phi$  may be multi-dimensional
- Informally, if  $X$  has dimension  $n$ , then we will have *n state variables*
  - recall that the same holds for  $U, Y$ : we may have multiple *input* and *output variables*
- Hybrid systems: those for which some variables are continuous and other are discrete
  - in some texts, a “hybrid system” have some variables depending on  $T = \mathbb{N}$  and some other on  $T = \mathbb{R}$
- This is exactly the case of cyber-physical systems!
  - plant + controller/monitor
  - plant is continuous, controller/monitor is discrete



# Some Background: Special Systems

- With some simplification, a system is *time-invariant* iff  $\forall t, t_0, t_1 \in T, x \in X, u \in \mathcal{U}. \phi(t, t_0, x, u) = \phi(t - t_0, 0, x, u) \wedge \eta(t, x, u(t)) = \eta(t_1, x, u(t_1))$ 
  - that is, the absolute time is not important
  - the *relative* time is
    - given a state  $x$ , system evolution from 1 to 3 seconds and from 10 to 12 seconds is the same
- For time-invariant systems, we can always set  $t_0 = 0$
- For time-invariant systems, we can also write  $\dot{x}(t) = \phi(x(t), u(t)), y(t) = \eta(x(t), u(t))$



# Some Background: Special Systems

- With some simplification, a system is *linear* iff
  - $U, Y, X$  are linear spaces
    - that is, any linear combination  $\sum_{i=1}^n a_i x_i$  is in  $X$  etc
  - $\mathcal{U}$  is a linear subspace of  $U^T = \{f \mid f : T \rightarrow U\}$ 
    - again, any linear combination  $\sum_{i=1}^n a_i u_i(t)$  is in  $\mathcal{U}$
  - fixed any 2 times  $t, t_0 \in T$  as first 2 arguments,  $\phi$  is linear in the remaining 2 arguments
    - $\phi(t, t_0, x, u) = A \cdot [x, u] + b$  for some  $A$  and  $b$
    - $A, b$  may depend on  $t, t_0$ , but not on  $x, u$
  - fixed any time  $t \in T$  as first argument,  $\eta$  is linear in the remaining 2 arguments
- Linear systems are easy to model, simulate and verify
- With some simplification, a system is:
  - a finite-state system if  $U, X, Y$  are finite sets (Kripke structure)
  - a finite-dimensional system if  $U, X, Y$  are linear finite-dimension spaces

# Some Background: Generating Functions

- For discrete-time systems, we have that
$$x(t+1) = \phi(t+1, t, x(t), u|_{[t, t+1]}) = \phi(t+1, t, x(t), u(t)) = f(t, x(t), u(t))$$
  - first and second argument of  $\phi$  are not independent...
  - $f$  has the same domain of  $\eta$
- For continuous-time systems, we focus on *regular* systems, i.e., those systems for which  $\phi$  is differentiable and there exists a function  $f$  s.t.
  - $\frac{d\phi(t, t_0, x, u)}{dt} = f(t, \phi(t, t_0, x, u), u(t))$
  - with the initial condition that exists an  $x_0 \in X$  s.t.
$$x_0 = \phi(t_0, t_0, x_0, u)$$
  - often, it is easier to provide  $f$  than  $\phi$
- Using Newtonian notation, we have  $\dot{x}(t) = f(t, x(t), u(t))$
- For time-invariant systems, we have
$$\dot{x}(t) = f(x(t), u(t)), y(t) = \eta(x(t))$$



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## Some Background: System For Students' Example

- $X \subseteq \mathbb{N}^3, U, Y \subseteq \mathbb{N}, T = \mathbb{N}$
- Parameters  $\alpha_i(t) \in [0, 1]$  is ratio of students passing an year  $t$
- $x_1(t + 1) = (1 - \alpha_1(t))x_1(t) + u(t)$
- $x_i(t + 1) = (1 - \alpha_i(t))x_i(t) + \alpha_{i-1}(t)x_{i-1}(t)$  for  $i = 2, 3$
- $y(t) = \alpha_3(t)x_3(t)$
- Note that, if  $\alpha_i(t) = 1$  for all  $t$ , then states are not needed, as we have  $y(t) = u(t - 3)$
- Summing up:

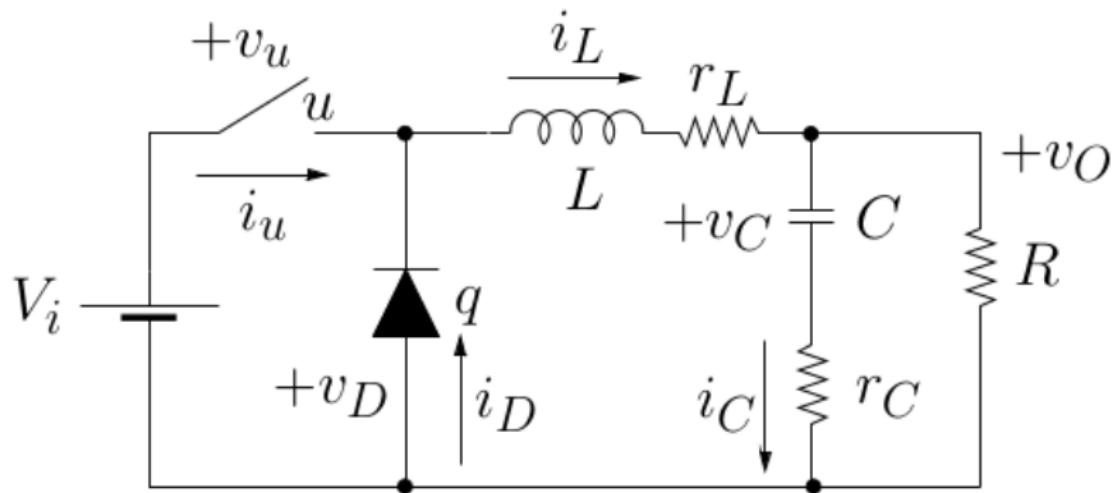
$$\bullet f(t) = \begin{pmatrix} (1 - \alpha_1(t))x_1(t) + u(t) \\ (1 - \alpha_2(t))x_2(t) + \alpha_1(t)x_1(t) \\ (1 - \alpha_3(t))x_3(t) + \alpha_2(t)x_2(t) \end{pmatrix}$$



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# Some Background: System For Buck DC/DC Converter

- $X \subseteq \mathbb{R}^2, U \in \{0, 1\} \times \mathbb{R}, Y \subseteq \mathbb{R}, T = \mathbb{R}$
- $L, C, R, r_L, r_C \in \mathbb{R}$  are system parameters
  - we will also use 6 real numbers  $a_{i,j}$  for  $i \in \{1, 2\}, j \in \{1, 2, 3\}$  which are functions of such parameters
  - e.g.,  $a_{2,3} = -\frac{1}{L} \frac{r_C R}{r_C + R}$
- Variables for state are  $i_L, v_O, v_D, i_D, v_u, i_u$  (real) and  $q$  (boolean)
- Variables for input are  $u$  (boolean) and  $V_i$  (real)
- $y(t) = v_O(t)$ , thus  $\eta$  is easy
- $\phi$  is defined by cases in the following slide
  - for the definition of  $\phi$ , some other (*auxiliary*) variables are useful:  $v_D, i_D, v_u, i_u$  (real) and  $q$  (boolean)
  - $R_{on} \approx 0, R_{off} \gg R_{on}$  are fixed parameters



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# Some Background: System For Buck DC/DC Converter

We omit  $(t)$  for better readability

There must exist a value for  $v_D, i_D, v_u, i_u \in \mathbb{R}, q \in \{0, 1\}$  s.t.

$$\dot{i_L} = a_{1,1}i_L + a_{1,2}v_O + a_{1,3}v_D \quad (1)$$

$$\dot{v_O} = a_{2,1}i_L + a_{2,2}v_O + a_{2,3}v_D \quad (2)$$

$$q \rightarrow v_D = R_{\text{on}}i_D \quad (3) \qquad \bar{q} \rightarrow v_D = R_{\text{off}}i_D \quad (7)$$

$$q \rightarrow i_D \geq 0 \quad (4) \qquad \bar{q} \rightarrow v_D \leq 0 \quad (8)$$

$$u \rightarrow v_u = R_{\text{on}}i_u \quad (5) \qquad \bar{u} \rightarrow v_u = R_{\text{off}}i_u \quad (9)$$

$$v_D = v_u - V_{in} \quad (6) \qquad i_D = i_L - i_u \quad (10)$$

Both ODEs and algebraic equations



# Modeling in Modelica

- Modelica is an open-source language for specifying (complex) systems
  - developed by experts starting in late 1990s
- Many implementations exist
  - OpenModelica+simForge, Dymola, Simulation X, MapleSim, MathModelica
  - here we will stick to OpenModelica+simForge
- Also see Modelica slides



# Modeling in Modelica

- Object-oriented language: classes and objects (i.e., class instances)
  - strongly typed
- Compositional modeling:
  - break up the system in subsystems (components)
  - connect the components
- Very useful for complex systems, with many components
  - some standard components already defined, e.g., resistors, flows etc
- May use equations, also with derivatives
- Generates a C program, thus it is very efficient



# Modeling in Modelica

- Synchronous data flow principle: time is the same for all components
  - such as clocks for digital systems, but in Modelica it may be continuous
- May specify “algorithms” using assignments, ifs, whiles, etc
  - all variables must be instances of some class
  - this also includes integers and reals
- Acausal modeling: simply first provide the equations for each object, then connect the objects between them
  - other modeling languages, e.g., Simulink, requires to first design the full chain of connections...
  - ...and to make computation in sequence
  - Modelica allows both causal and acausal modeling
  - physical “reality” is lost
- Modelica easier for modelers, Simulink easier for computers



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# Modelica: Acausal Modeling

## Acausal Modeling

The order of computations is not decided at modeling time

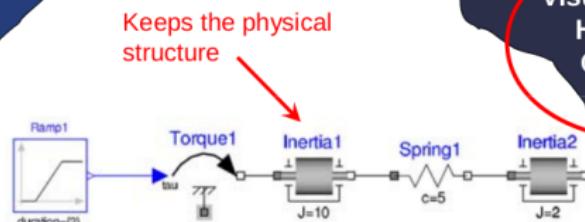
|                        | Acausal                                  | Causal   |
|------------------------|--|--|
| Visual Component Level |  |  |
| Equation Level         | A resistor equation:<br>$R \cdot i = v;$ | Causal possibilities:<br>$i := v/R;$<br>$v := R \cdot i;$<br>$R := v/i;$ |

# Modelica: Acausal Modeling

## What is Special about Modelica?

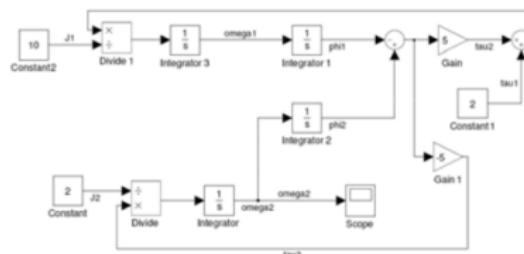
Multi-Domain  
Modeling

Acausal model  
(Modelica)



Visual Acausal  
Hierarchical  
Component  
Modeling

Causal  
block-based  
model  
(Simulink)



# Modelica: Hybrid Modeling

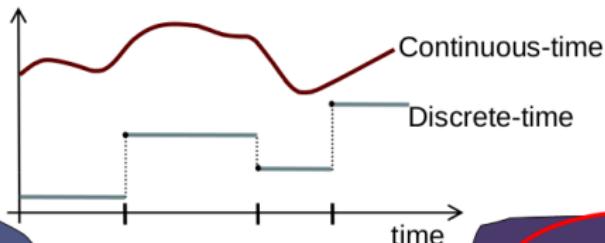
## What is Special about Modelica?

Multi-Domain  
Modeling

Visual Acausal  
Component  
Modeling

Hybrid modeling =  
continuous-time + discrete-time modeling

Typed  
Declarative  
Equation-based  
Textual Language



Hybrid  
Modeling

# Modelica: Toy Example

- Text file with .mo extension, let us say model.mo

```
class Example
  output Real x, y, z;
  algorithm
    when initial() then //at 0, both this...
      x := 0; // Pascal-like assignments
    elsewhen sample(0, 1) then // ... and this
      x := 1;
      y := pre(x); //0 till 1, then always 2
    elsewhen sample(0, 0.5) then
      //elsewhen order is important! from bottom to top
      x := 2;
      z := pre(x); //0 till 0.5, then always 1
    end when;
  end Example;
```



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# Modelica: Toy Example

- Text file with .mos extension, let us say run.mos

```
loadModel(Modelica);
getErrorString(); // should be used after every command,
                  // skipped in the following
loadFile("model.mo");
//Example is defined in model.mo
simulate(Example, stopTime=10);
//x, y, z are variables of Example
plot({x, y, z}, externalWindow=true,
      fileName="Example_res.mat");
```

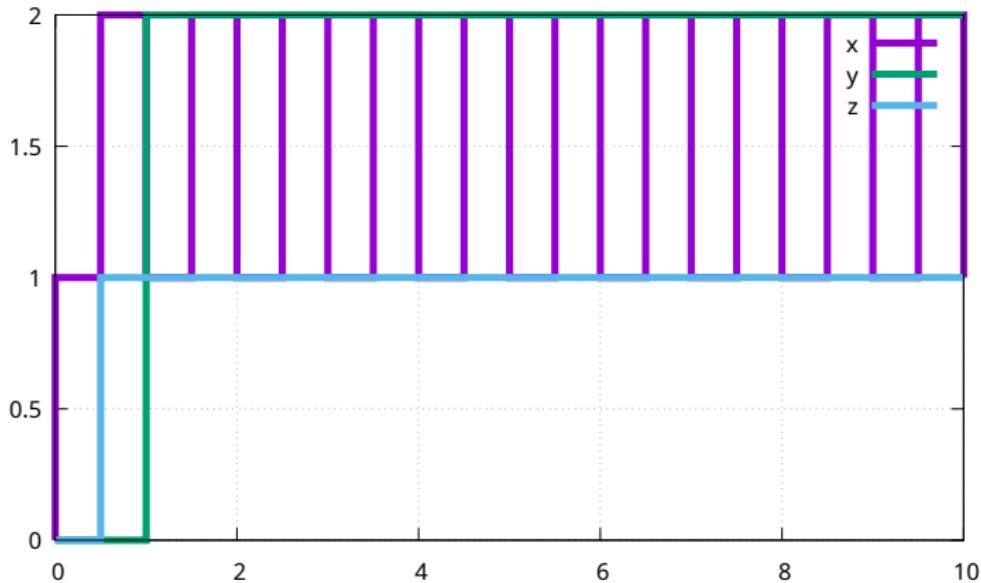


# Modelica: Toy Example

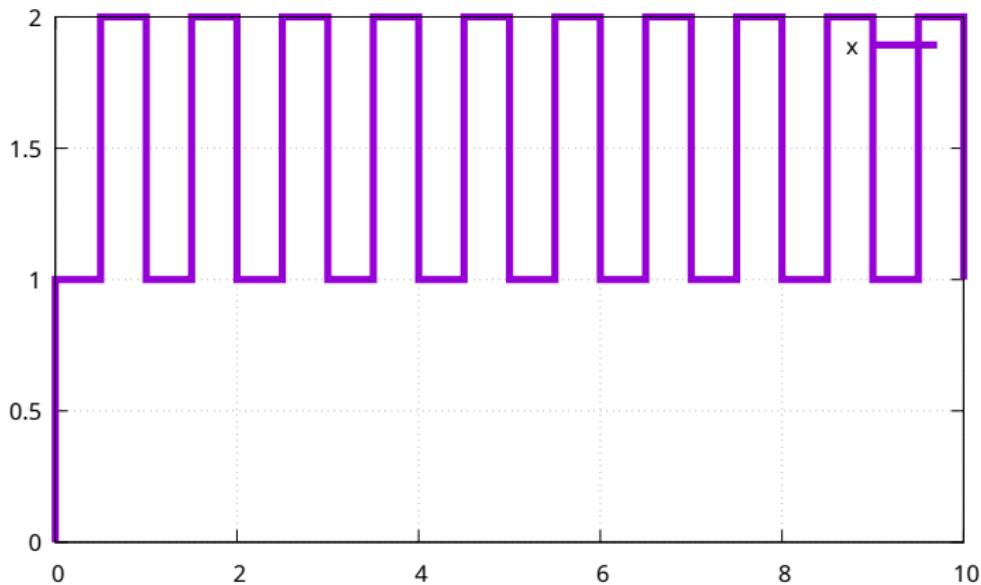
- Run the command `omc run.mos`
  - of course, you must have installed `omc` for your OS
- This has the following effect:
  - generates a C program `model.c`
  - compiles `model.c` to obtain the executable file `model`
  - executes `model`
  - outputs both a file `Example_res.mat` and a graphical window with the graph of variables `x`, `y`, `z` as function of time



# Modelica: Commands Chain



# Modelica: Commands Chain

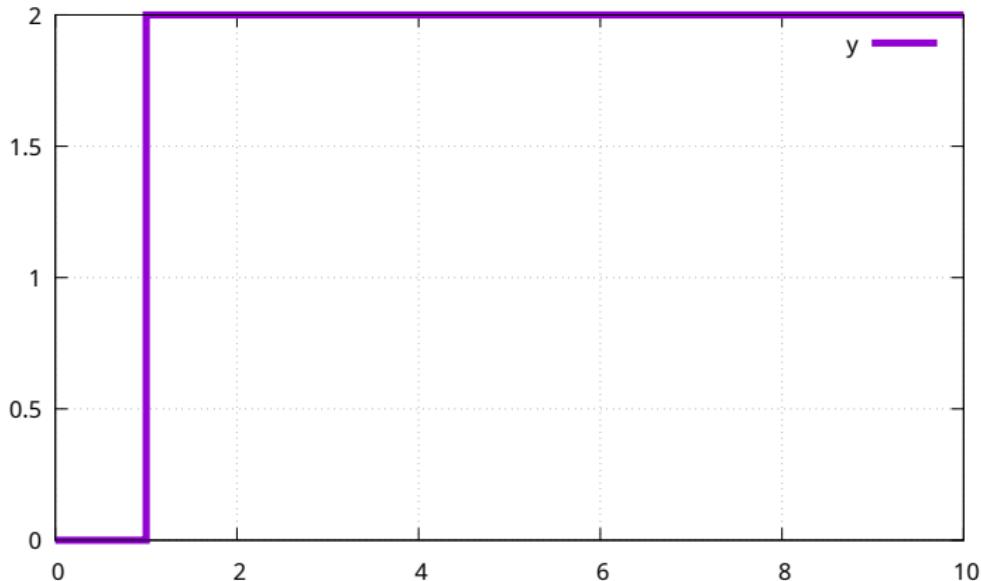


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# Modelica: Commands Chain

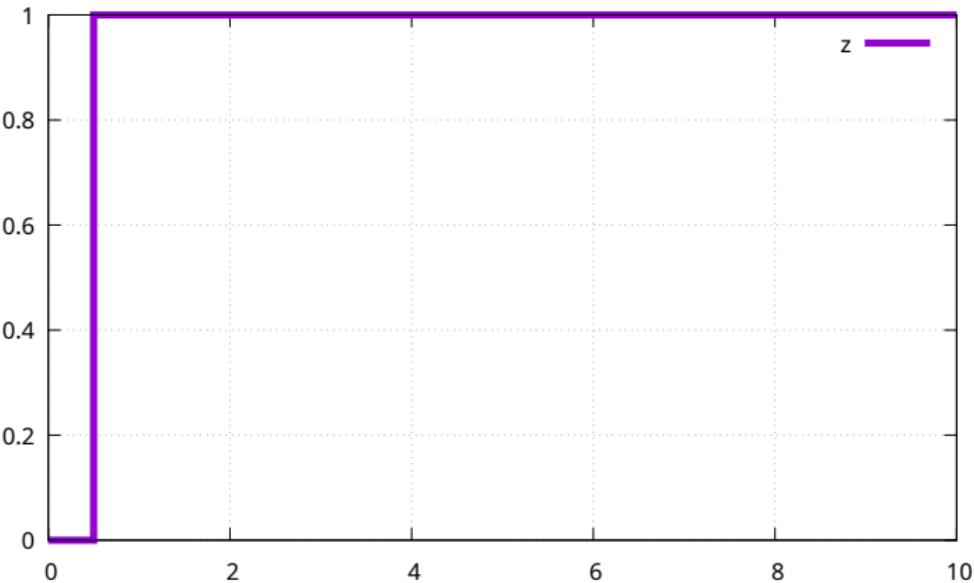


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# Modelica: Commands Chain



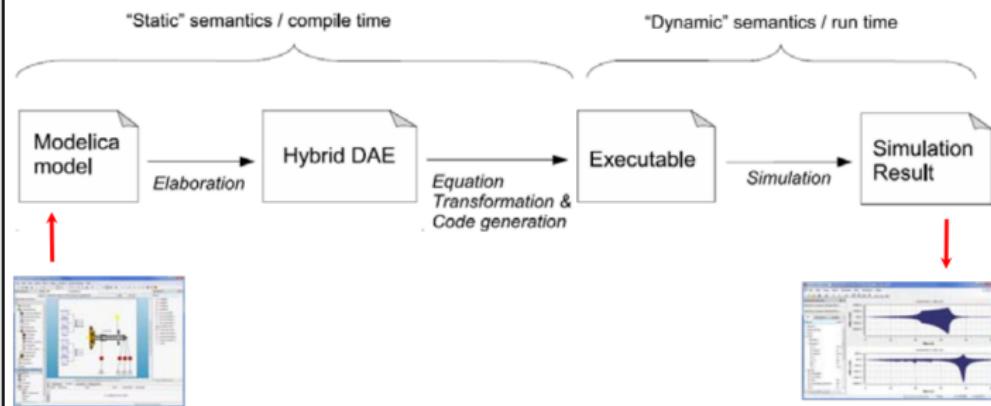
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# Modelica: Commands Chain

## Typical Simulation Process



# Modelica: Toy Example Examined

```
class Example
  output Real x, y, z;
  algorithm
    when initial() then //at 0, both this...
      x := 0;
    elsewhen sample(0, 1) then // ... and this
      x := 1;
      y := pre(x); //0 till 1, then always 2
    elsewhen sample(0, 0.5) then
      x := 2;
      z := pre(x); //0 till 0.5, then always 1
    end when;
  end Example;
```



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# Modelica: Toy Example Examined

- Example is a class defined by the modeler: Modelica is OO
- It has 3 real-valued variables, which may become the input for other blocks
- The dynamics is an algorithm based on the `sample` construct
  - `when initial()`  $C$  executes code in  $C$  at time 0
  - `when sample( $A$ ,  $B$ )`  $C$  executes code in  $C$  every  $A + Bx$  seconds, for  $x \in \mathbb{N}$
  - there may be multiple `elsewhen sample( $A$ ,  $B$ )`  $C$  triggered at a given time
  - they are all executed, starting from the bottom of the file
  - now explain the output of the previous example...
- In expressions, `pre(var)` holds the value of `var` *before* the current event



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## Simplest Model – Hello World!

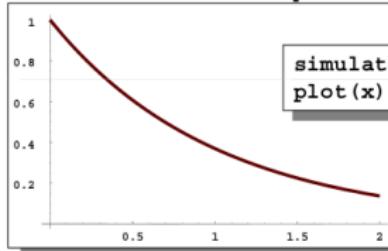
### A Modelica “Hello World” model

Equation:  $x' = -x$

Initial condition:  $x(0) = 1$

```
class HelloWorld "A simple equation"
  Real x(start=1);
equation
  der(x) = -x;
end HelloWorld;
```

### Simulation in OpenModelica environment



```
simulate(HelloWorld, stopTime = 2)
plot(x)
```

# Modelica: Derivatives and Algebraic Equations

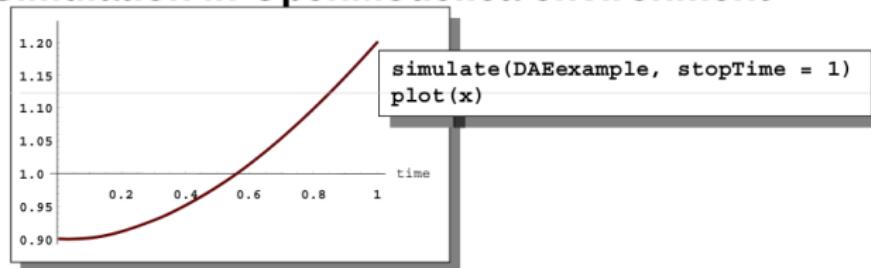
## Model Including Algebraic Equations

### Include algebraic equation

Algebraic equations contain no derivatives

```
class DAEexample
  Real x(start=0.9);
  Real y;
equation
  der(y) + (1+0.5*sin(y))*der(x)
  = sin(time);
  x - y = exp(-0.9*x)*cos(y);
end DAEexample;
```

### Simulation in OpenModelica environment



# Modelica: Derivatives and Algebraic Equations

- time is a special variable, holding current simulation time
- System dynamics of previous example is defined as

$$\dot{y} + \left(1 + \frac{\sin y}{2}\right)\dot{x} = \sin t$$

$$x - y = e^{-0.9x} \cos y$$

- Can be transformed in “normal” form by adding state variables:

$$\dot{x} = \frac{\sin t - y_1}{1 + \frac{\sin y}{2}}$$

$$\dot{y} = y_1$$

$$z_1 = e^{-0.9x}$$

$$z_2 = \cos y$$

$$x = z_1 z_2 + y$$

$$y = x - z_1 z_2$$



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# Modelica: Subsystems and Connections

- Till now, stand-alone systems with just one component
- Modelica allows compositional modeling of many components
- Each component is modeled autonomously, by simply looking at the interaction with the environment (input/output)
- Complex systems are made of *connected* components
- Connectors can be explicitly defined
  - causal: input/output relation is explicitly stated
  - acausal: input/output relation is left unspecified
  - Modelica will understand which is input and which is output



# Modelica: Toy Example With 2 Components

Mind the difference between = and :=

```
model ContinuousBehav

  Boolean x;
  Real i (start = 1);

  equation
    (if x then 0.5*time else -0.1*time)*der(i) = time;
  end ContinuousBehav;
```



# Modelica: Toy Example With 2 Components

```
model GenerateBoolInputs

  Boolean x;
  parameter Real sampling = 1.0;

  algorithm
    when initial() then
      x := false;
    elsewhen sample(sampling, sampling) then
      x := not(x);
    end when;
  end GenerateBoolInputs;
```



# Modelica: Toy Example With 2 Components

```
model BoolCont

GenerateBoolInputs gbi;
ContinuousBehav cb;

equation
  gbi.x = cb.x;

end BoolCont;
```



# Modelica: Toy Example With 2 Components

May also collect parts of commands in a file `file.mos` and use  
`runScript("file.mos")`

```
loadModel(Modelica);
getErrorString();
loadFile("model.mo");
simulate(BoolCont, stopTime=10);
plot({gbi.x, cb.i}, externalWindow=true,
      fileName="BoolCont_res.mat");
```



# Modelica: Passing of Time

- For all objects defined, the time passes in the same way
  - it is a kind of common clock, as in digital circuits
- This is of course consistent with physical reality
  - components are close enough...
- It is always continuous time, but using `sample` we can also have discrete time



# Modelica: Algorithms and Equations

- Both may be used, the modeler has to choose
  - of course,  $x := x + 1$  inside an algorithm is ok,  $x = x + 1$  in an equation is not
  - using imperative vs. declarative style is left to the modeler
  - in some cases, algorithm is more natural, in some other equation has to be preferred
  - note that loops and ifs are available in both formats
  - e.g.,  $a = (\text{if } b \text{ then } 1 \text{ else } 2);$  vs  $\text{if } (b) \text{ then } a:=1;$   
 $\text{else } a:=2; \text{ end if};$
  - or simply  $a := (\text{if } b \text{ then } 1 \text{ else } 2);$
- Algorithms, as well as equations solving, does not cause time to pass
  - number of computation steps required is not important



# Modelica: Algorithms

- Generally speaking, when  $A$   $B$  clauses triggers the corresponding block  $B$  when condition  $A$  is true
- $A$  can be any boolean expression, not only sample
- Functions may also be defined and used
  - time does not pass during function calls
  - again, number of computation steps is not important
  - must have input and output
- External C or Fortran functions may be called

```
external "C" result = myfun();  
annotation(Include = "#include \"myfile.c\"");
```



# Modelica: Events

- Discrete events happens in a discrete number of time points
  - given that the simulation terminates somewhere, it is actually a finite number of points
- We saw `initial` and `sample`, there is also `terminal`
  - triggered at the end of the simulation
- Simulation ends either because of:
  - the `stopTime` attribute inside `simulate` command
  - a `terminate` statement



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# Modeling in Simulink

- Simulink is a graphical extension to MATLAB
  - MATLAB itself is proprietary, but UnivAQ provides it to students
- Main goal: modeling and simulation of systems
  - also non-linear ones
- Also see [https://ctms.engin.umich.edu/CTMS/index.php?aux=Basics\\_Simulink](https://ctms.engin.umich.edu/CTMS/index.php?aux=Basics_Simulink)
- No way of simply writing a text file: you have to use the GUI and manipulate graphical objects
  - model files are saved in a binary proprietary SLX format



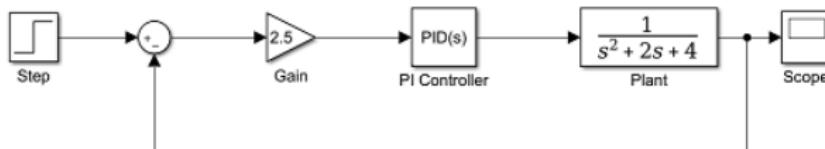
# Modeling in Simulink

- Two major classes of objects: blocks and lines
  - blocks used to generate, modify, combine, output, and display *signals*
  - lines used to connect blocks, i.e., transfer signals from one block to another
  - again, a common clock for all objects in a model
- Suppose you create a new or open an existing Simulink model file
- How to add a new block:
  - click “Library Browser”
  - select the type of block you need
    - hundreds of types available, could also be searched by name
  - drag it to the model window
  - by double clicking, you can edit the properties



# Modeling in Simulink

- How to add a new connecting line:
  - simply drag the mouse from the first object to the second object
- If you are connecting an object with a line:
  - first make a dangling line from the destination
  - connect the end of such line with the “source” line
  - this will make the source line bifurcated



# Modeling in Simulink

Most notable types of blocks:

- Sources: used to generate various signals
- Sinks: used to output or display signals
- Continuous: continuous-time system elements
  - transfer functions, state-space models, PID controllers, etc.
- Discrete: linear, discrete-time system elements
  - discrete transfer functions, discrete state-space models, etc.
- Math Operations: contains many common math operations
  - gain, sum, product, absolute value, etc.
- Ports & Subsystems: contains useful blocks to build a system

