Modelling and simulation of physical systems

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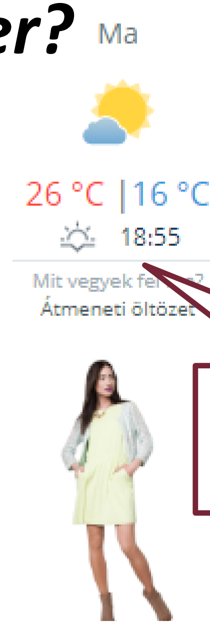
Motivation

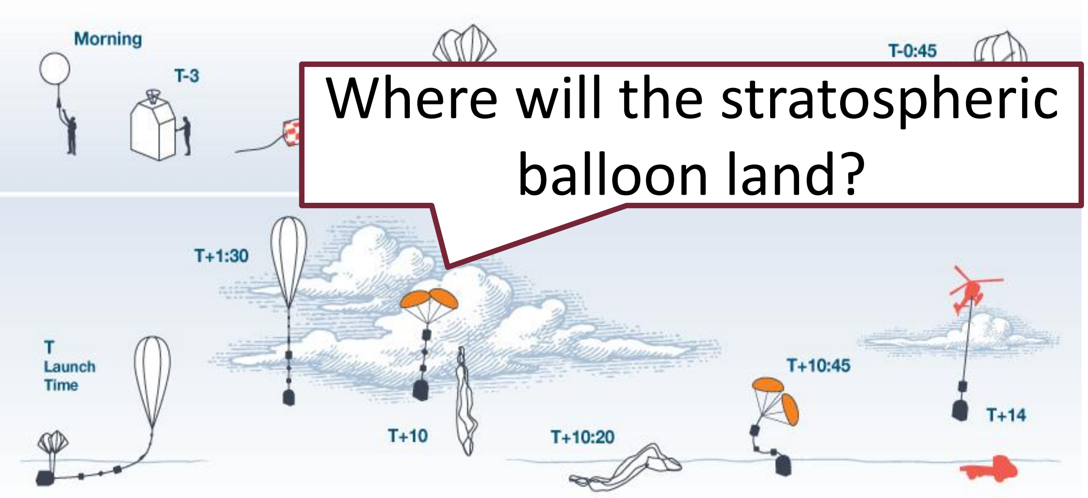
How to predict the weather?

Shall I go surfing this weekend?

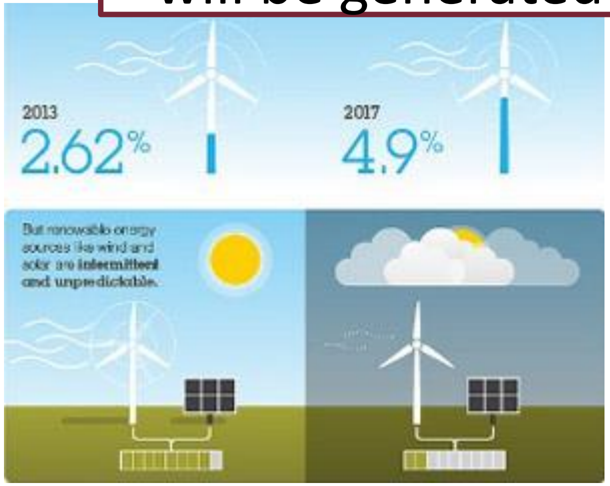


Should I take my umbrella today?

How much enegy will be generated?

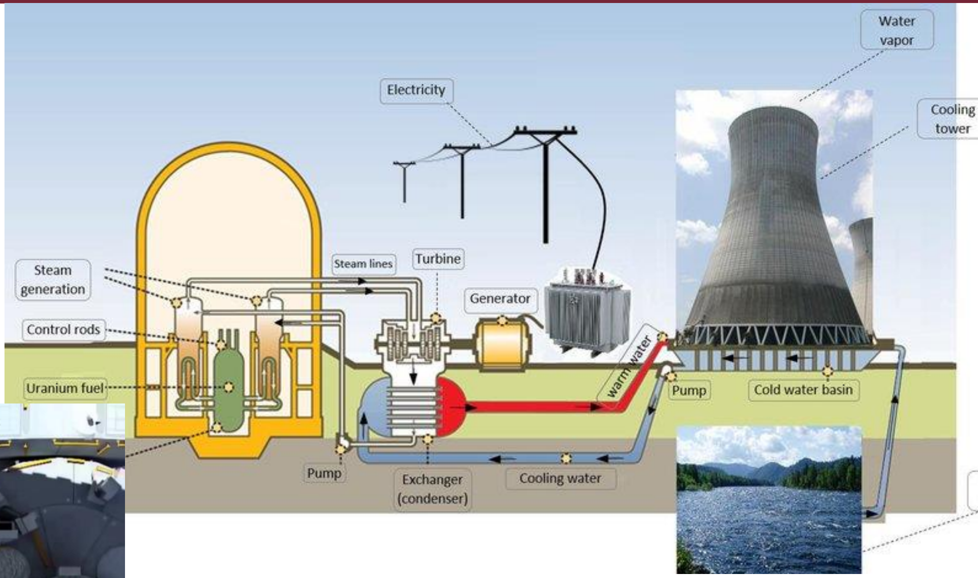


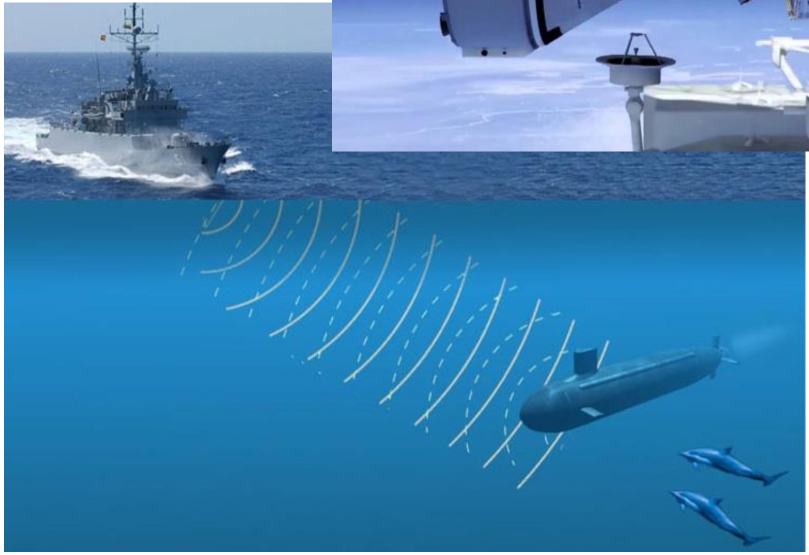
Where will the stratospheric balloon land?



Motivation

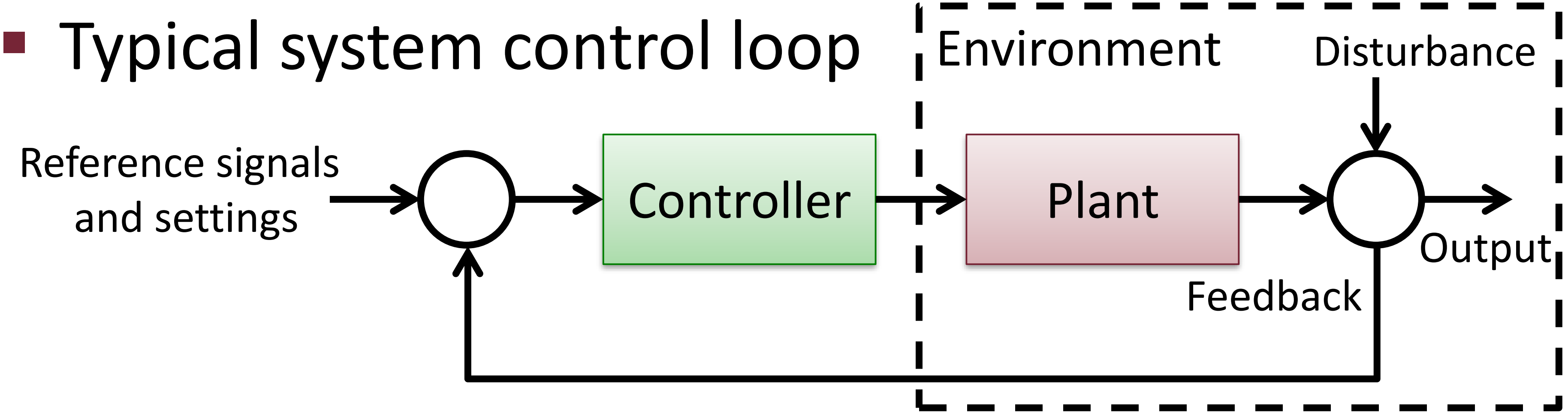
How to ensure the designed controller (software) works correctly?





Controller, Plant, and Environment

- Typical system control loop



- Challenge: validate the design of the controller
  - On-site testing and calibration can be
    - Expensive (time + cost)
    - Dangerous
  - Instead: run simulation
    - Must model *physical properties* of plant & environment

Physical systems

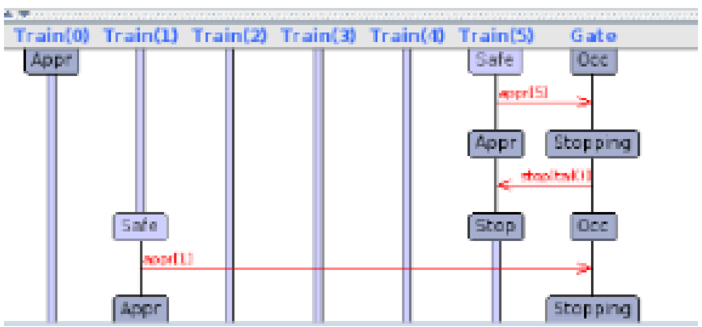
- Models up to this point:
  - „Controllable” system, model
  - System under design
  - Modeling goal: facilitate design process, (formal) analysis and verification of internal behaviour
- Physical systems:
  - Laws of physics can not be changed
  - Existing system
  - Modeling goal: assure designed system interacts well with environment

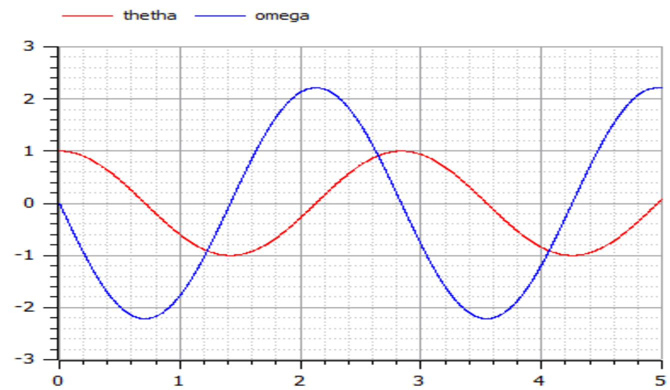
PRESCRIPTIVE

DESCRIPTIVE

Discrete vs continuous models

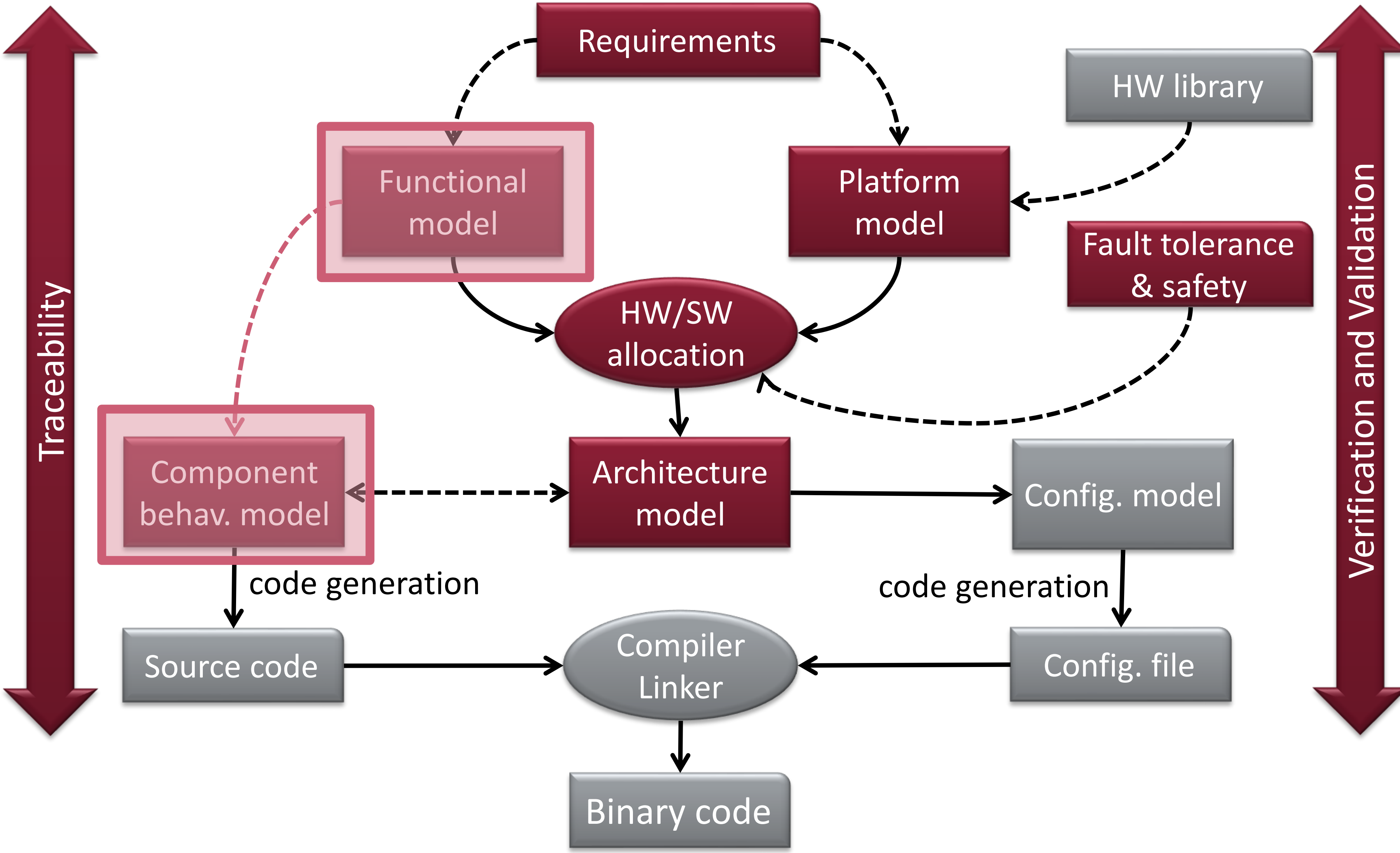
Discrete	Continuous
Reactive, state-based models	Differential equation systems
Changes described by assignments	Behaviour described by mathematical equations
Simulation - logical clocks	Simulation – numerically solving equation systems



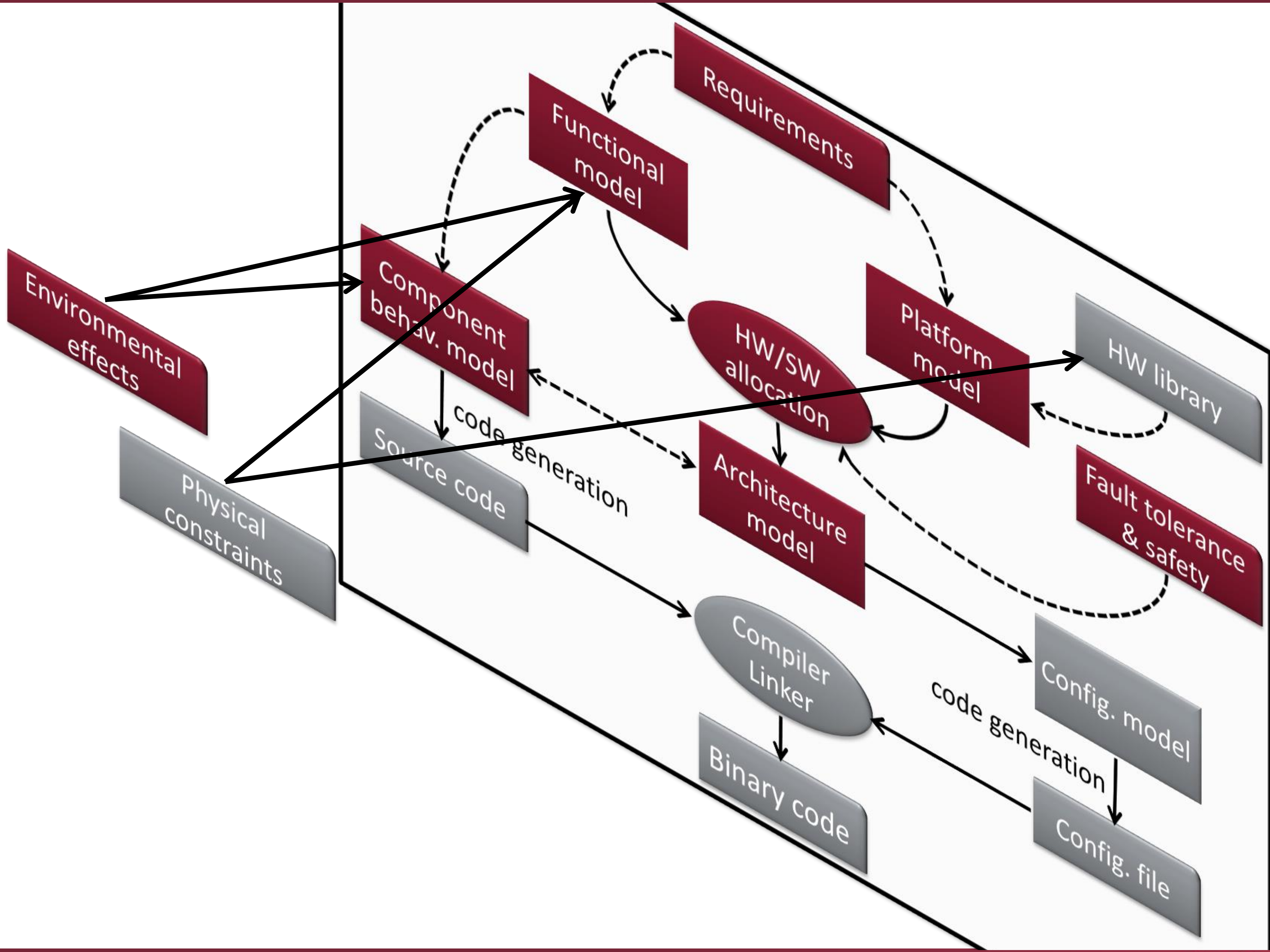


- Reality: Practically all real systems are hybrid
  - Reactive components mixed with continuous changes

Platform-based systems design



Platform-based systems design



Learning Objectives

Modeling physical parameters and constraints

Describe continuous behaviour of physical systems
Include rules constraining physical properties
Capture properties and constraints using the SysML language
Use the Modelica language to describe physical systems

Simulation of discrete and continuous models

- Work with systems of discrete and continuous states
- Capture both continuous-time and discrete time properties
- Perform discrete event and continuous time simulation
- Understand challenges of simulation in industrial settings

Outline

Modeling physical systems

Simulation basics

Simulation of discrete and continuous systems

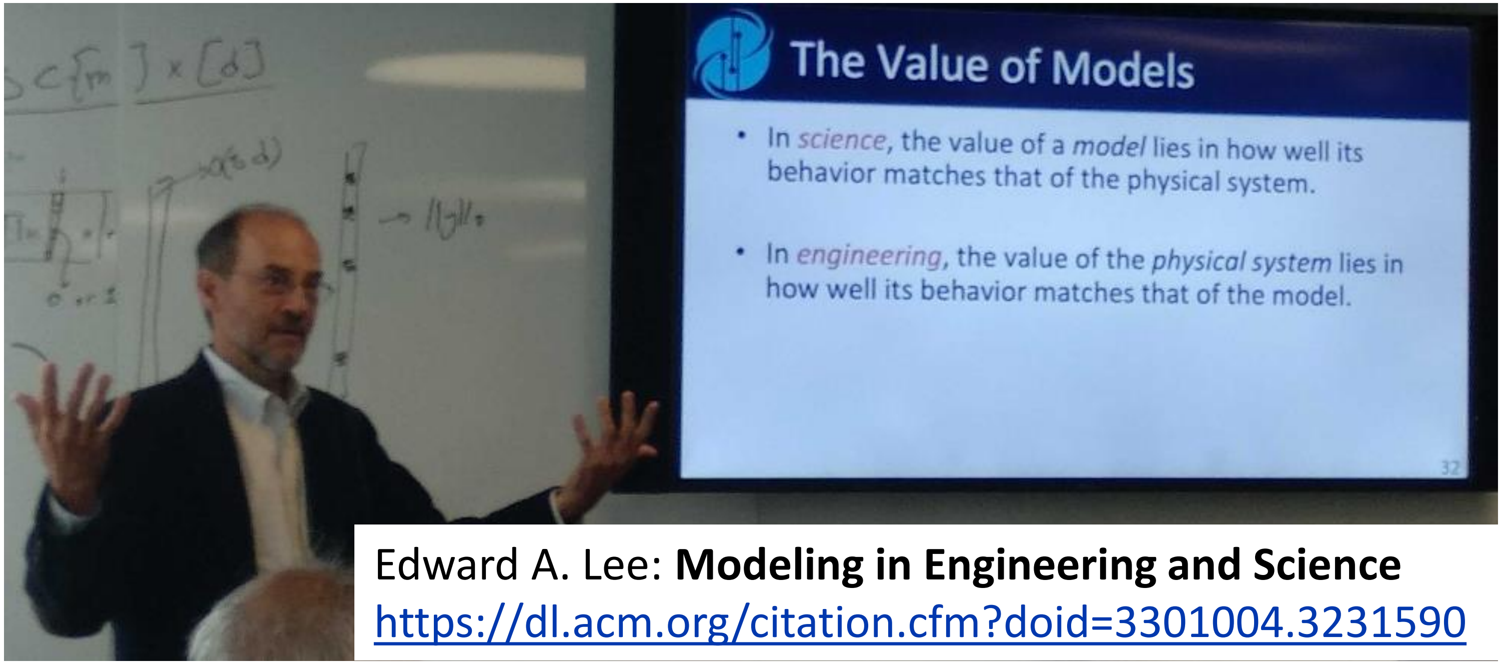
Motivating examples and case studies

Modeling physical systems

Modeling basics → SysML elements → Modelica

Physical models

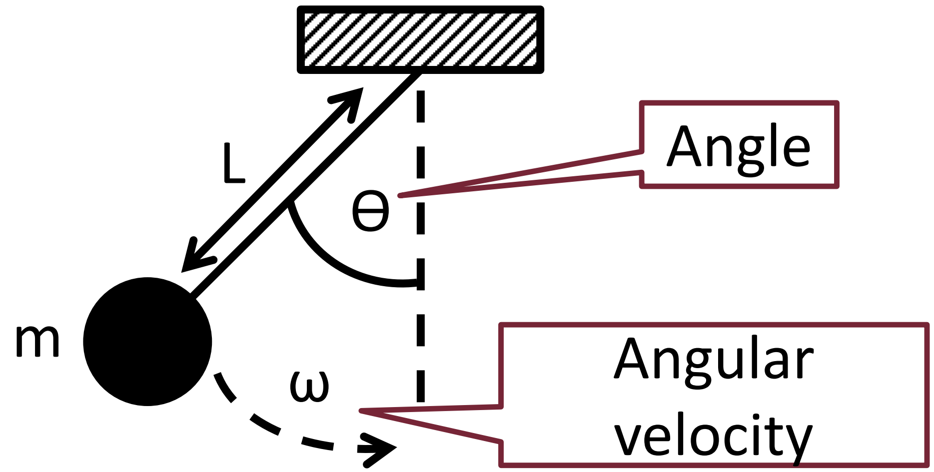
Software models	Physical models
Usually discrete	Usually continuous
Dissected – system is built by integration of components	In many cases everything has an impact on everything (e.g. weather – temperature)
Understandable, maintainable, usable	„God doesn't build in straight lines"
Any engineer can create the model	Good model requires domain expertise



Edward A. Lee: **Modeling in Engineering and Science**
https://dl.acm.org/citation.cfm?doid=3301004.3231590

Example: modeling a simple pendulum

- Simple pendulum



- Behavior of the pendulum as a function of time:

$$\begin{pmatrix} \dot{\theta}(t) \\ \dot{\omega}(t) \end{pmatrix} = \begin{pmatrix} \omega(t) \\ -\frac{g}{L} sin\theta(t) \end{pmatrix}$$

Angular acceleration

Assignments and equations

- **Causal** connection ≈ assignment in programming language

```
y := x + 3
```

  - Right-hand-side value determines left-hands-side variable
  - Typical use: to implement controller
- **Acausal** connection ≈ mathematical equation

$$y = x + 3 \Leftrightarrow y - 3 - x = 0$$

  - Always holds; if any of the variables has a new value, it enforces that the other variables change accordingly
  - Typical use: to model behaviour of plant / environment

Requirements

- Model **can be simulated** → Modeling tools
  - Neither over- nor underdetermined equation system (theoretical requirement)
  - Modeling tools have additional constraints
- **Representative** model
  - Obeys physical laws → formulate in model
  - Accurate representation of real world systems
    → compare simulation with real measurements
- General **usability**
  - Maintainable, reusable, etc. → block-based modeling

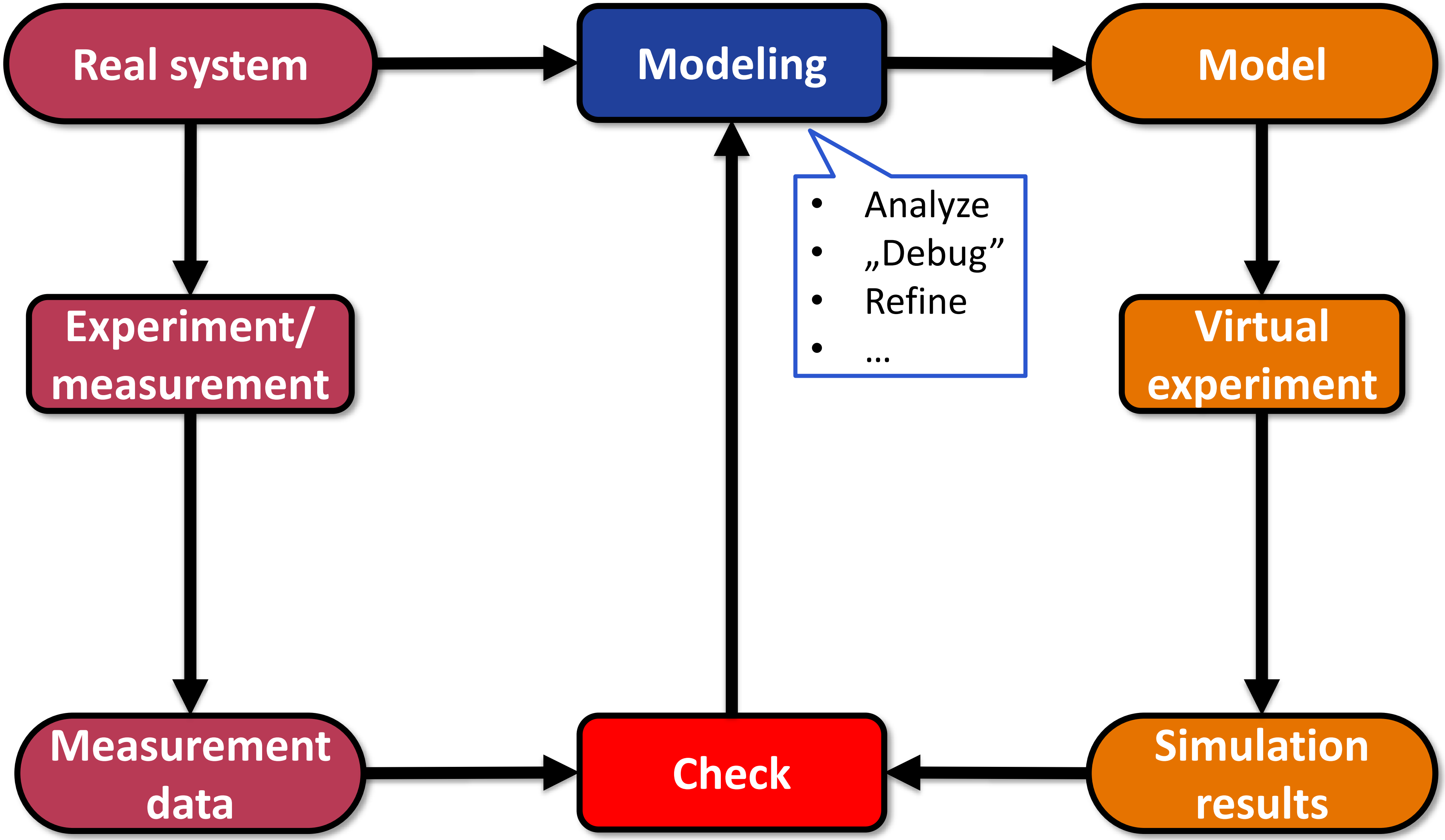
How to create a model

1. Decompose the system
2. Customize existing components
   - Better to use components provided by tools

   → (Just like programming languages)
   - Assign parameter bindings
3. Adjust connections
4. **Check model accuracy**

- Accurate modeling is difficult
  - Models are created by domain experts
  - There are complete books on modeling
- Simulation can be used for verification
  - (non-exhaustive, just like testing)

Checking physical model accuracy



Modeling physical systems

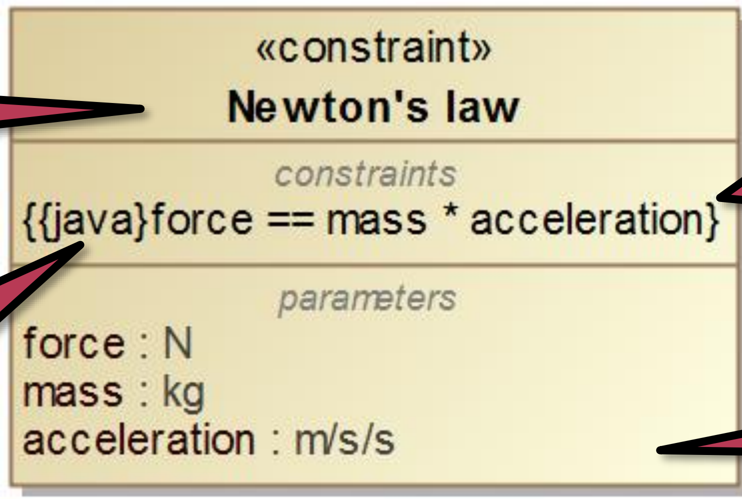
Modeling basics → SysML elements → Modelica

Constraint blocks

- **Constraint**: equations with parameters bound to the properties of the system
- **Constraint block**: supports the definition and the reuse of constraints. It holds
  - a set of parameters and
  - an equation constraining the parameters

Name of the constraint

May have language specification



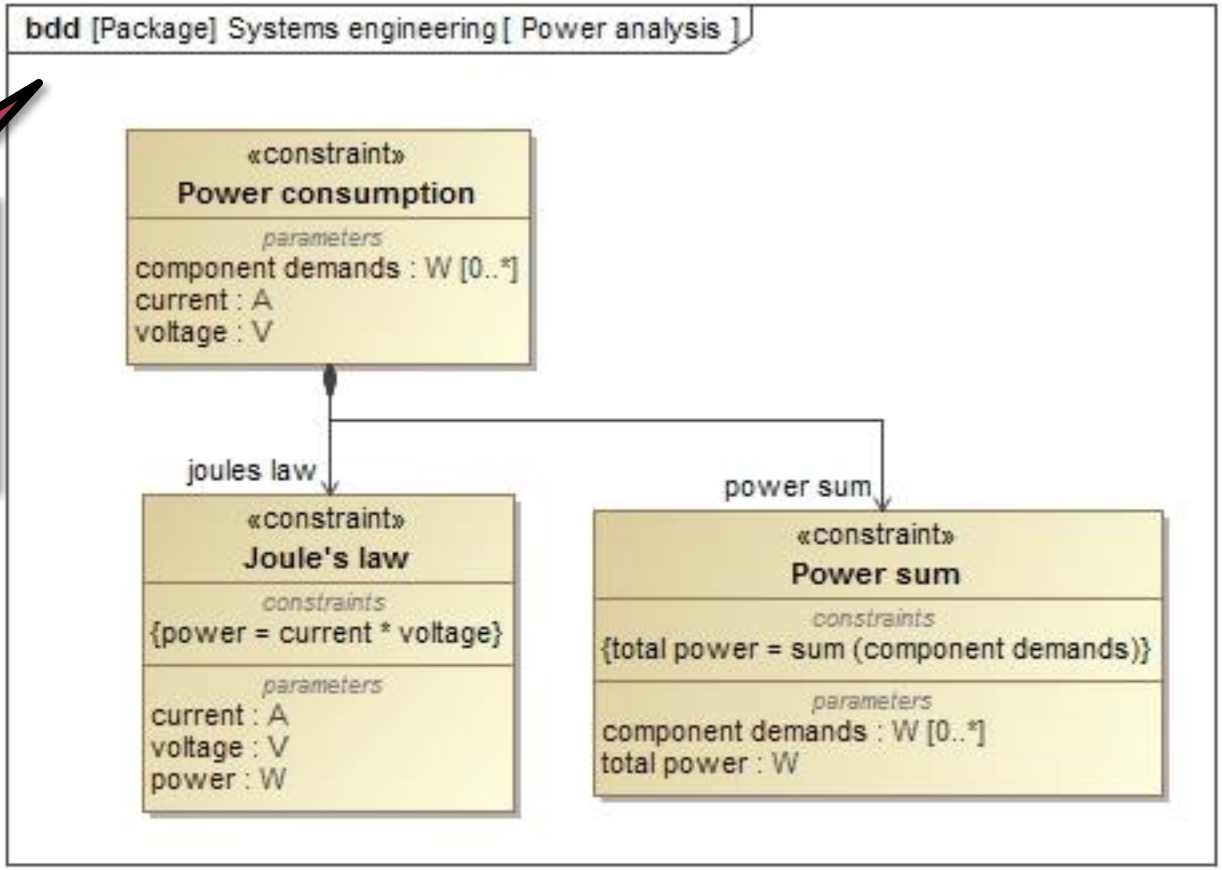
Equation – **no dependency between variables**

Parameters with types

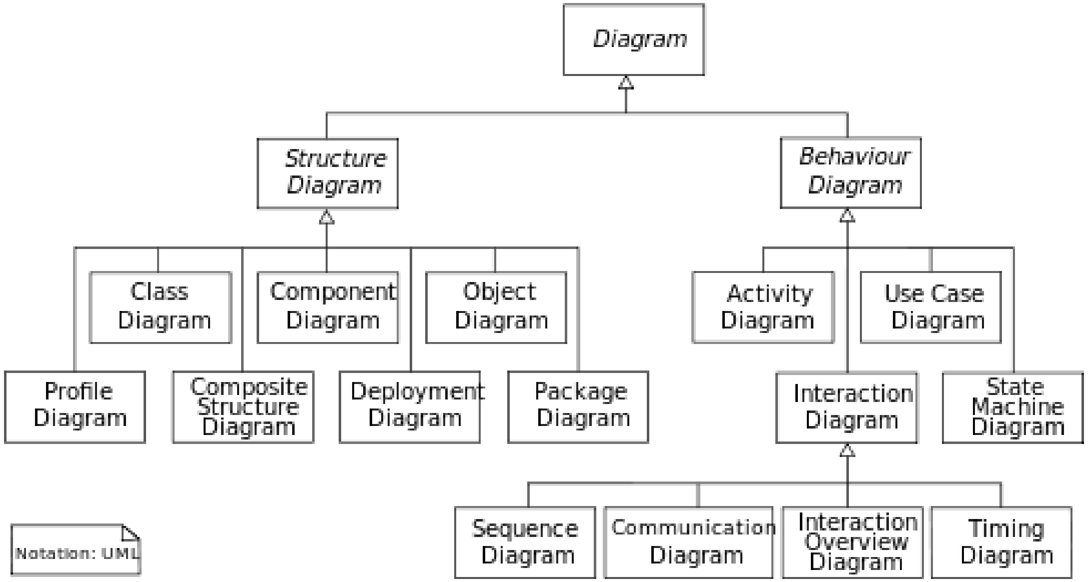
Constraint definition

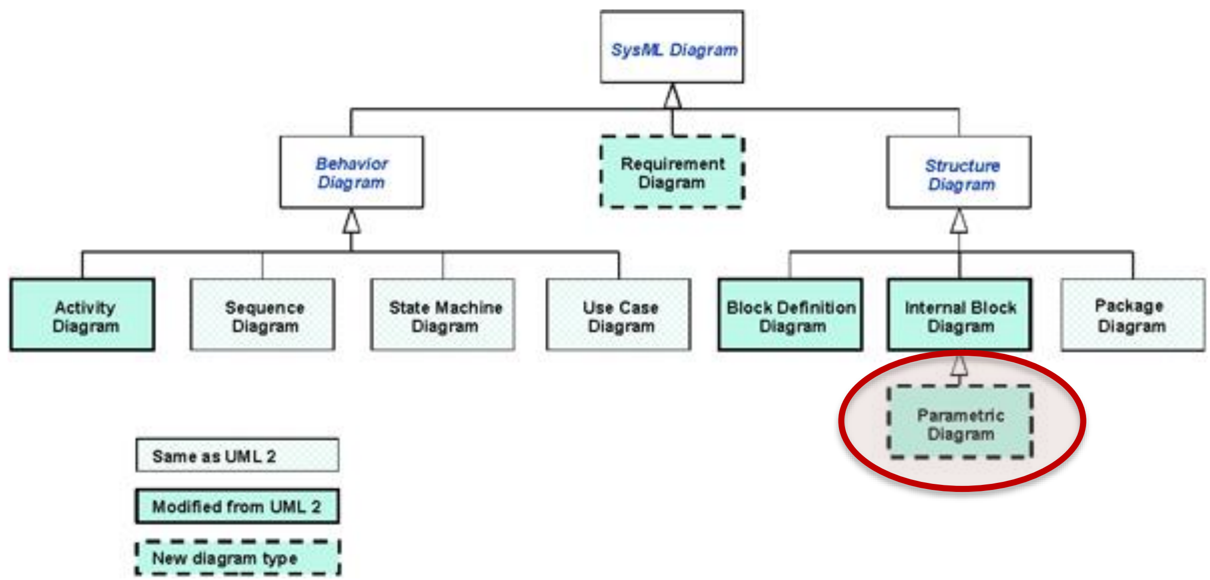
- **Composition** is used to define complex constraints from simple equations

Hierarchy depicted in a BDD



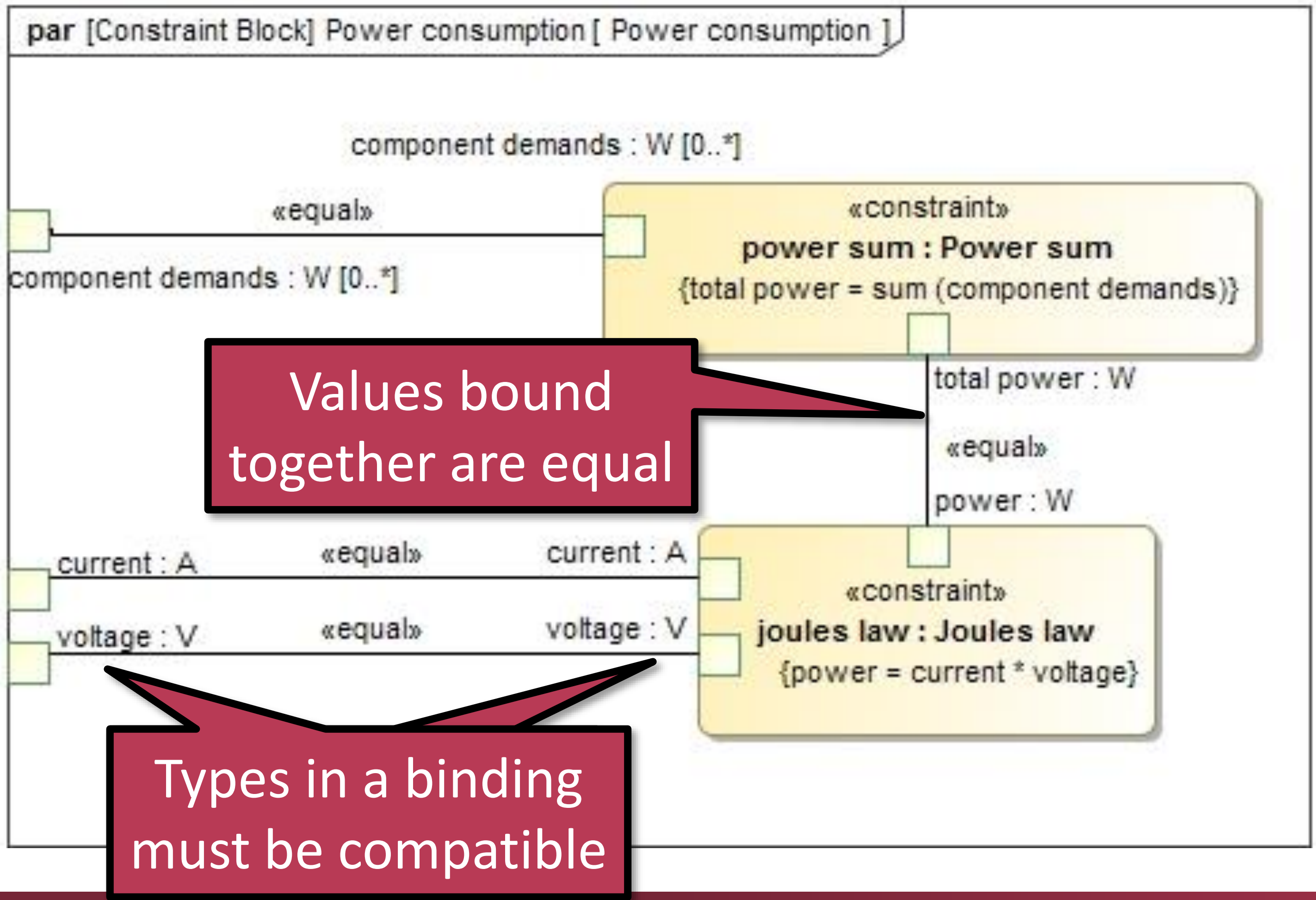
Parametric Diagram (PAR)





Parameter bindings

- Goal: describe the application of constraints in a particular context



Applications of parametrics

- Parametric specification
  - Define parametric relationships in the system structure
- Parametric analysis
  - Evaluating constraints on the system parameters to calculate values and margins for a given context
  - Checking design alternatives
  - Tool support: ParaMagic plug-in for MagicDraw
- Exact values may come from other sources
  - There are modeling standards with better support for this modeling aspect…
  - …such as Modelica

Modeling physical systems

Modeling basics → SysML elements → **Modelica**

Modeling Tools

- Modelica
  - OMEdit
  - Dymola
- Matlab/Simulink
- Domain specific tools
  - Ansys Simplorer (electrical systems)
  - AUTOSAR → Course: BMEVIMIAV15
  - CANoe (Engine control unit)

Overview of Modelica

- **Modelica** is an object-oriented, equation-based language designed to model complex physical systems containing process-oriented subcomponents of different nature
  - Describing both continuous-time and discrete-time behaviour
- The **Modelica Standard Library** provides more than 1000 ready-to-use components from several domains
  - Full high-school + 1st year university physics (and much more)
- Implementations
  - Commercial e.g. by Dymola, Maplesoft, Wolfram MathCore
  - Open-source: JModelica
- Modeling and simulation IDE: OpenModelica - OMEdit

Example: Modelica code for simple pendulum

Model name

Continuous time variables, constants

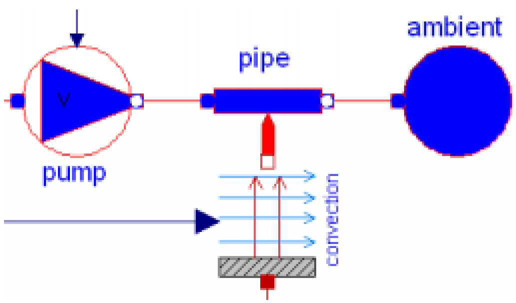
```
model SimplePendulum
    parameter Real L=2.0;
    constant Real g=9.81;
    Real theta (each start = 1.0);
    Real omega;
equation
    der(theta) = omega;
    der(omega) = -(g/L)*theta;
 end SimplePendulum;
```

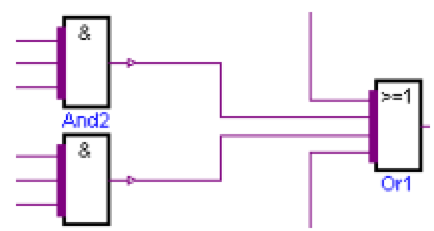
Initial value

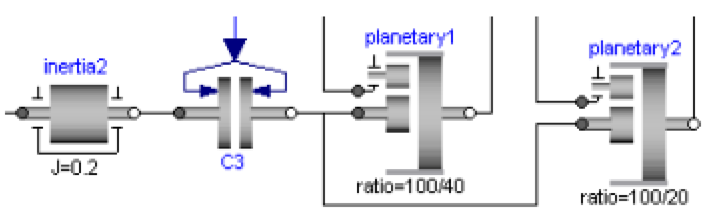
(Differential) equations

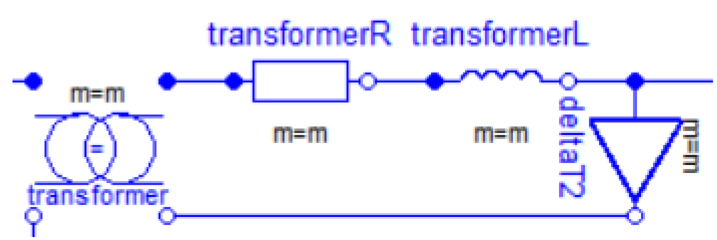
Modelica Standard Library

- Provides reusable building blocks (called classes) for Modelica models
- Version 3.2.1. has more than 1340 classes and models
- Various domains







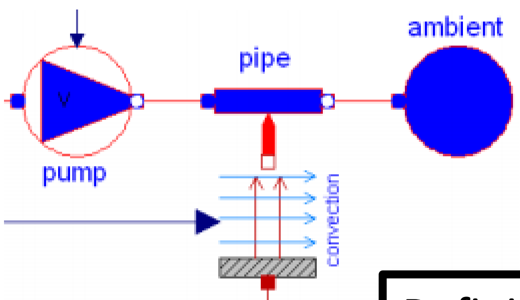


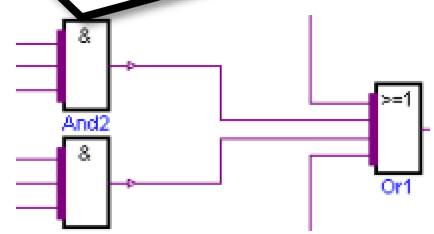
Modelica Standard Library

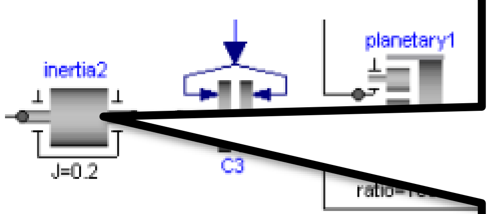
- P
  M
- V
- V

Definition in Modelica textual syntax:

```
equation
  auxiliary[1] = x[1];
  for i in 1:n - 1 loop
    auxiliary[i + 1] = D.Tables.AndTable[auxiliary[i], x[i + 1]];
       end for;
  y = pre(auxiliary[n]);
```





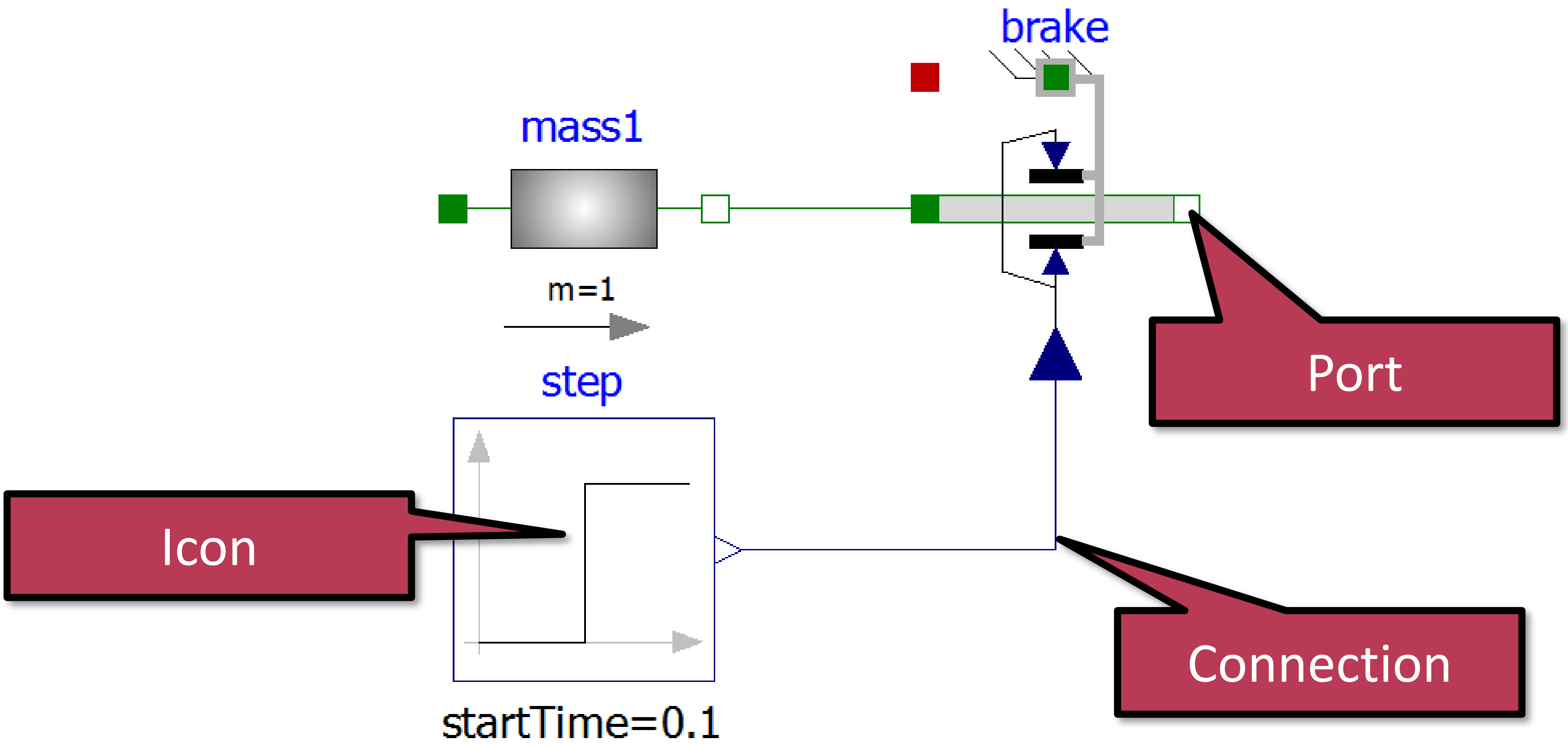


Definition in Modelica textual syntax:

```
equation
       phi = flange_a.phi;
       phi = flange_b.phi;
       w = der(phi);
       a = der(w);
       J*a = flange_a.tau + flange_b.tau;
```

Example plant model – train brakes

- Physical model for braking system carrying a mass



- Graphical notation in OpenModelicaEditor (~**ibd**)

Simulation

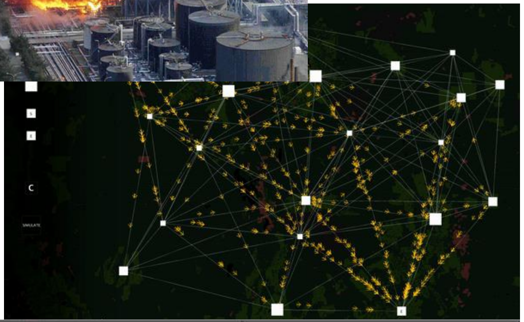
Simulation basics → Discrete systems → Timed systems → Continuous systems → Practical aspects

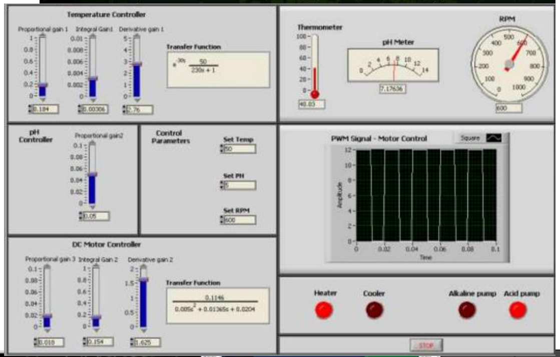
Model-based verification

- Modelling
  - Builds an abstract mathematical representation
- *Simulation*
  - Executes (some parts of) the **behaviour model**
  - Virtual experiment
- Testing
  - Executes (some parts of) the real system
- Other types of verification
  - Formal verification
  - Monitoring (can be used on simulated models)

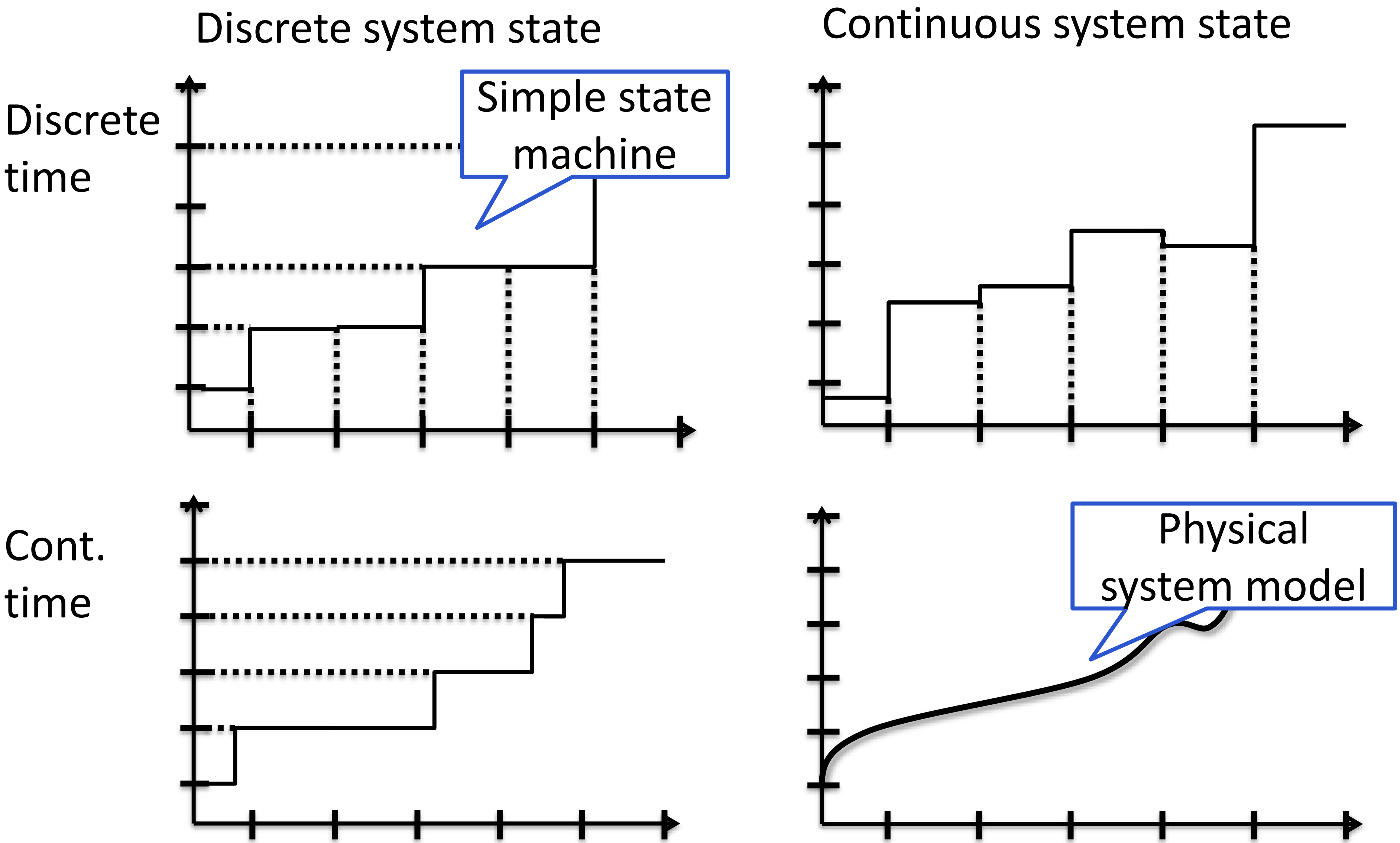
Advantages over real experiments

- Real system doesn't change
  - Error in simulation doesn't cause real problem
  - Model can simply be reset
- Simulation is much faster
  - Hours can be simulated in seconds
  - (Real-time simulation is also possible)
- Parameters can be adjusted easily
- Easier to analyze
  - Can be controlled, replayed
  - No need for complex monitoring system





Types of behavior models



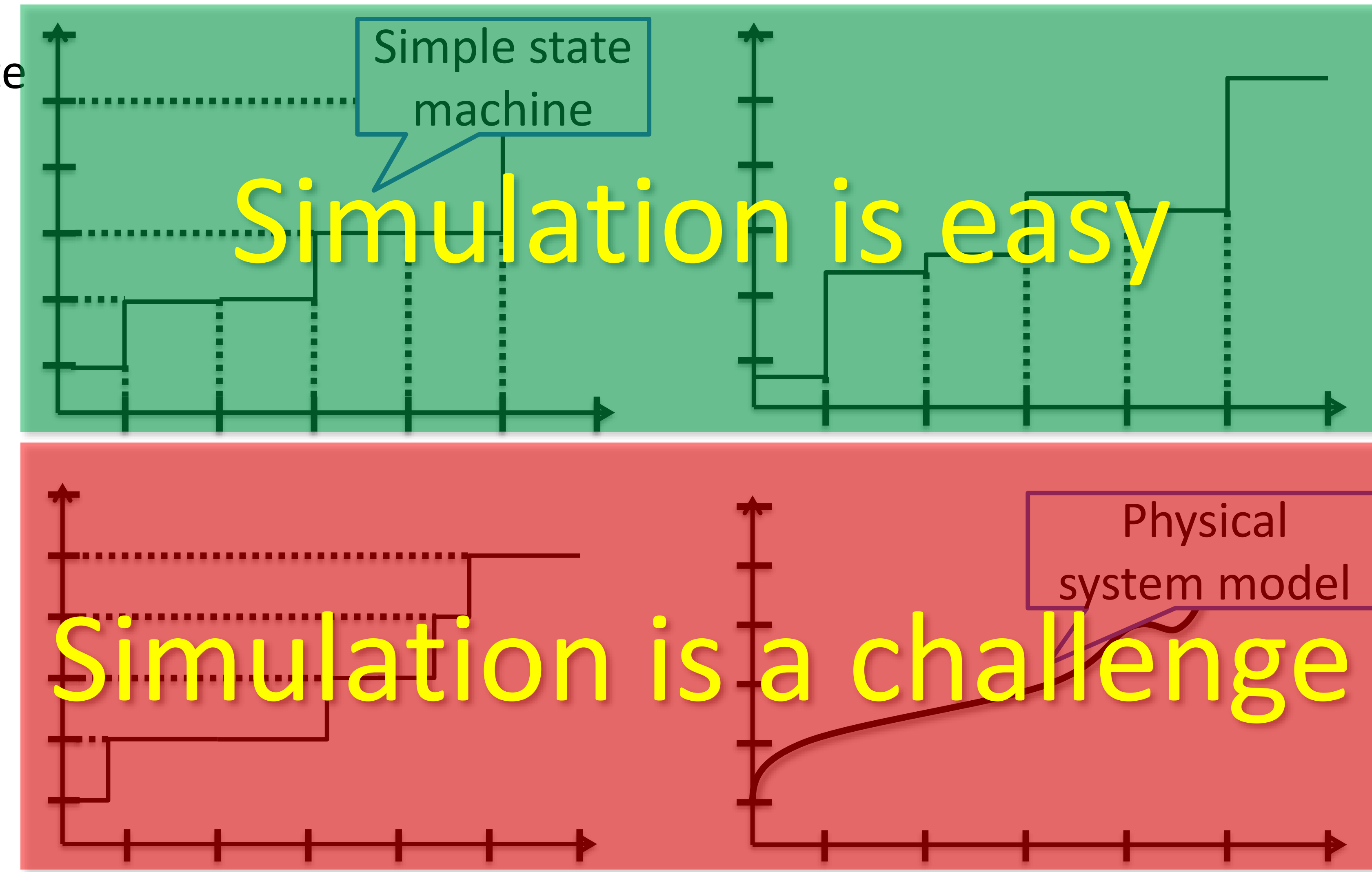
Types of behavior models

Discrete system state

Continuous system state

Discrete time

Cont. time



Types of simulation

- DES: Discrete event simulation
  - Event-based model (e.g. timed state machine)
  - Simulation step by step
    - Considering events (timestamps), guards and actions
    - Event queue – order is important
  - Challenges: synchronization
- Time stepped dynamic model
  - Continuous model
    (performance model, physical model)
  - Problem: discrete time simulator

  → Discretization of time

Simulation

Simulation basics → **Discrete systems** → Timed systems → Continuous systems → Practical aspects

Goals of System Simulation

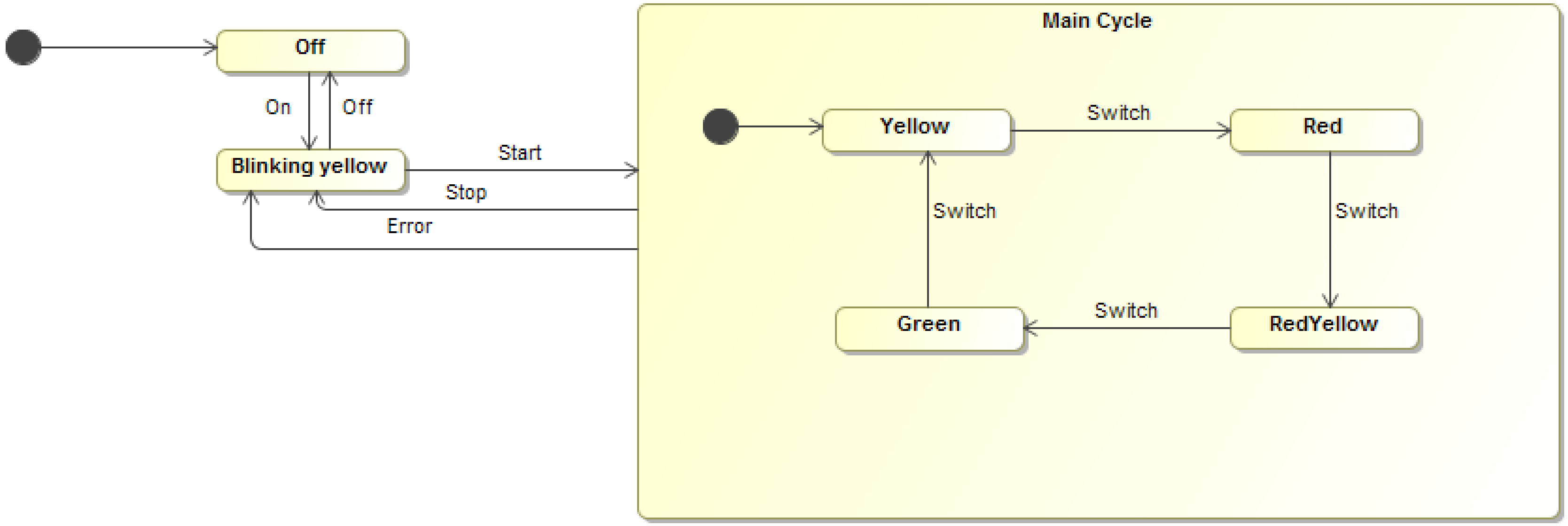
- Check the design of the system
  - Material flows -are there bottlenecks?
  - Queue locations and sizes -do they get blocked or starved?
  - Resources -are they sufficient, do they starve important operations?
  - Failure modes -what are they and what causes them?
- Check if it has the required capacity
- See what different types of downtime do to performance
- Improve the design

Components of a D. E. Simulation

- Simulations contain
  - ***Events*** causing changes in the system state
    - ***Event space*** – set of possible events: input events, timed events, etc.
  - ***Queues*** where entities wait their turn
    - Significant in case of *asynchronous* communication
    - *Synchronous* systems – **logical clock** model
- Only one event at once
  - Two events can have the same *time stamp* but they have to have an *order* (see: state charts with *exit*, *entry* and *do* actions)

DEMO CAMEO simulation

- Example: Traffic Light
  - Events: On, Off, Start, Stop, Switch, Error



Simulation

Simulation basics → Discrete systems → **Timed systems** → Continuous systems → Practical aspects

Variables and time

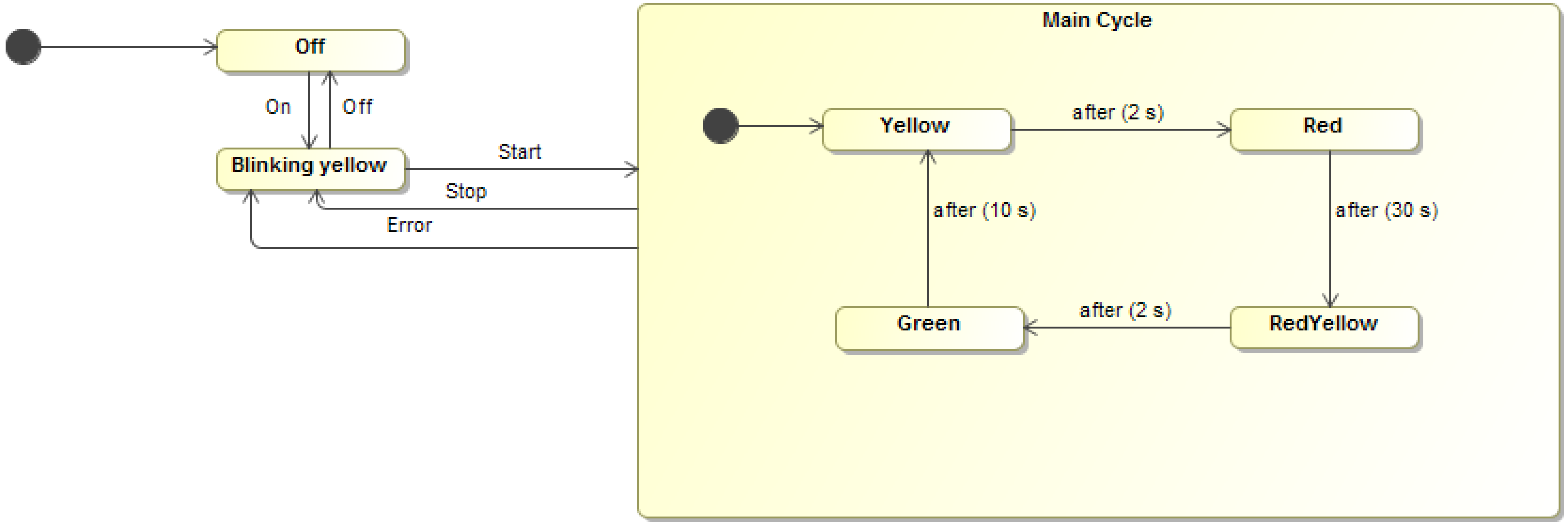
- Sytem state:
  - Represented by variables (explicit or implicit)
  - Continuous/discrete
- Representation of time
  - Continuous/discrete (logical clock - tick)
- Simulation uses virtual time
  - Virtual time ≠ runtime
  - (Except for real time simulation)
- Time is a variable!
  - *Although a special one*

If the only continuous component is time, discrete simulation is still possible.

DEMO Timed simulation with Cameo

- Example: Timed traffic Light
  - Events: On, Off, Start, Stop, ~~Switch~~, Error

Timed event

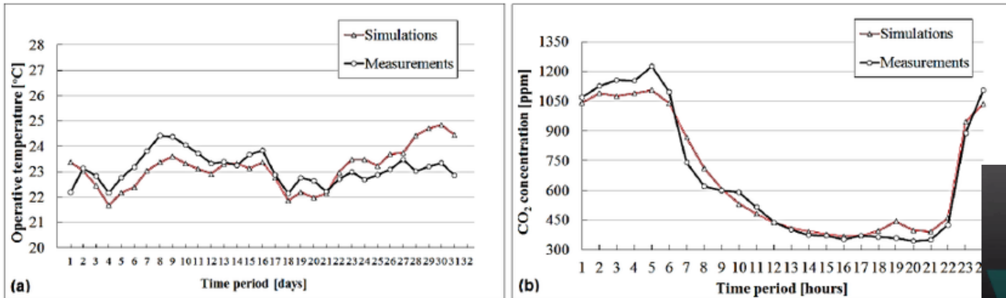


Simulation

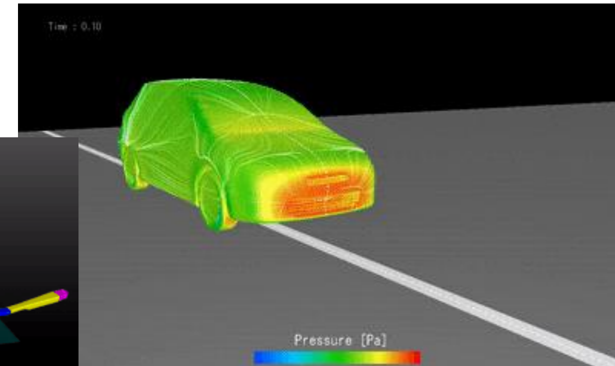
Simulation basics → Discrete systems → Timed systems → **Continuous systems** → Practical aspects

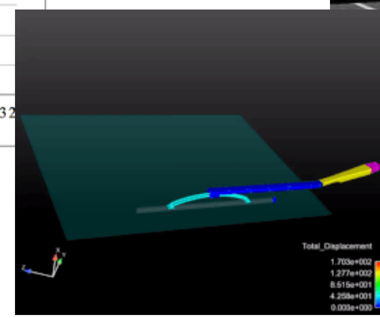
Goals of system simulation

- Ensure model correctness

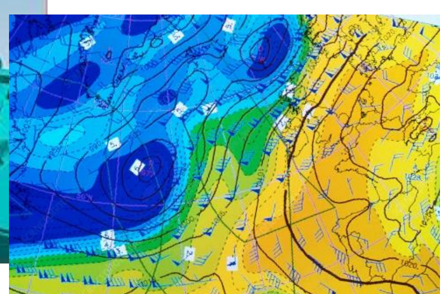


- Ensure correct interactions with designed system

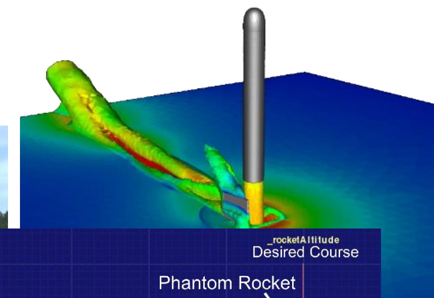
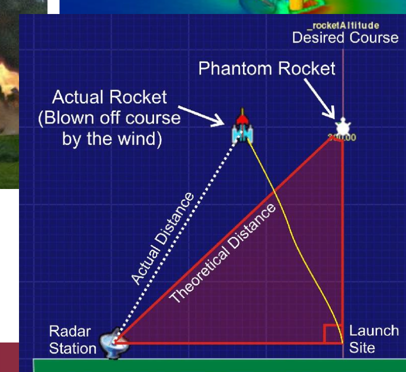




- Analyse/predict system behaviour

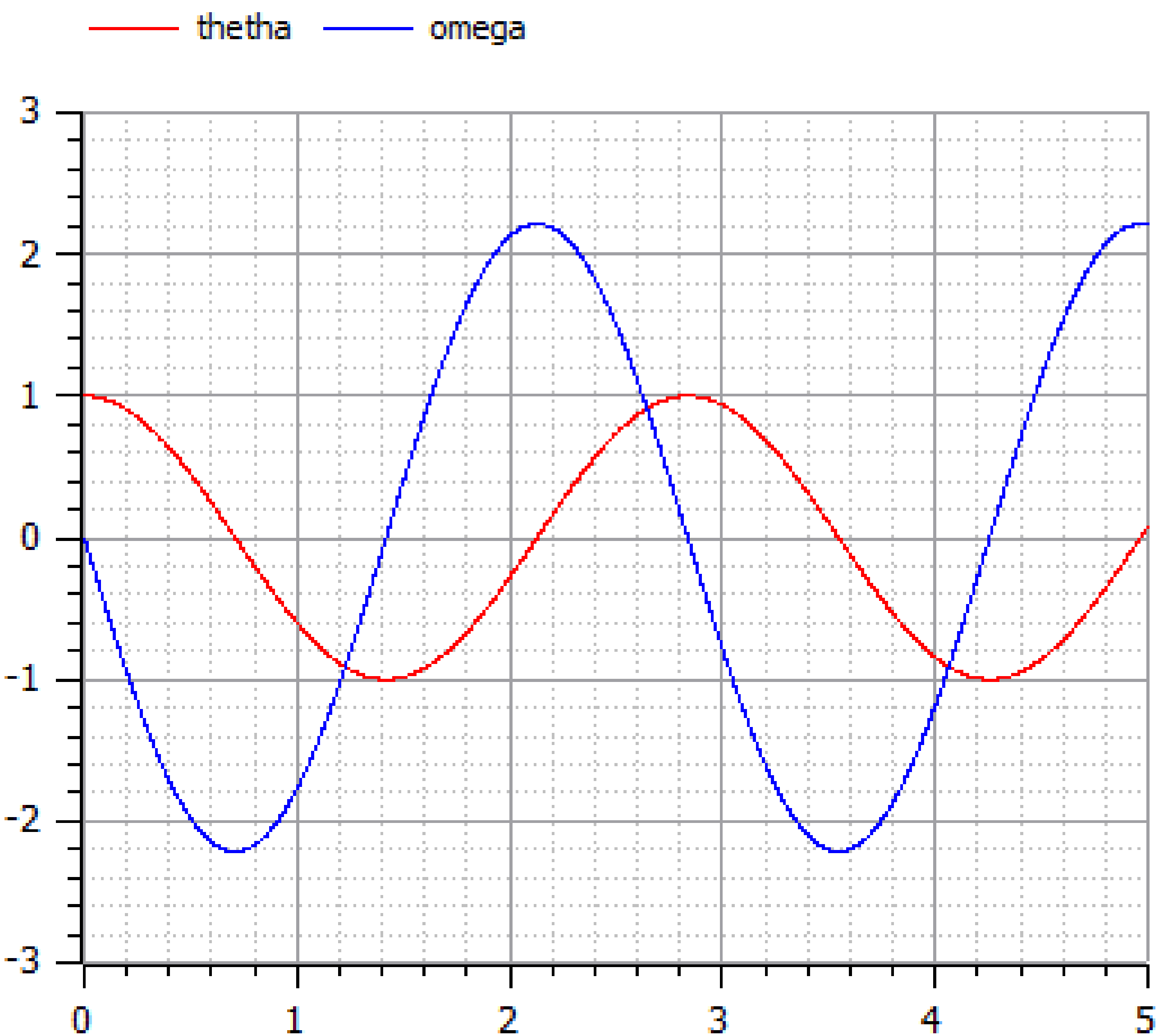
- Perform tests

Simulation of continuous systems

- Simulating a model means to calculate the values of its variables at certain time instants
- Different algorithms and strategies for simulation
  - The task is to solve Ordinary Differential Equations (ODEs) generated from the model
  - Numerical techniques
  - ODE specific solvers exist for this purpose

Example: Pendulum simulation results



Challenge

- Good model can be simulated incorrectly

aggajjar

OFFLINE

1 Posts

Thank you

Bouncing Ball Simulation Problem

Apr-24-17 06:40:35

Dear all,
I am not able to understand how to use when loop for bouncing ball problem. The standard code given in Michael Tiller's book is as follows:

```
model BouncingBall "The 'classic' bouncing ball model"
type Height=Real(unit="m");
type Velocity=Real(unit="m/s");
parameter Real e=0.8 "Coefficient of restitution";
parameter Height h0=1.0 "Initial height";
Height h;
Velocity v;
initial equation
h = h0;
equation
v = der(h);
der(v) = -9.81;
when h<0 then
reinit(v, -e*pre(v));
end when;
end BouncingBall;
```

Good model of a bouncing ball

Condition of bouncing: h<0

This code works extremely fine but let's say when I make h==0 (instead of h<0 i.e. ball hits the ground) in when statement then I get weird output in simulation and I am not able to understand it. So, any help would be appreciated.

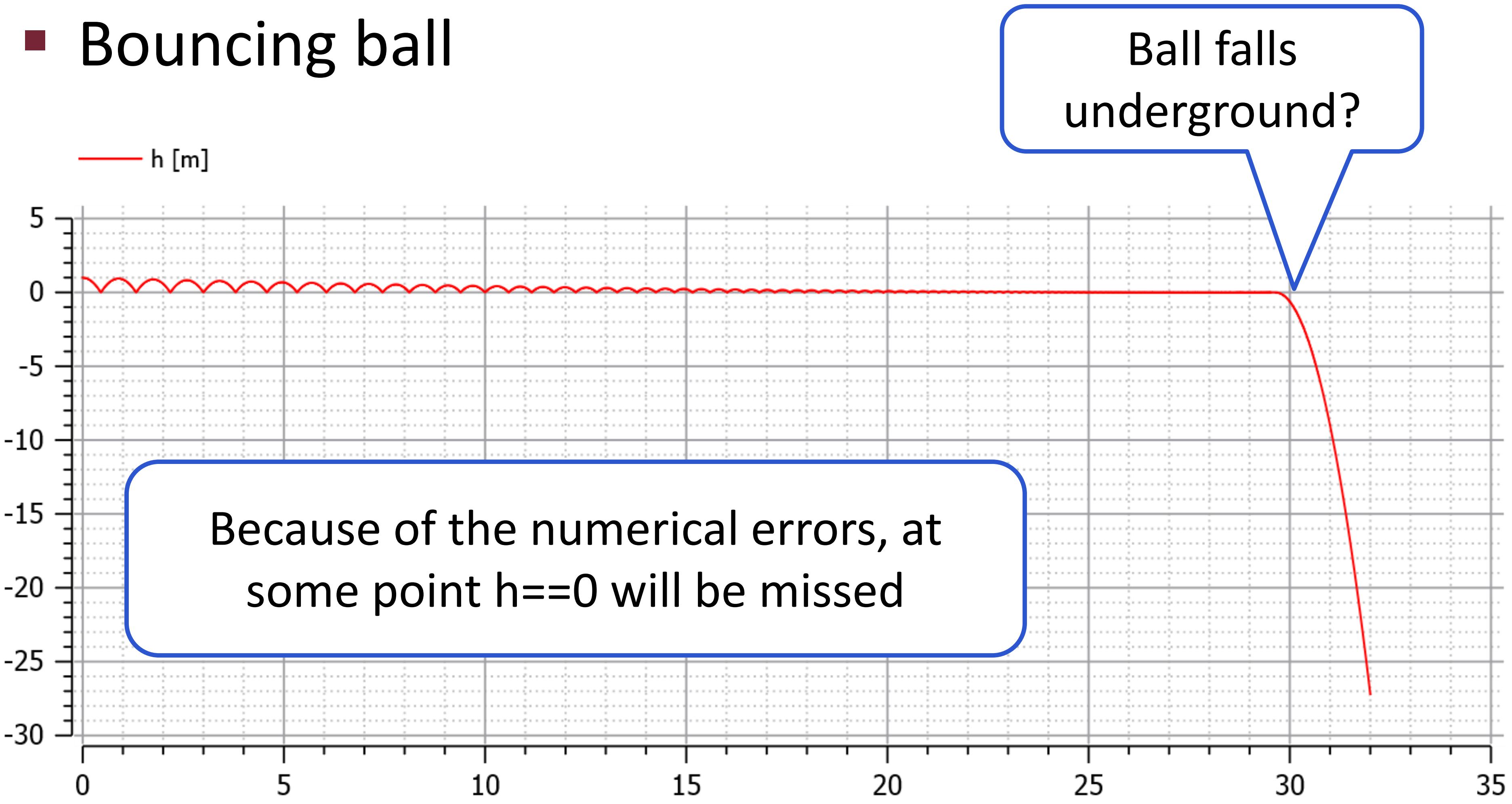
Problem when changed to h==0

Thank you.

Edited by: aggajjar - Apr-24-17 06:43:15

Incorrect simulation example

- Bouncing ball



Continuous simulation challenges

„The problem with simulation is that no matter what results you need, you are probably going to be able to get them."
[ApPLIED 2019]

- People tend to forget the limitations of simulation
  - Model limitations
    - Complex physics
    - Modeling connections is hard
    - Some environmental impacts will always be neglected
  - Limitations caused by time-stepped simulation
    - Communication delays
    - Induced reactions
  - Differential equation solver limitations
  - Propagation of numerical errors
- Correct configuration requires both domain and simulation knowledge

Simulation

Simulation basics → Discrete systems → Timed systems → Continuous systems → **Practical aspects**

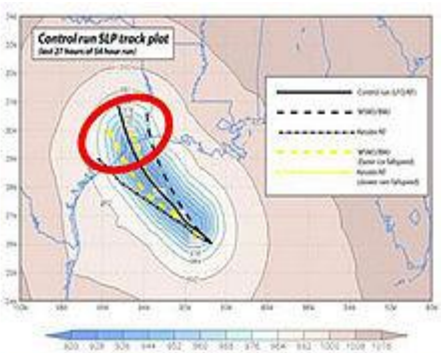
Ensemble simulation

- Problem: uncertainty in initial physical conditions

→No exact initial state

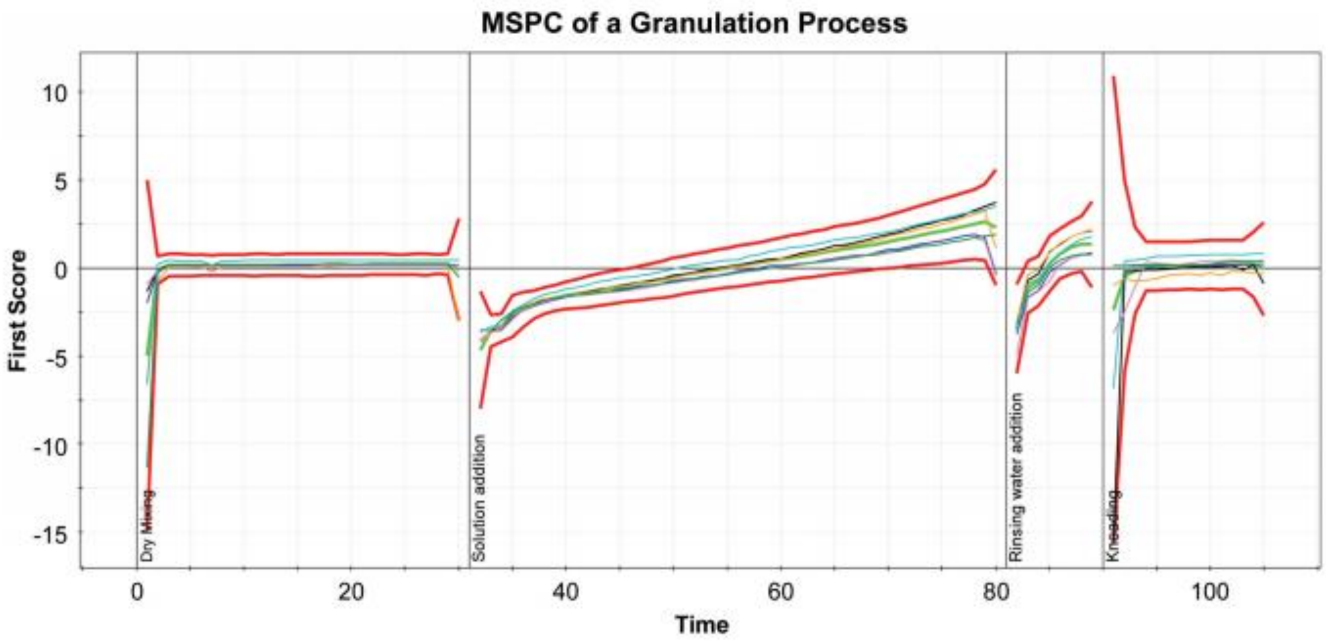
- Solution: Ensemble simulation
  - Repeat simulation multiple times from different states
  - Approximate probabilities of outcomes
- Example: weather
  - Hurricane Rita, 2005 September 07
  - ~ a month after Katarina destroyed New Orleans

  → Most probably heading for Houston



Hybrid simulation

- Most industrial models are hybrid
  - Contains both discrete and continuous components
  - Discrete changes effect the dynamic behaviour



Co-simulation

- Models of system components may differ
  - Model domain characteristics
    - E.g. discrete/continuous
    - Desired simulation techniques
  - Modeling environment and capabilities
  - Creator (protection of intellectual property)

Co-simulation: The parallel simulation of different models in a controlled environment, allowing them to communicate, synchronize, etc. without raising IP protection concerns

- Solution: FMI standard

TLM simulation

- Most simulation limitations exist to avoid loops
  - Cyclic dependencies between variables
  - There will be a delay
    - Easy solution: always calculate with previous values
    - Better solutions: at least one delay per cycle

- Transmission Line Modeling
  - Every transmission/propagation (energy, force, etc.) in the model has a velocity

  → Delay exists in the real system!
  - Control simulation so that the simulation delay is the same
  - More precise, (much) less efficient simulation

Motivating case studies

Case studies from the OpenCPS Project

OpenCPS project

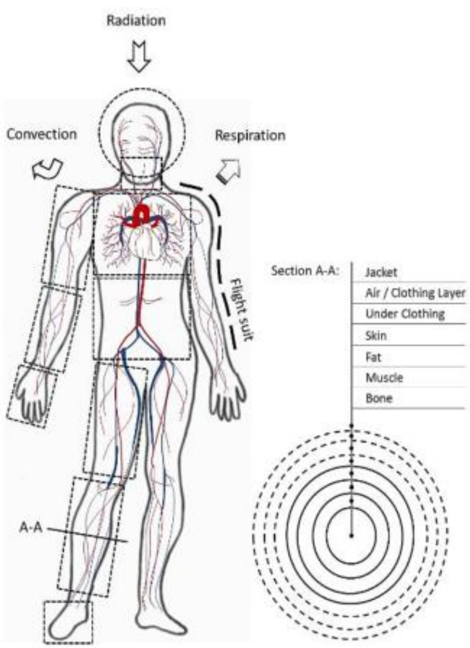
- Open Cyber-Physical System Model-Driven Certified Development
- 4 countries
- 18 industrial partners, including

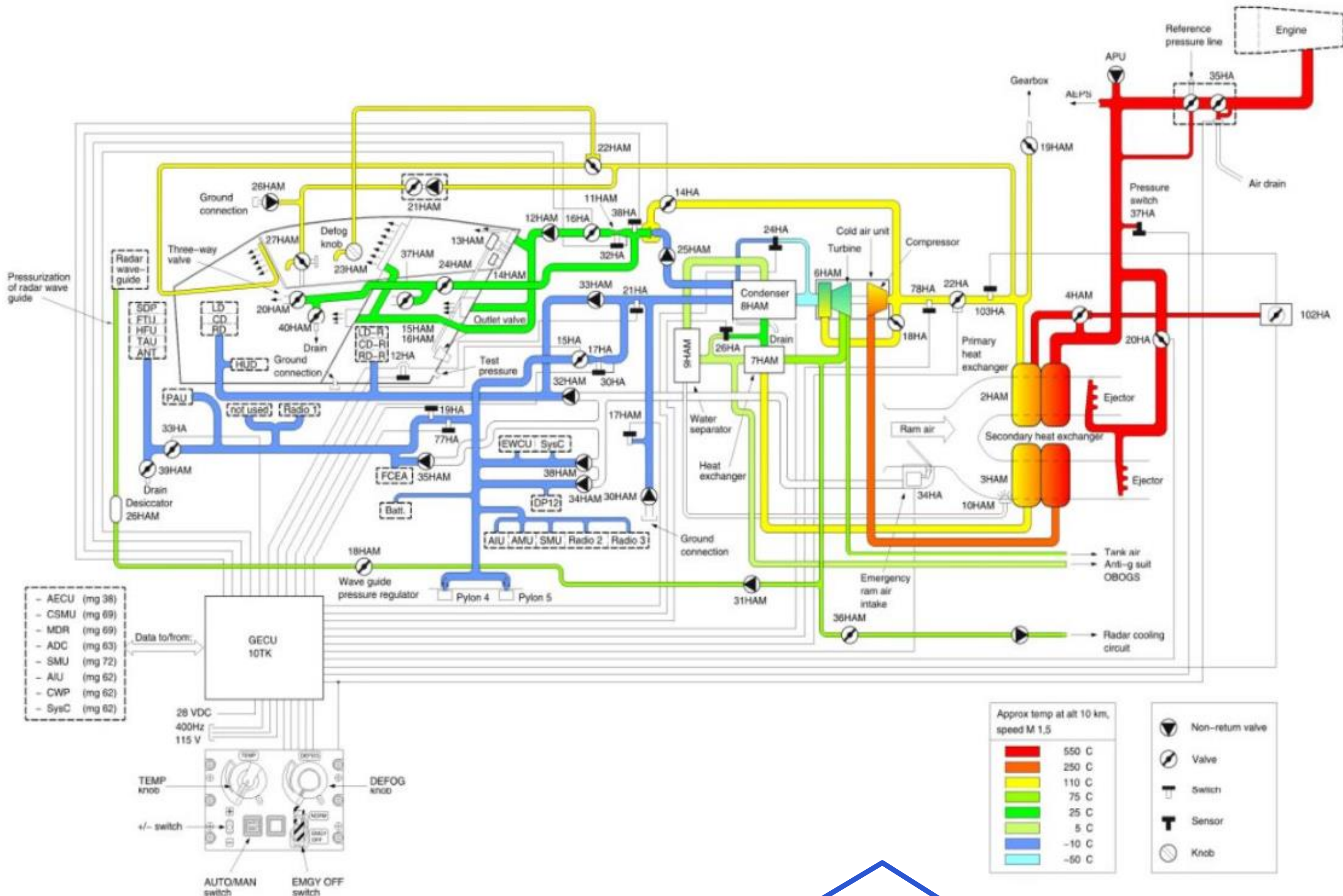
SAAB eDF SHERPA ENGINEERING cea ERICSSON SIEMENS

IncQueryLabs Ltd

- Industrial demonstrators in various fields
  - Building, **Aeronautics**, **Mechanics**, Naval, Power plant, Gaz turbines, **Automotive**

Thermal model of an aircraft

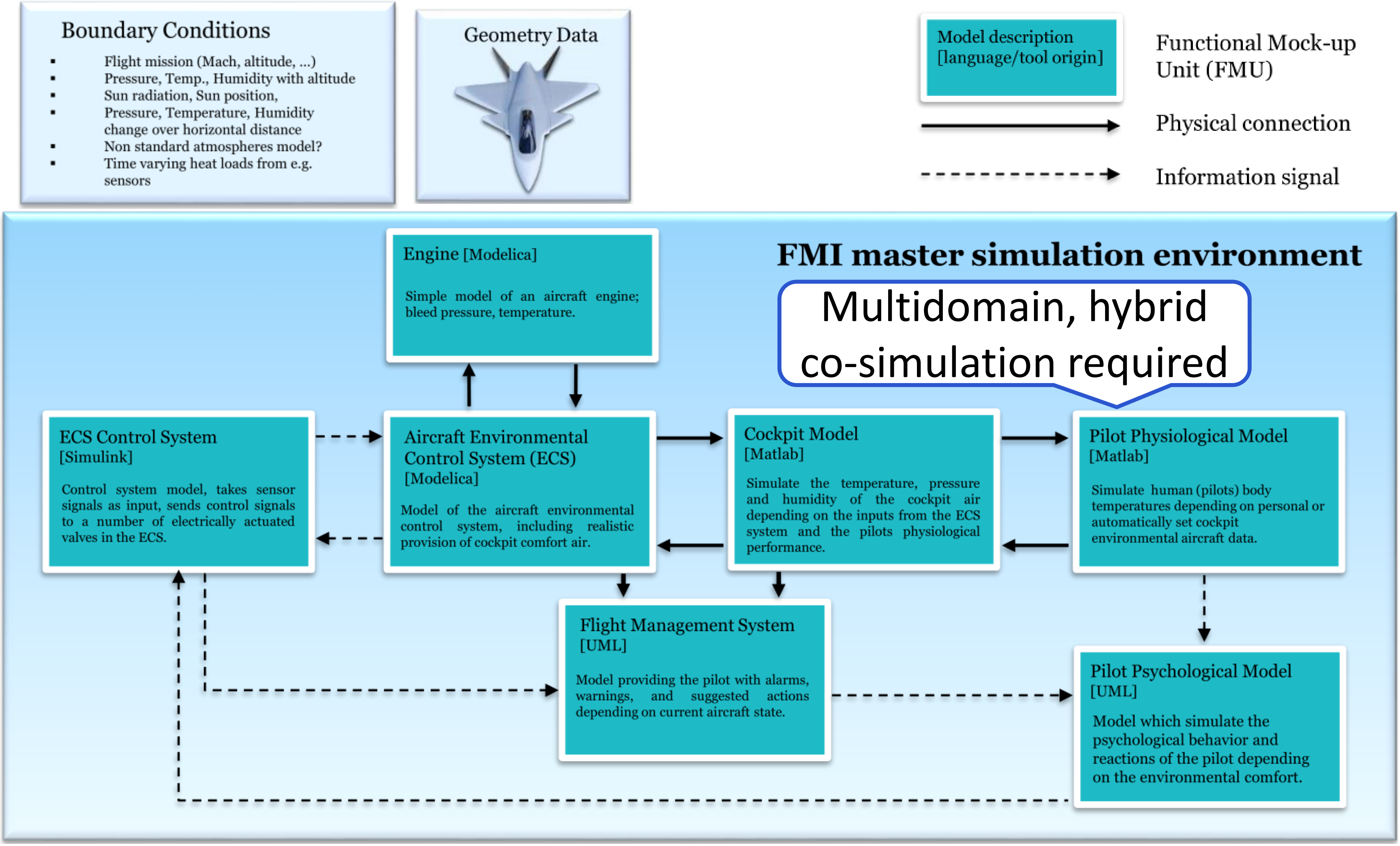




Copyright:

Huge, complex system

Thermal model of an aircraft



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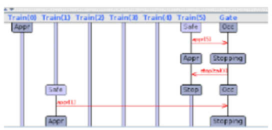
Project experiences, lessons learnt

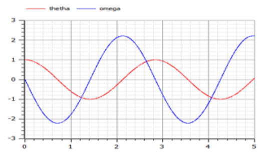
- Saab’s aircraft model
  - Huge complexity
  - Continuous components required very small simulation step size → highly inefficient simulation
  - Solution: better tools, distributed algorithm
- SKF’s bearing model
  - Required very precise simulation
  - Solution: TLM simulation
- Sherpa’s hybrid electric vehicle model
  - Required fast and accurate simulation
  - (My) solution: New simulation algorithm

Summary

Discrete vs continuous models

Discrete	Continuous
Reactive, state-based models	Differential equation systems
Changes described by assignments	Behaviour described by mathematical equations
Simulation - logical clocks	Simulation – numerically solving equation systems





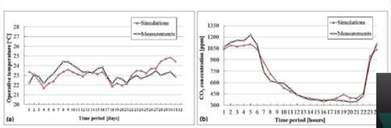
- Reality: Practically all real systems are hybrid
  - Reactive components mixed with continuous changes

Requirements

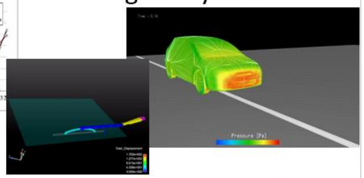
- Model **can be simulated** → Modeling tools
  - Neither over- nor underdetermined equation system (theoretical requirement)
  - Modeling tools have additional constraints
- **Representative** model
  - Obeys physical laws → formulate in model
  - Accurate representation of real world systems
    - → compare simulation with real measurements
- General **usability**
  - Maintainable, reusable, etc. → block-based modeling

Goals of system simulation

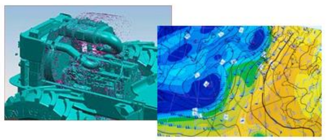
- Ensure model correctness



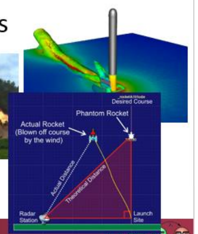
- Ensure correct interactions with designed system



- Analyse/predict system behaviour



- Perform tests



Simulation of continuous systems

- Simulating a model means to calculate the values of its variables at certain time instants
- Different algorithms and strategies for simulation
  - The task is to solve Ordinary Differential Equations (ODEs) generated from the model
  - Numerical techniques
  - ODE specific solvers exist for this purpose