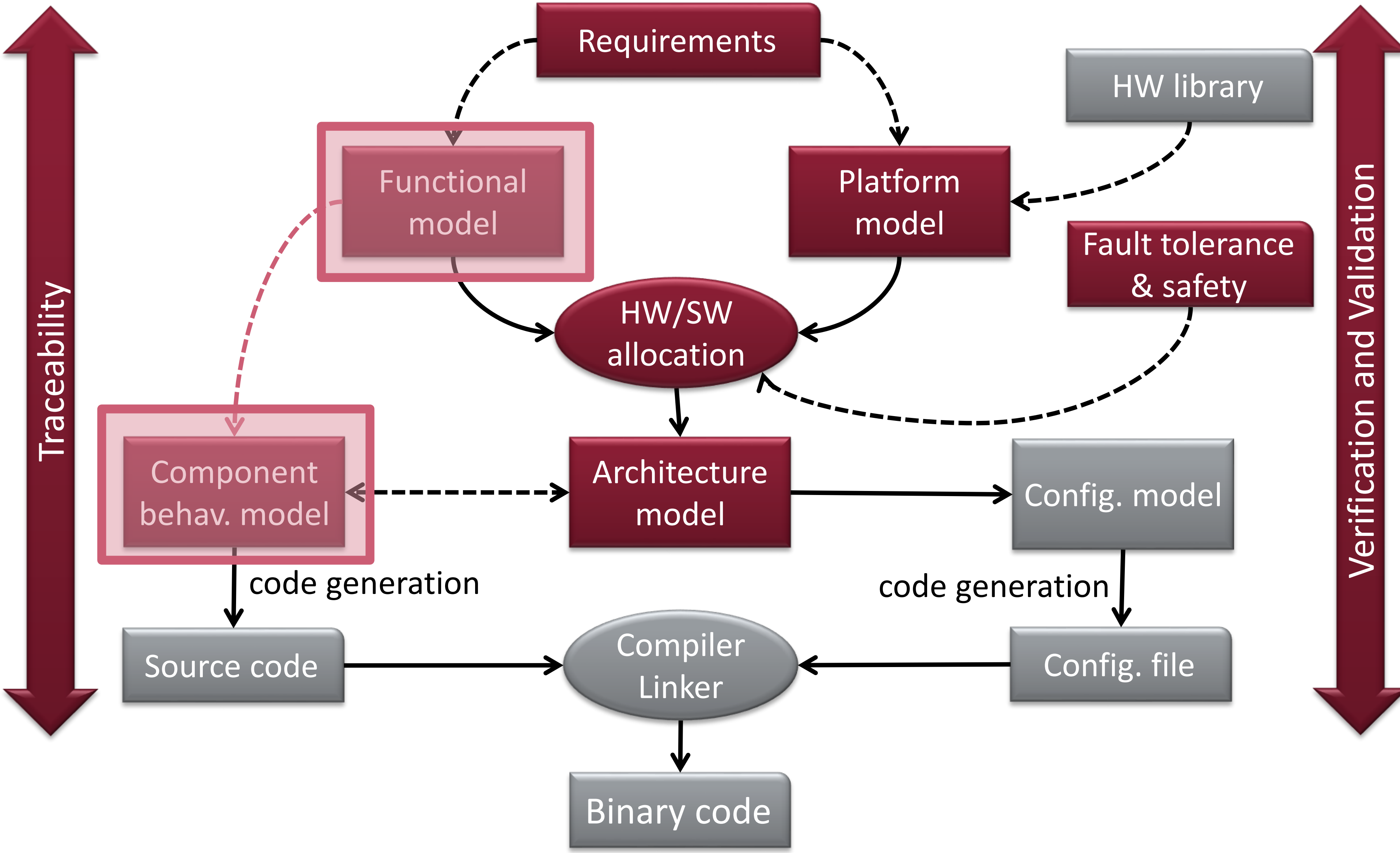
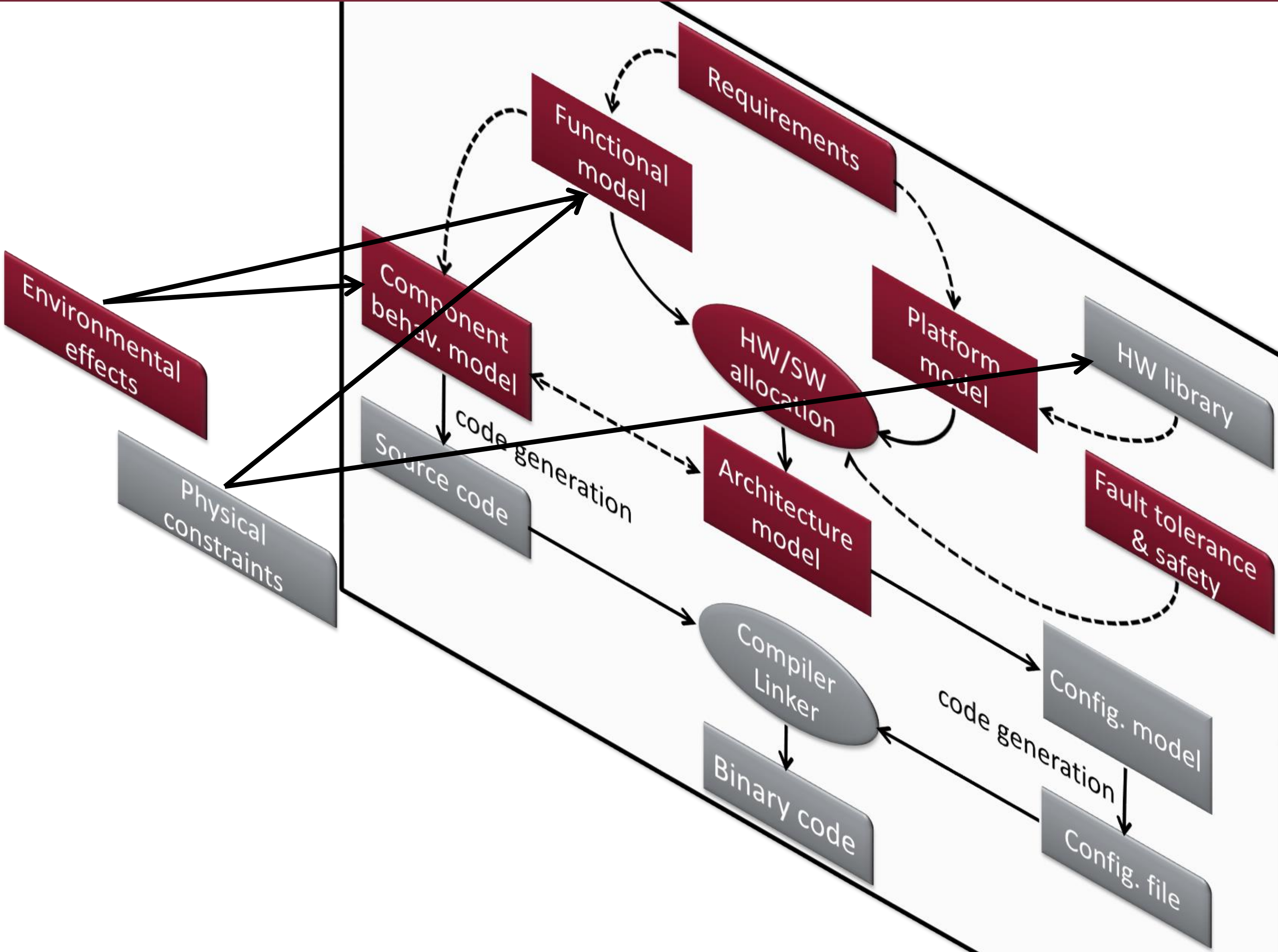
Modeling physical properties

Controller, plant and environment model

Platform-based systems design



Platform-based systems design



Learning Objectives

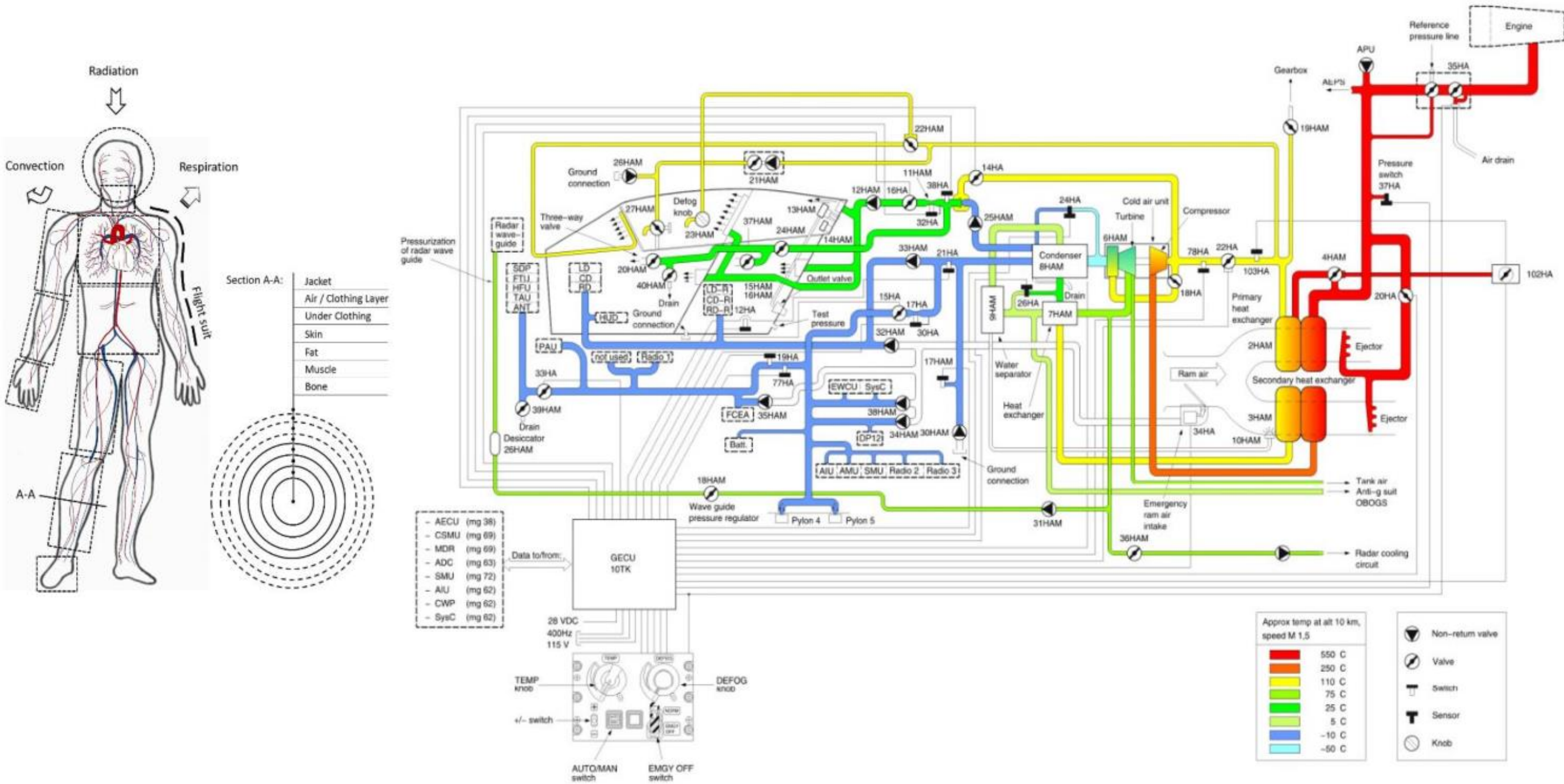
Modeling physical parameters and constraints

- Include physical properties in a model
- Include rules constraining physical properties
- Capture properties and constraints using the SysML language

Joint analysis of the system and the environment

- Modeling the controller, the plant, and the environment
- Capture both continuous-time and discrete time properties
- Identify the connection between the system, the plant, and the controller
- Analyze system properties and execute simulations using models
- Learn the basic modeling concepts of the Modelica language

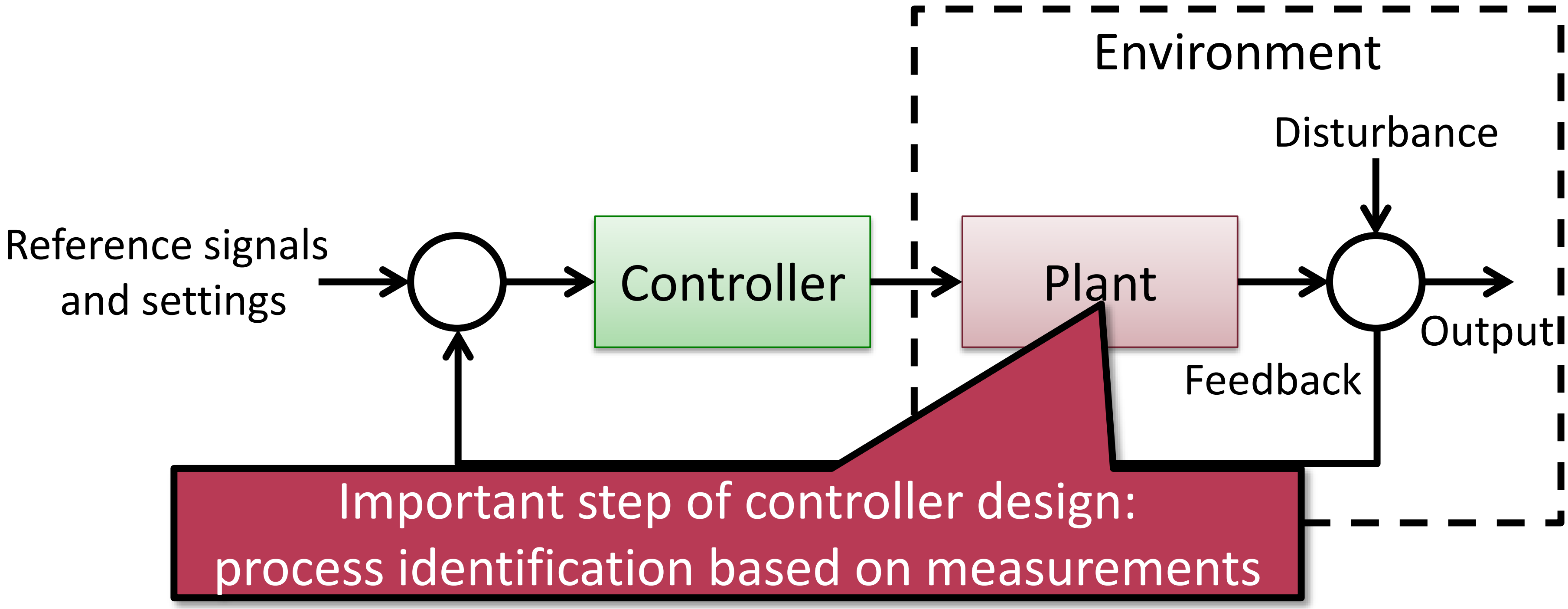
Thermal model of an aircraft



Copyright:

Controller, Plant, and Environment

- Typical system control loop



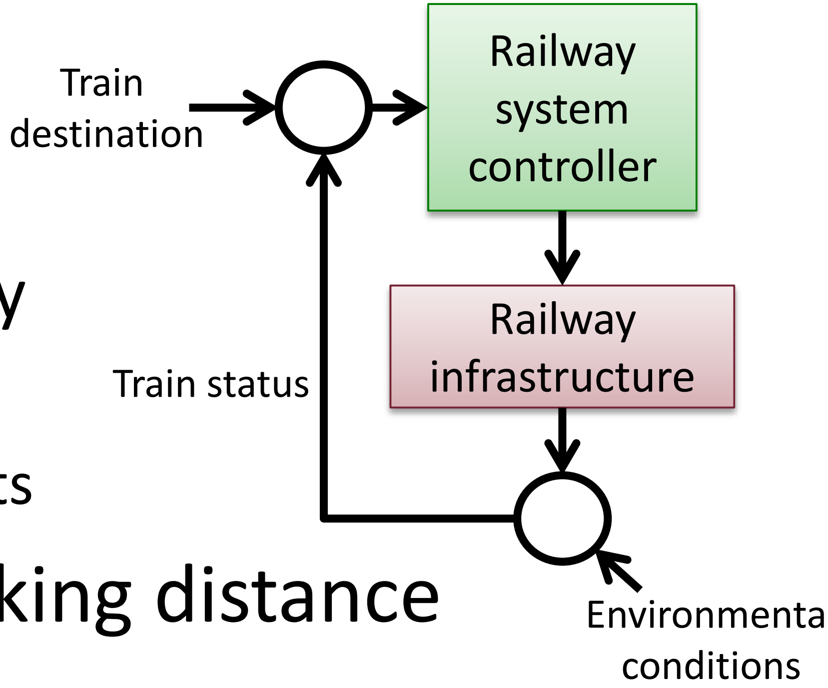
- Co-designing controller and the plant would be the ideal setting

Controller design

- Controller functional design using blocks
  - BDD: defines element hierarchy and containment
  - IBD: template for component internal structure
- Challenge: validate the design of the controller
  - On-site testing and calibration can be
    - Expensive (time + cost)
    - Dangerous
  - Instead:
    - create plant model and environment model with physical properties and
    - run simulations

Example railway system controller

- Controller aims to
  - monitor the trains
  - apply brakes when necessary
    - too close to each other
    - prevent derailment at turnouts
- Parameters influencing braking distance
  - Weather conditions
  - Speed
  - Landscape
  - … (anything else?)



Thermal model of an aircraft

Boundary Conditions

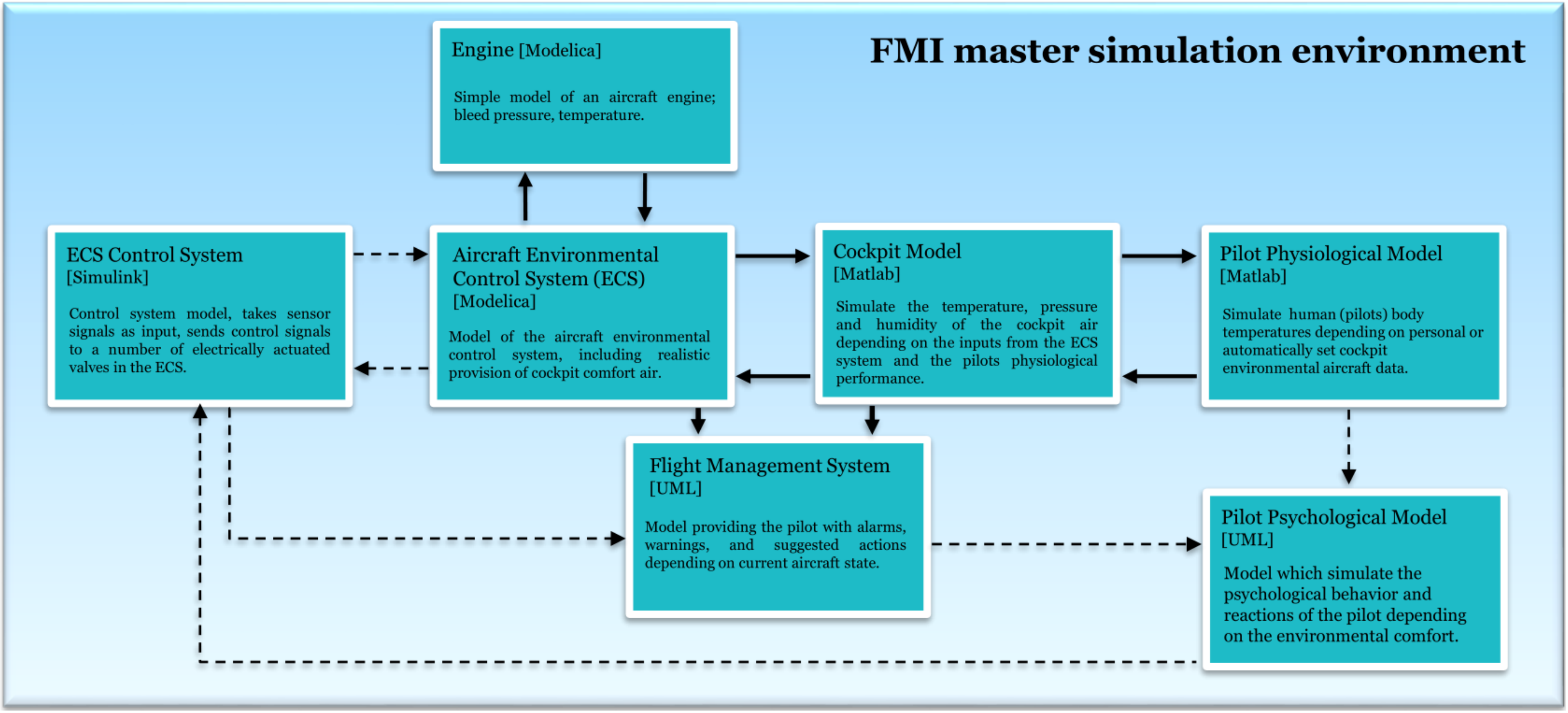
- Flight mission (Mach, altitude, ...)
- Pressure, Temp., Humidity with altitude
- Sun radiation, Sun position,
- Pressure, Temperature, Humidity change over horizontal distance
- Non standard atmospheres model?
- Time varying heat loads from e.g. sensors

Geometry Data

Model description [language/tool origin] — Functional Mock-up Unit (FMU)

Physical connection

Information signal

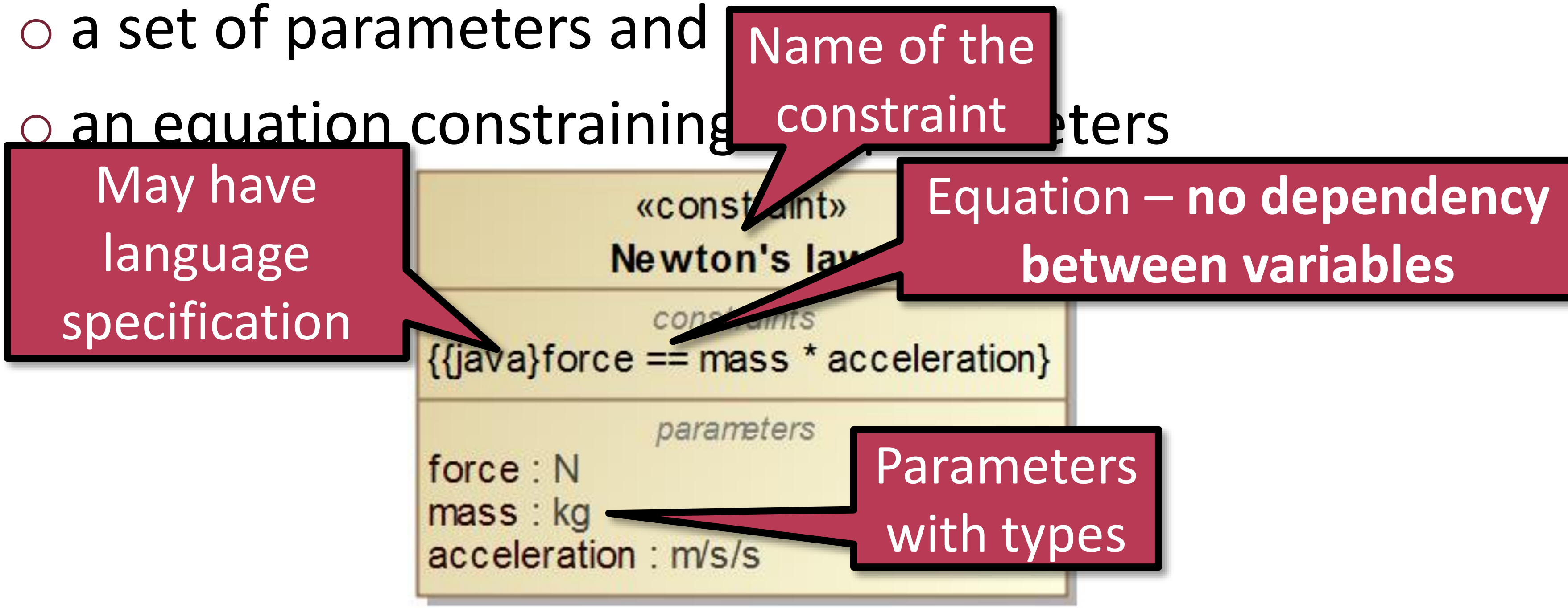


Constraints and physical parameters in SysML

Constraint blocks

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 eters



Assignments and equations

- An assignment in a typical programming language is a **causal** connection, where the left hand side is the dependent variable:

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

- An **acausal** connection is like a mathematical equation; there is no notion of inputs/outputs. So

```
y = x + 3
```

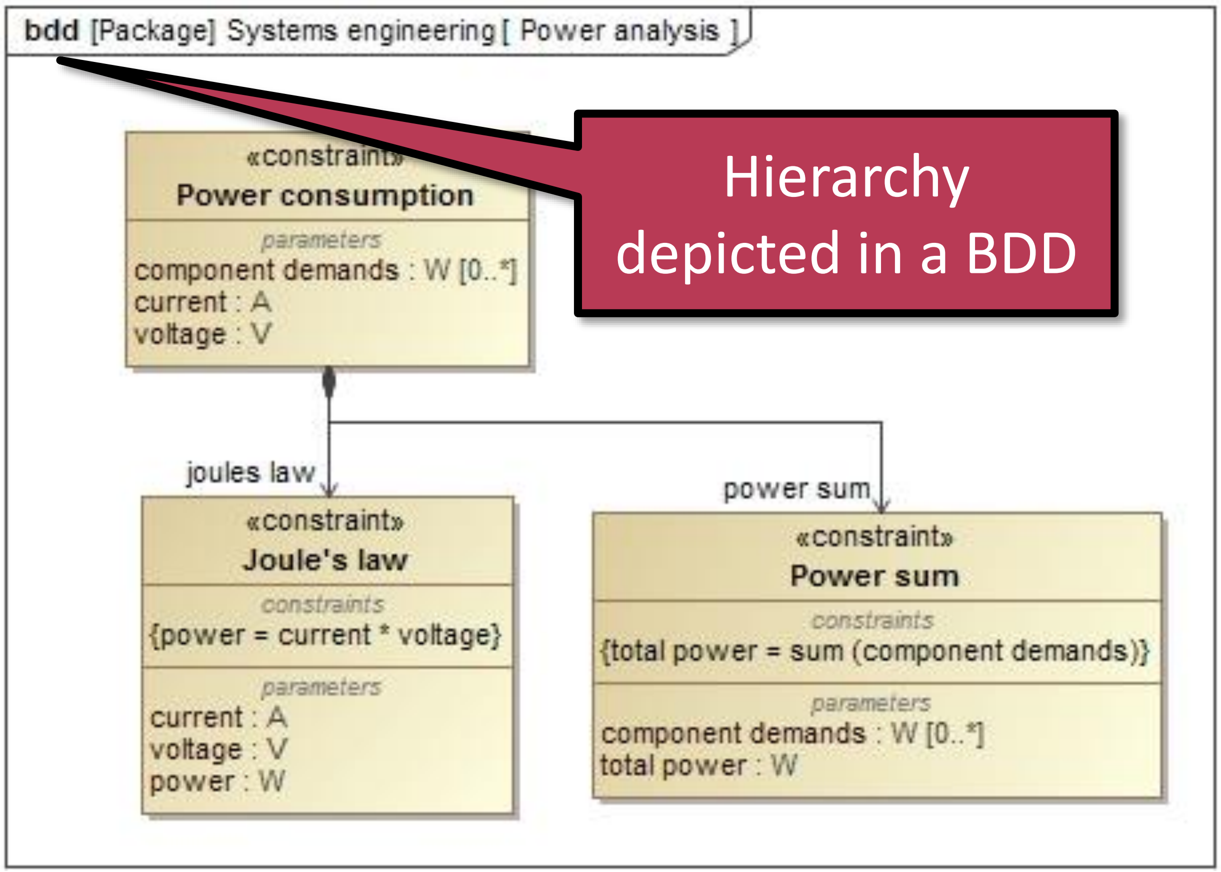
  and

```
y - 3 - x = 0
```

  have the same meaning.
  - If any of the variables has a new value, it enforces that the other variables change accordingly.

Constraint definition

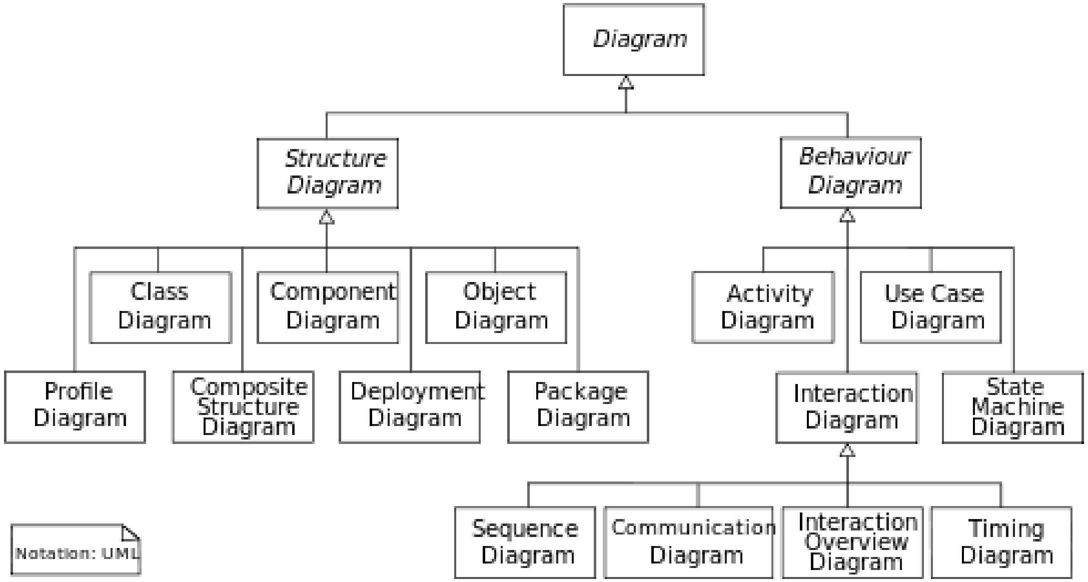
- **Composition** is used to define complex constraints from simple equations

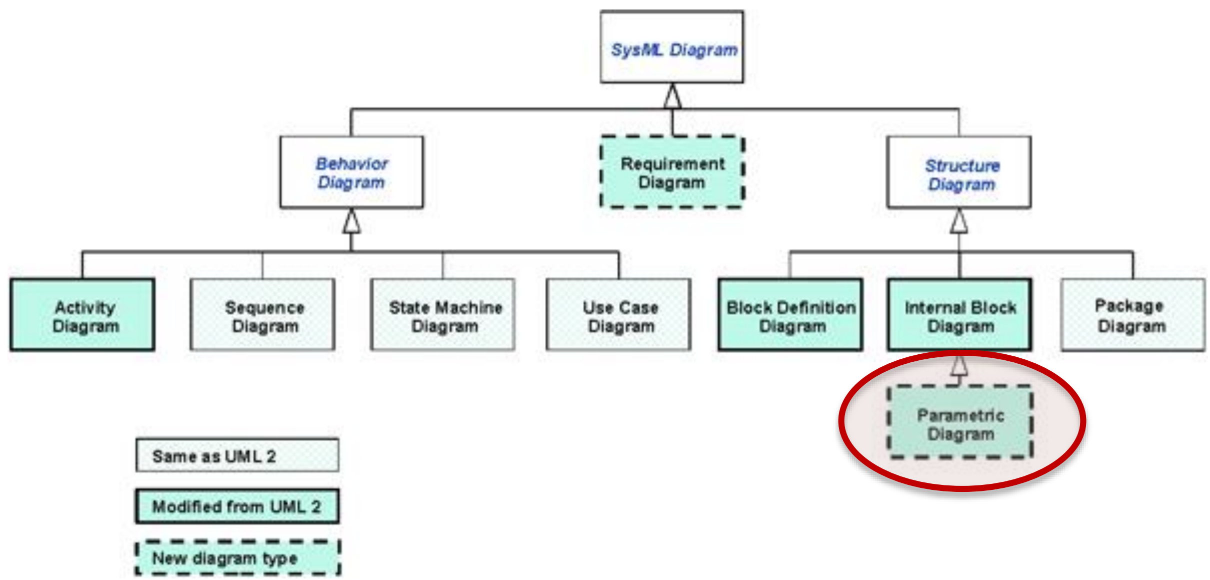


Parametric diagram

Specification of bindings between system parameters

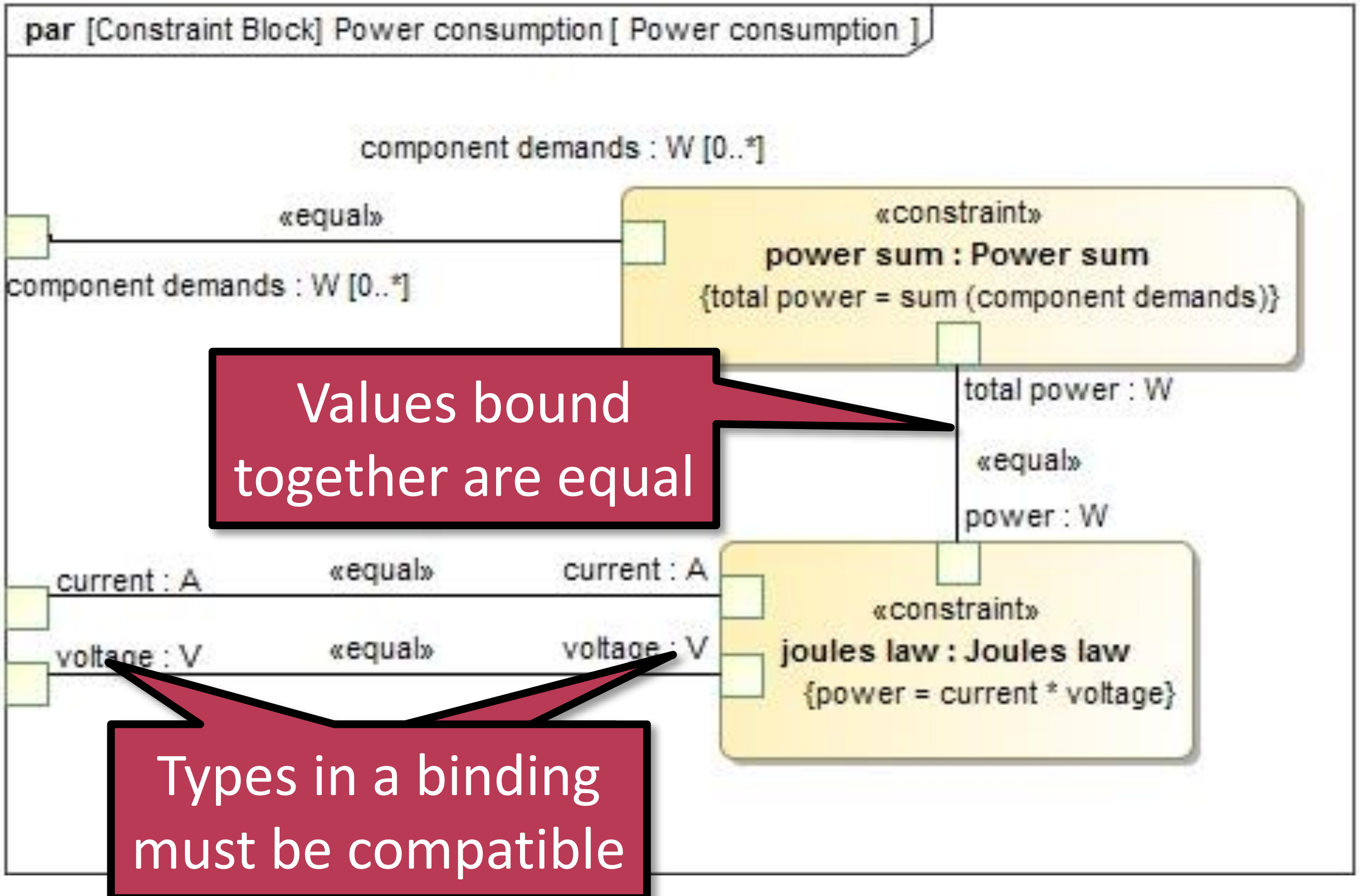
Parametric Diagram (PAR)





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
- There are modeling standards with better support for this modeling aspect…
  - …such as Modelica

Modelica

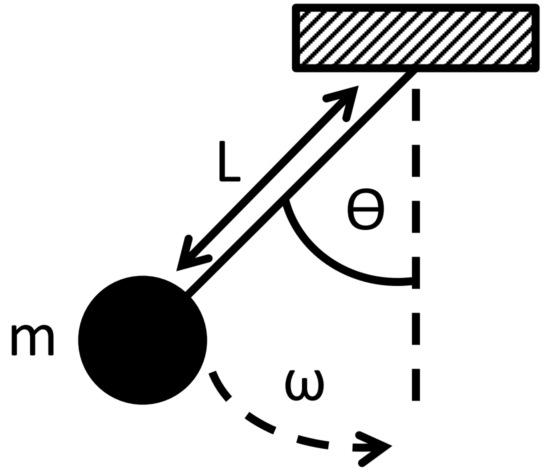
A language for modeling and simulating
complex physical systems

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

Example: modeling a simple pendulum

- Simple pendulum



- Behavior of the pendulum as a function of time:

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

Modelica code for simple pendulum

Model name

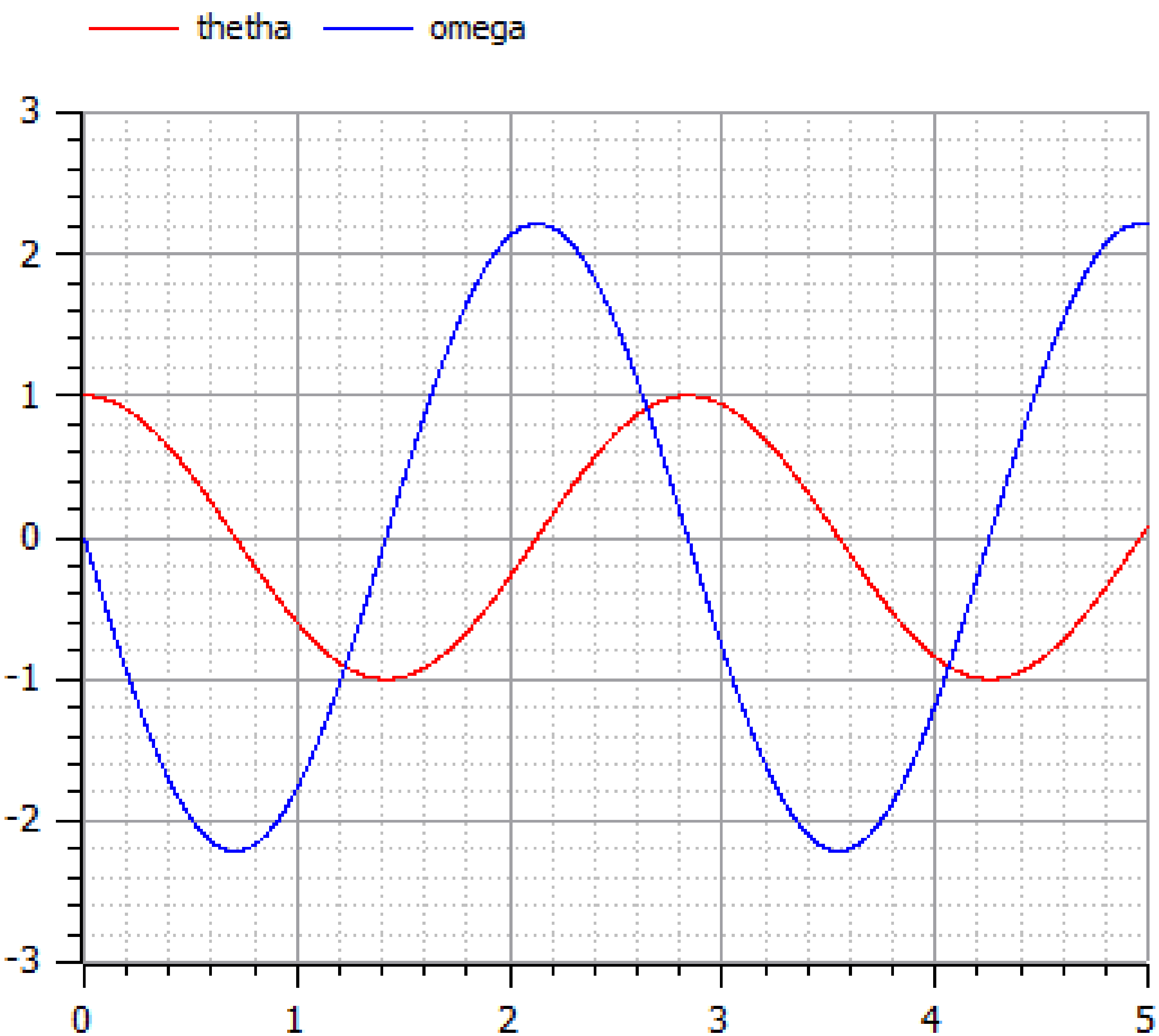
Continuous time variables, constants

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

Initial value

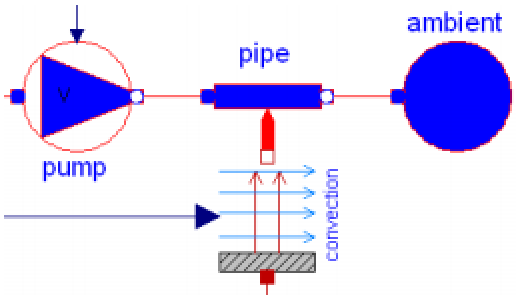
(Differential) equations

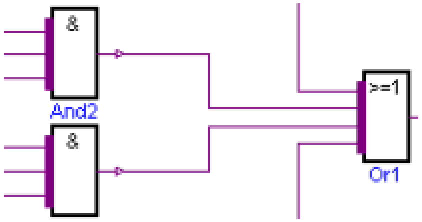
Pendulum simulation results

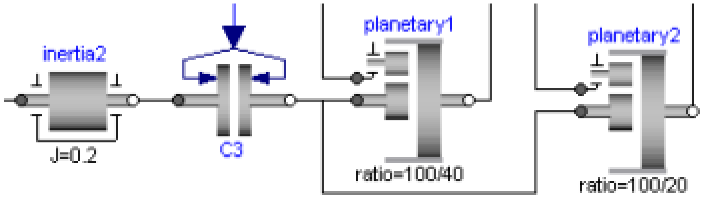


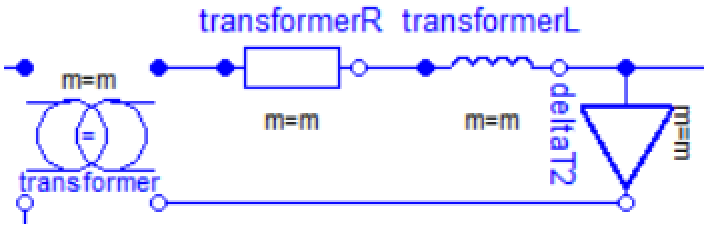
Modelica Standard Library

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







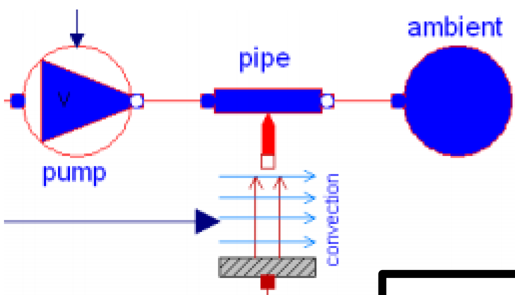


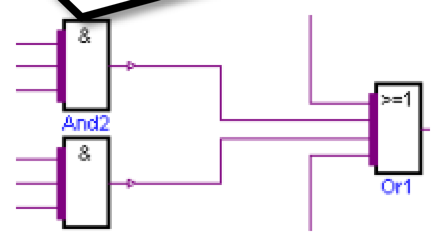
Modelica Standard Library

- P
  M
- V
- V

Definition in Modelica:

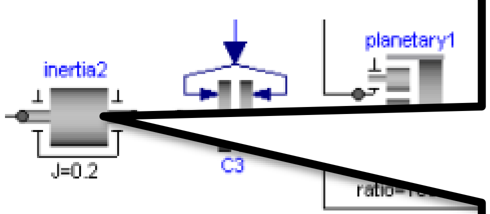
```
equation
  auxiliary[1] = x[1];
  for i in 1:n - 1 loop
    auxiliary[i + 1] = D.Tables.AndTable[auxiliary[i], x[i + 1]];
       end for;
  y = pre(auxiliary[n]);
```





Definition in Modelica:

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

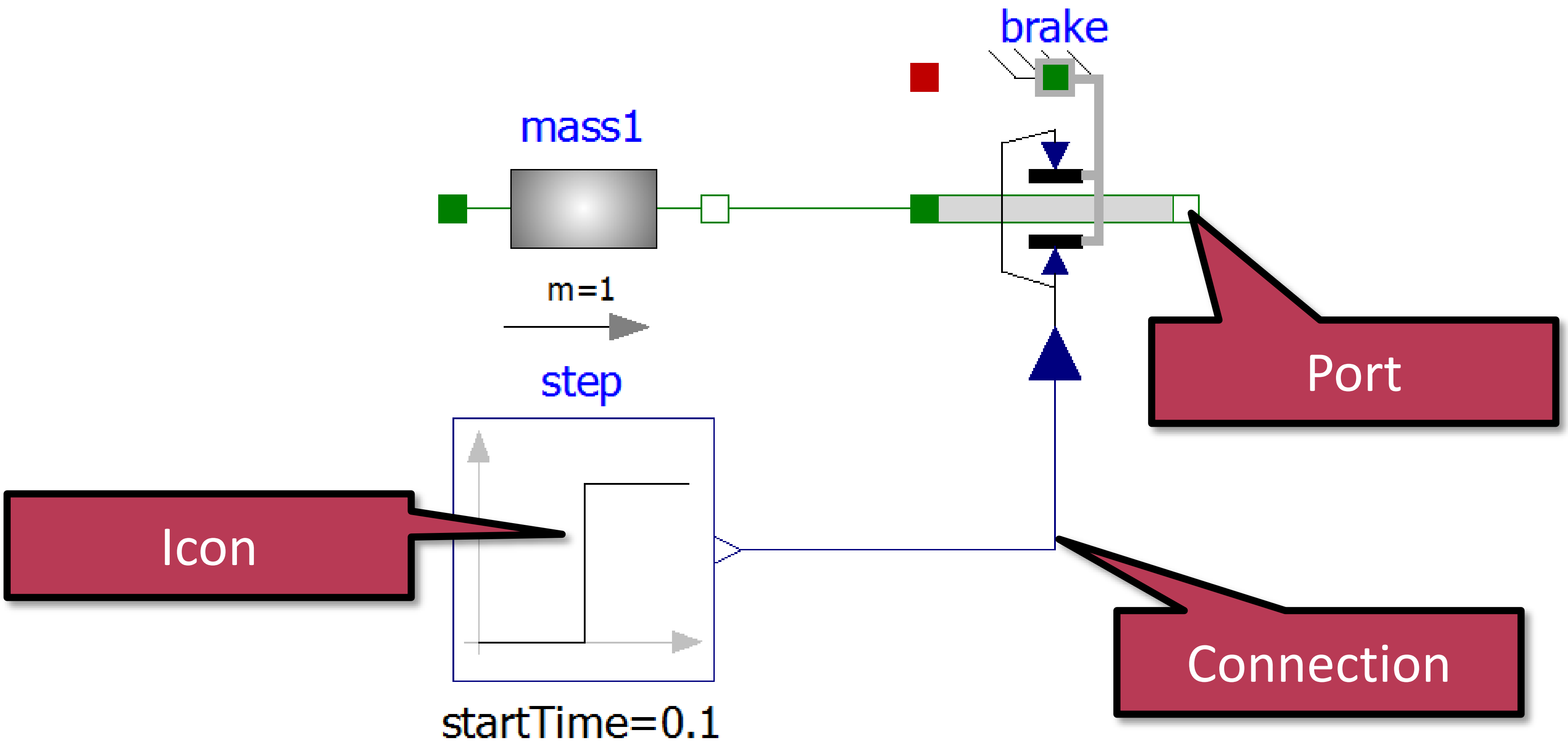


Modelica and Simulation

- Simulating a model means to calculate the values of its variables at certain time instants
- Advantages
  - Observing dangerous/expensive bevaviour at low cost with no risks
  - Resolves scaling issues (size, duration)
- Different algorithms and strategies for simulation
  - The task is to solve Ordinary Differential Equations (ODEs) generated from the model
  - Numerical techniques

Example plant model – train brakes

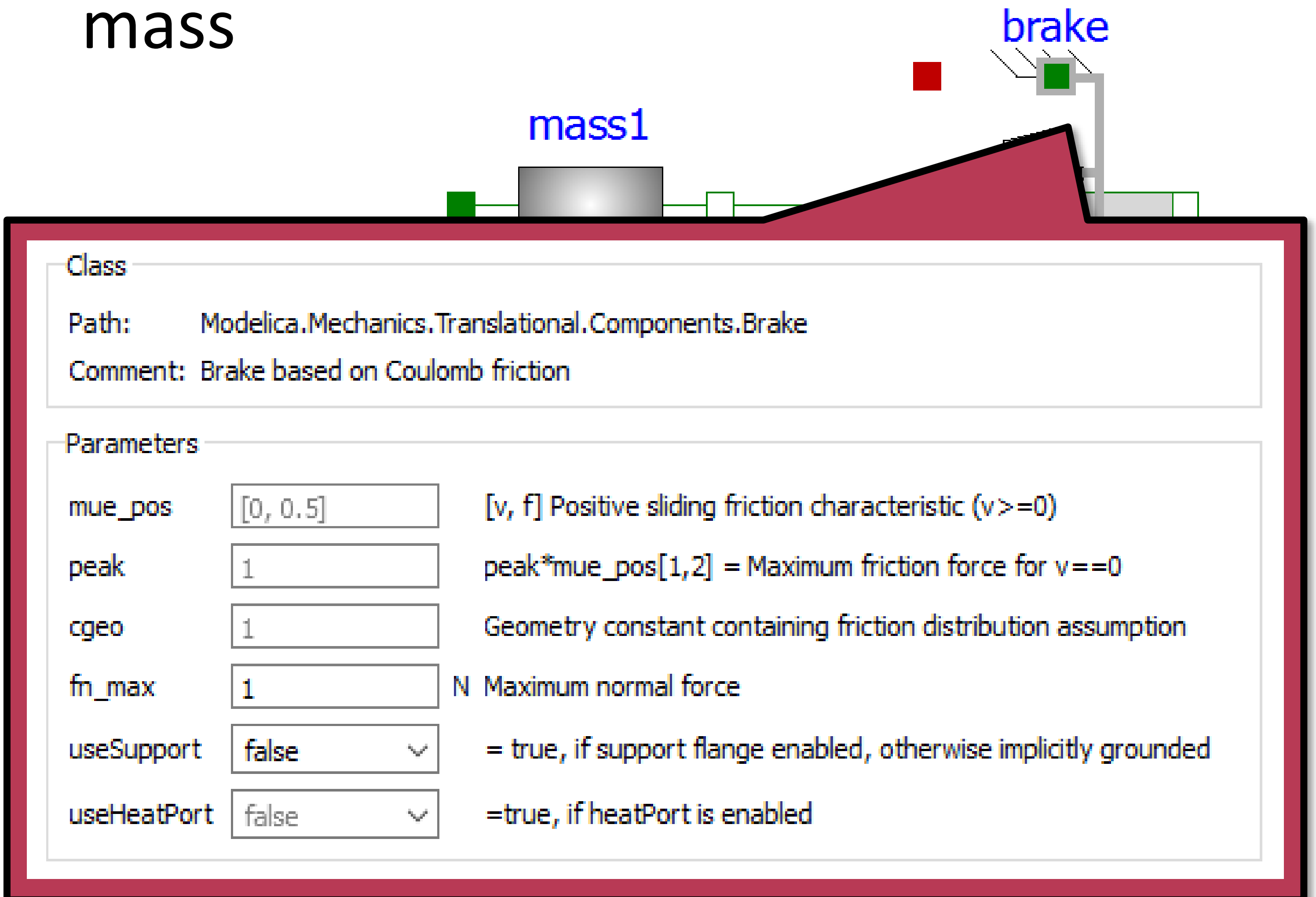
- Physical model for braking system carrying a mass



- Graphical notation in OpenModelicaEditor

Example plant model – train brakes

- Physical model for braking system carrying a given mass



Example plant model – train brakes

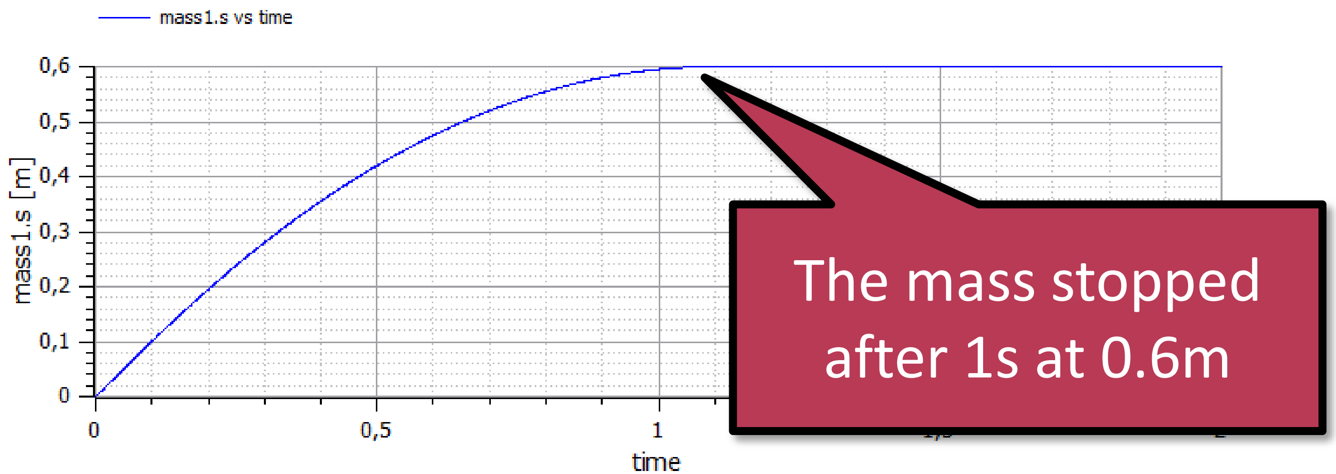
```
model BrakeExample
      Brake brake(
            fn_max=1
            useSupport=false);
      Mass mass1(
           m=1,
            s(fixed=true),
            v(start=
      Step step(
           startTime
           height=2)
equation
      connect(mass1.flange_b, brake.flange_a);
      connect(step.y, brake.f_normalized);
 end BrakeExample;
```

Brake, Mass, and Step are inbuilt classes to Modelica Library

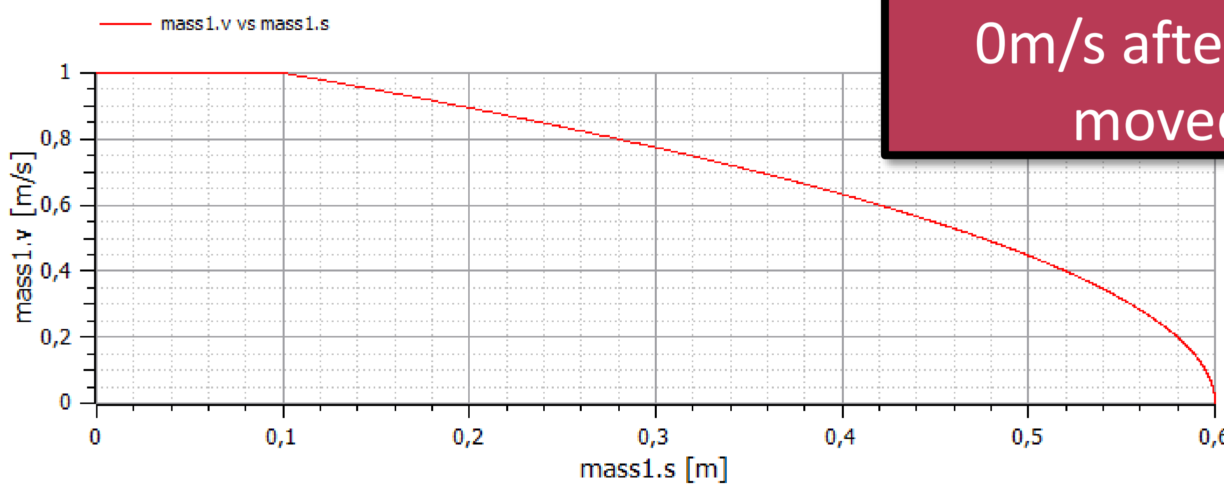
Can describe both causal and acausal connections between ports

Brake times and distance

- Plot values w.r.t. time (displacement)



- X-Y plot (speed w.r.t. displacement)



Summary

- Complex system design requires modeling of physical parameters
  - SysML constraint block, parametric diagram
- Modeling both discrete-time and continuous-time behaviour of cyber-physical systems
  - Modeling language for this purpose: Modelica
- Connecting models to study joint behavior
  - Simulation of models is especially useful when implementing and testing the system is expensive