Open Standards and Software for Dynamic System Simulation - Modelica

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Modelica Association

Open Source Modelica Consortium

Outline

Part #1: Object-Oriented Modelling & Modelica

- Principles of Equation-Based Object-Oriented Modelling (EOOM)
- The Modelica Language
- Automatic generation of executable code
- Related standards: FMI, SSP, DCP
- Case study: satellite attitude modelling and control

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Part #2: The Community

- The Modelica Association and its projects
- The Open Source Modelica Consortium and OMC

Principles of Equation-Based Object-Oriented Modelling

Declarative Modelling

Models should describe how a system behaves

not how the behaviour can be computed

There are no input and output variables in real life

The best formalization of a simulation model

is more easily understood by a human

not by a computer

Principle #1: Declarative Modelling

Equation-Based modular (→ Object-Oriented) description

- The model of each component is described by equations
- The model is independent of the components it is connected to
- Physical connections ↔ *connection equations*

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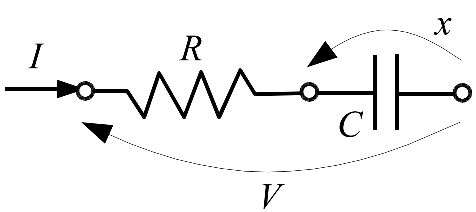
Example: RC component



$$x + RI = V$$
$$C\,\dot{x} = I$$

(DAE – declarative model)

Principle #1: Declarative Modelling

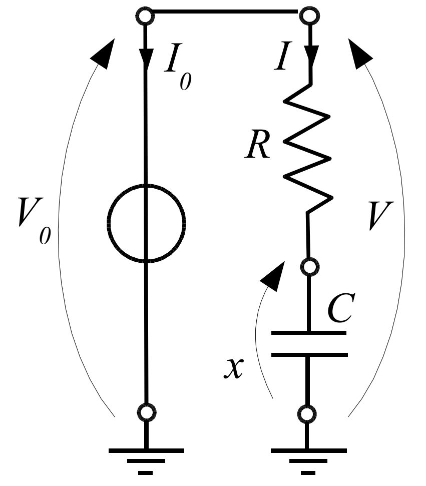
The solution work-flow is only determined at the *overall system level*

$$x + RI = V$$
$$C\dot{x} = I$$
(RC network)

$$V_0 = f(t)$$ (voltage generator)

$$V_0 = V$$ (Kirchoff's law - mesh)

$$I_0 + I = 0$$ (Kirchoff's law - node)



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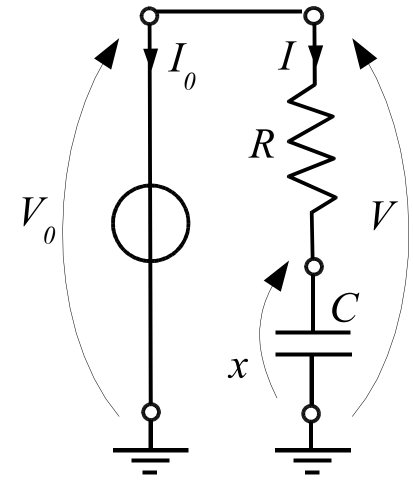

$$V_0 = f(t)$$
$$V = V_0$$
$$I = \frac{V - x}{R}$$
$$I_0 = -I$$
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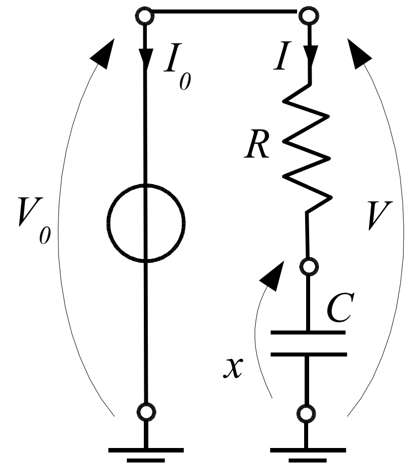

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x := x_initial
t := t_initial
loop
   V_0 = f(t)
   V := V_0
   I := (V - x)/R
   I_0 := -I
   dx_dt := I/C
   x := x + h*dx_dt
   t := t + h
end loop
```

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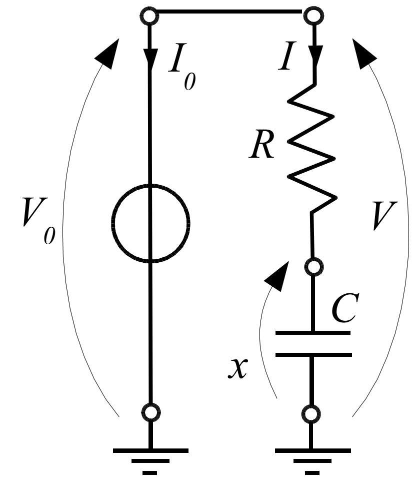

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```

performed automatically by a tool!

Principle #1: Declarative Modelling

The same component can be reused in different contexts

$$x + RI = V$$
$$C\dot{x} = I$$
(RC network)

$$I_0 = f(t)$$
(**current** generator)

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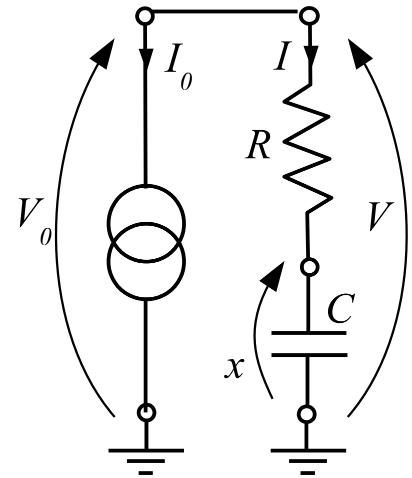

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x := x_initial
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   x  := x + h*dx_dt
   t  := t + h
end loop
```

Modularity

Models interact through physical ports

their behaviour depends explicitly on the port variables

not on the actual connected components

A model can be internally described

as the connection of other models

Principle #2: Modularity

- Physical ports: coupled effort and flow variables
  - Electrical systems: *Voltage and Current*
  - 1D Mechanical systems (Trans): *Displacement and Force*
  - 1D Mechanical systems (Rot): *Angle and Torque*
  - Hydraulic systems: *Pressure and Flow*
  - Thermal Systems: *Temperature and Thermal Power Flow*
  - …

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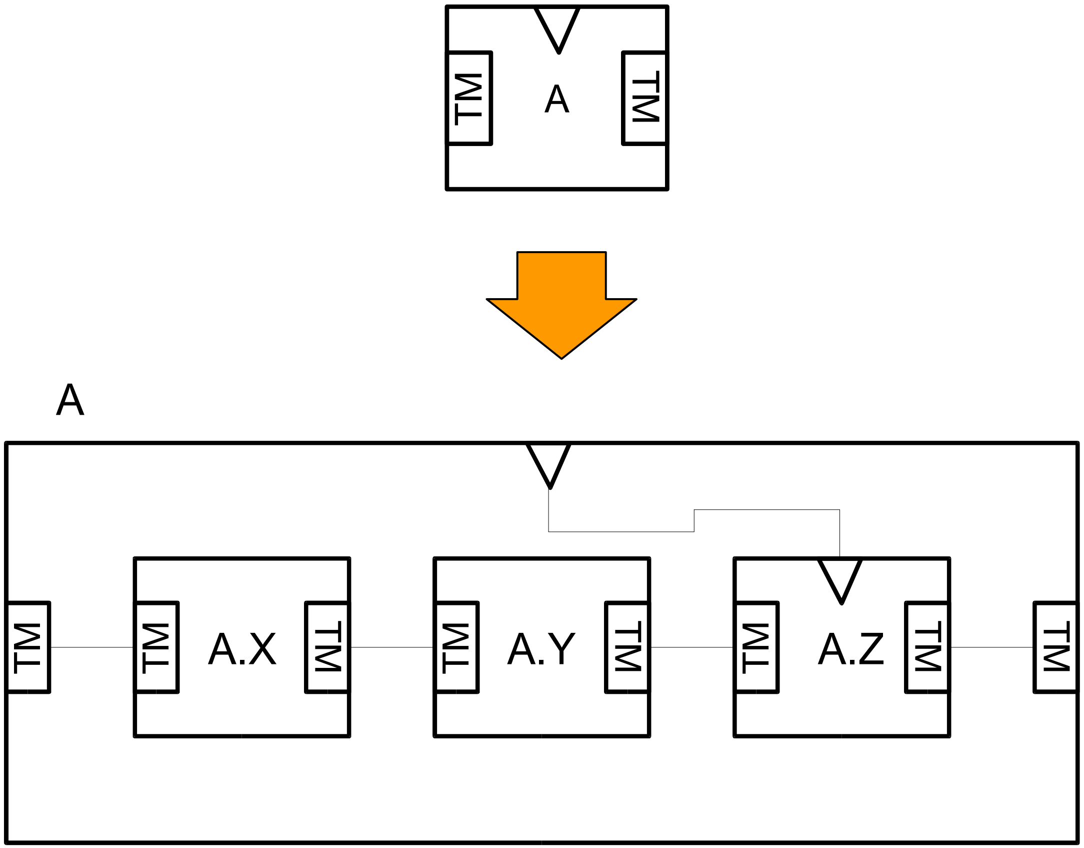
- Connection of *N* ports ↔ Connection *equations*

$e_1 = e_2 = \ldots = e_N$ (Same voltage / displacement / angle / pressure)

$\sum f_j = 0$ (Currents / Forces / Torques / Flows sum to zero)

Principle #2: Modularity



Inheritance

Parent-Child (“is-a”) relationships

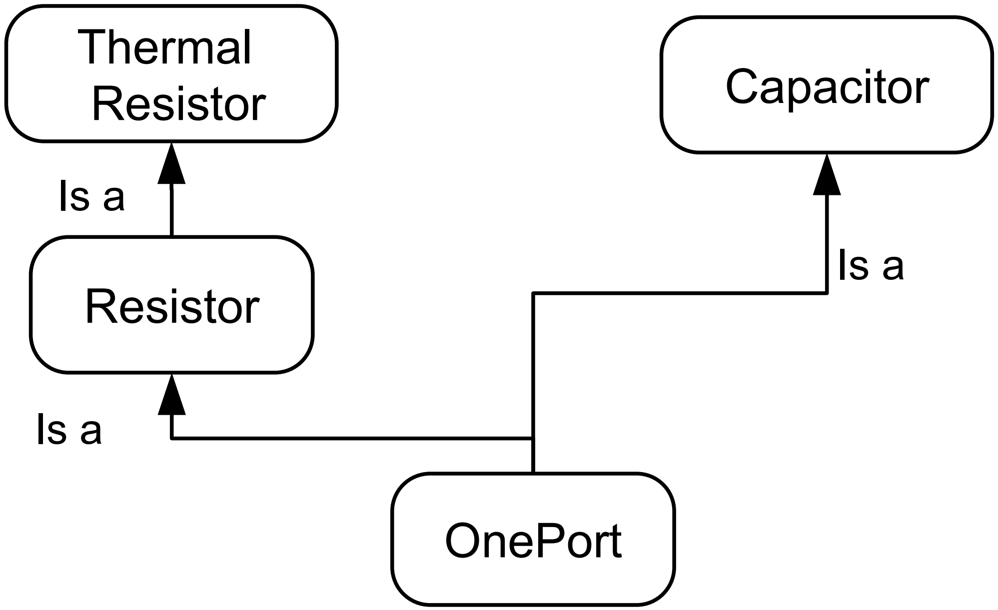
can be established among models

A child model inherits the parent features

(variables, parameters, equations, sub-models)

and adds its specific ones

Principle #3: Inheritance



Equation-Based Object-Oriented Modelling

Description of basic components by differential-algebraic equations, discrete-event equations and a-causal ports

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Modular and hierarchical composition (object connection diagrams)

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Object-Oriented features
(inheritance, encapsulation)

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Modular and hierarchical composition
(object connection diagrams)

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Object-Oriented features
(inheritance, encapsulation)

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Automatic generation of simulation code

The Modelica Language

Modelica Fact Sheet

- Language for equation-based, object-oriented dynamic system modelling
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- Developed and maintained by non-profit Modelica Association
- Companion Modelica Standard Library of basic models
- Tool-Independent language definition
- Supported by 9 commercial and 2 open-source simulation tools
- Extensive Open-Source & Commercial Model Libraries
- Development of new models eased by EOO approach

Example Models

```
type Voltage = Real(unit="V", nominal = 1e4);
type Current = Real(unit="A", nominal = 1e4);
type Power = Real (unit="W", nominal = 1e8);
type Resistance = Real (unit="V/A");
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connector Pin
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  flow Current i;
end Pin;
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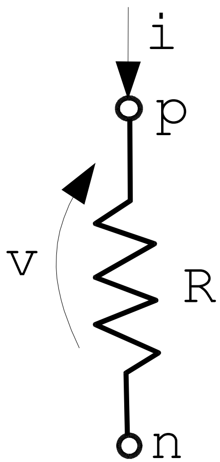


```
model Resistor
  Pin p,n;
  Voltage v;
  Current i;
  parameter Resistance R;
equation
  v = p.v - n.v;
  i = p.i;
  0 = p.i + n.i;
  v = R*i;
end Resistor;
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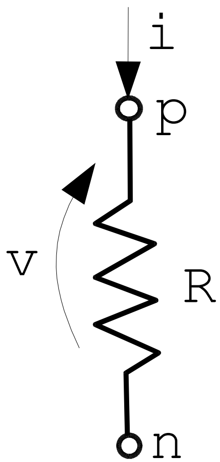


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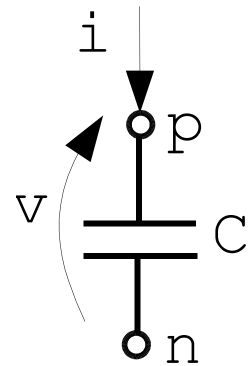


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  parameter Capacitance C;
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  i = C*der(v);
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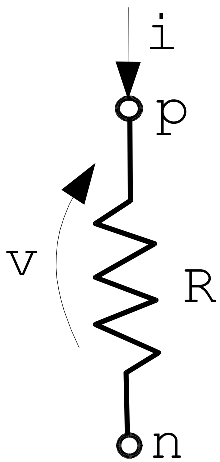


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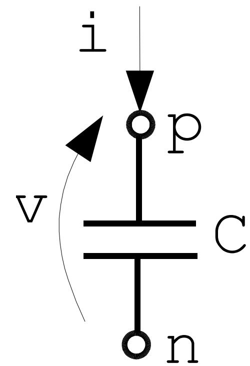


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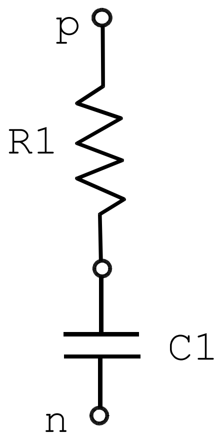
Models in DECLARATIVE form!

Modular & Hierarchical Composition

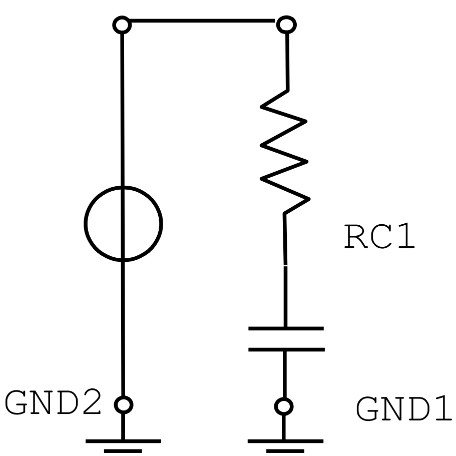



```
model RCNet
  parameter Resistance Rnet;
  parameter Capacitance Cnet;
  Resistor R1(R=Rnet);
  Capacitor C1(C=Cnet);
  Pin p,n;
equation
  connect(R1.n, C1.p);
  connect(R1.p, p);
  connect(C1.n, n);
end RCNet;
```

Modifiers
(parameter propagation)

Equivalent to:

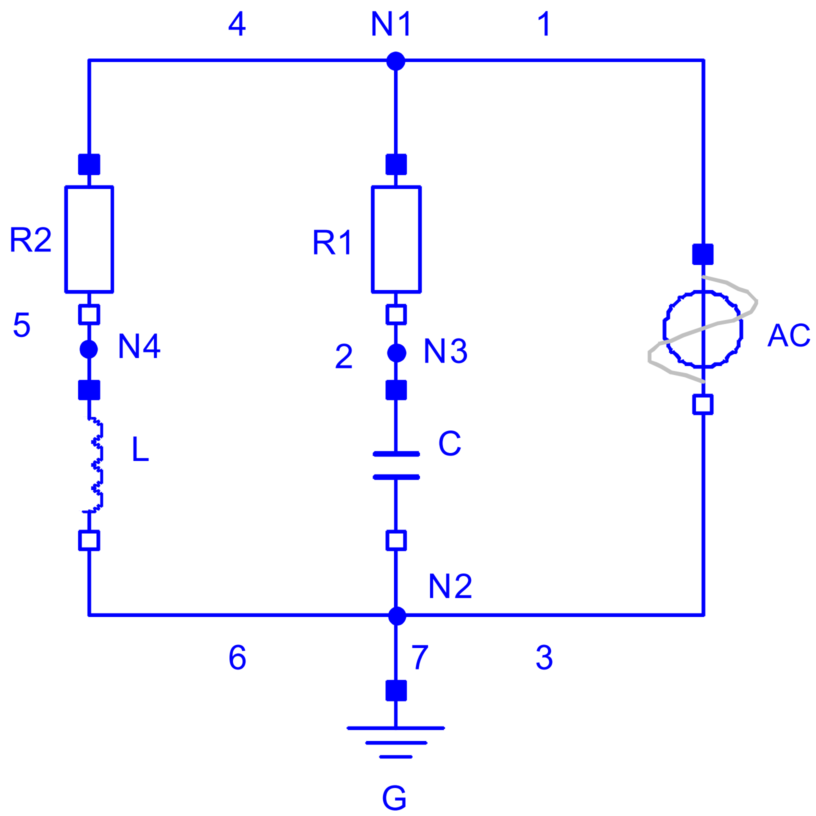
```
R1.n.v = C1.p.v;
R1.n.i + C1.p.i = 0;
```




```
model SimpleCircuit
  RCnet RC1(Rnet=100, Cnet=1e-6);
  Vsource V0;
  Ground GND1, GND2;
equation
  connect(RC1.n, GND1.p);
  connect(RC1.p, V0.p);
  connect(V0.n, GND2.p);
end SimpleCircuit;
```

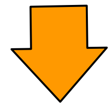
Graphical Annotations and Object Diagrams

- Graphical annotations allow to build and visualize composite models graphically
- The underlying model description is textual



Inheritance: Factoring Out Common Features

Resistor and Capacitor have common features



Factor them out in a base class OnePort

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Computational Model for Continuous-Time Systems

Model (DAEs) $F(x, \dot{x}, v, p, u, t) = 0$

Causalization

(solving for $\dot{x}, v$)

State-Space representation. (ODEs)

$$\dot{x} = f(x, p, u, t)$$
$$v = g(x, p, u, t)$$

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ODE Time integration

Export as state-space block
for other simulation environmens
or co-simulation

Related Standards: FMI

Functional Mock-Up Interface

- Open Standard for *causal* dynamic model exchange
- Internal representation of an FMU: state-space system with inputs and outputs
  - DLL or C-code for computation
  - XML description of variables and parameters
- Automatically generated from OO models with only input and output connectors at the top level
  - Actuator inputs
  - Sensor outputs

Related Standards: FMI

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- Supported by all Modelica tools and by over 130 simulation tools *https://fmi-standard.org/tools/*
- FMI-ME (model exchange): $$\dot{x} = f(x, p, u, t)$$ $$v = g(x, p, u, t)$$
- FMI-CS (co-simulation) $$x_{k+1} = f_h(x_k, p, u_k, t_k)$$ $$v_k = g(x_k, p, u_k, t_k)$$

Related Standards: SSP & DCP

- Open Standard for *parametrization* and *connection* of FMUs to form complete system models
- Allows to describe system models built by assembling FMUs
- System integration level

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- Open Standard for *parametrization* and *connection* of FMUs to form complete system models

ssp System Structure & Parameterization

- Allows to describe system models built by assembling FMUs
- System integration level

dcp Distributed Co-Simulation Protocol

- Open Standard Protocol for co-simulation of FMI-CS blocks
- Supports multiple distributed simulation architectures
  - Over TCP/IP
  - Over Bluetooth
  - Over USB
  - Over CAN Bus

Case Study

Satellite Attitude Modelling and Control

Joint work with
prof. Marco Lovera

Dept. Aerospace Engineering
Politecnico di Milano

Requirements

- Support the design of satellite attitude control systems
  - Actuator sizing
  - Feasibility study with idealized actuators, sensors, and control laws
  - Detailed engineering design of equipment and control laws

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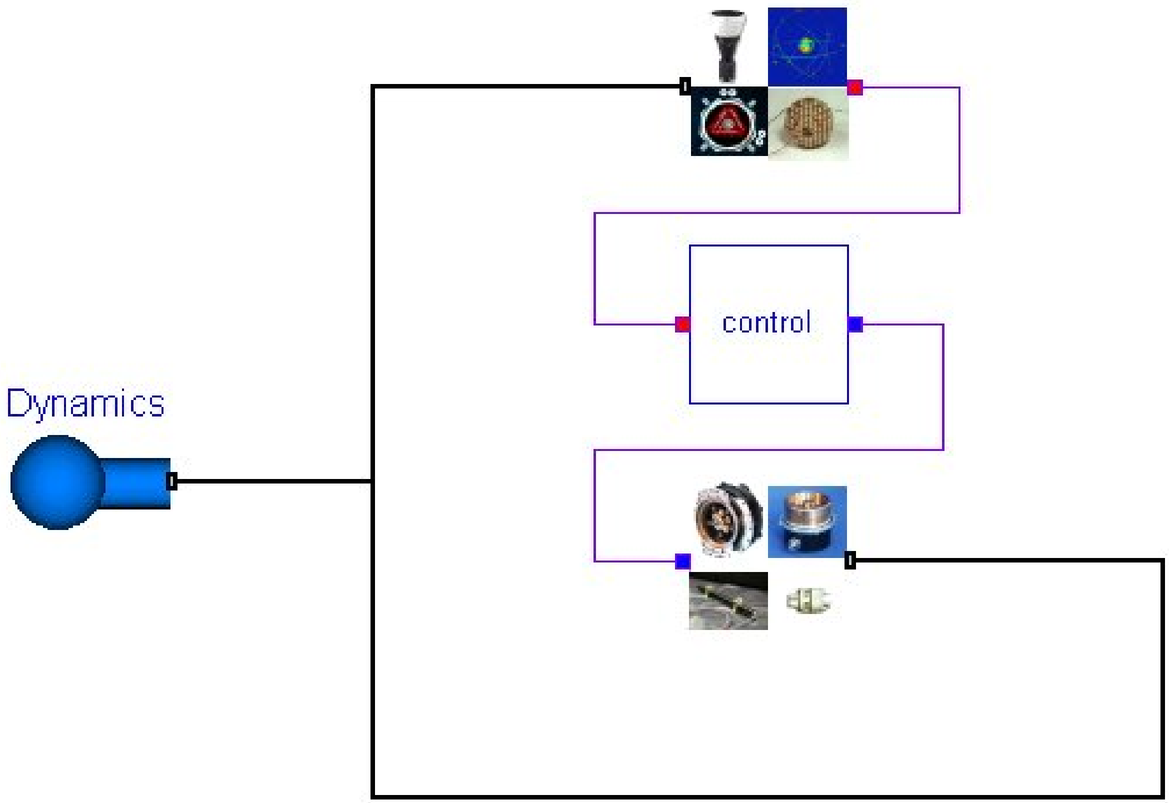
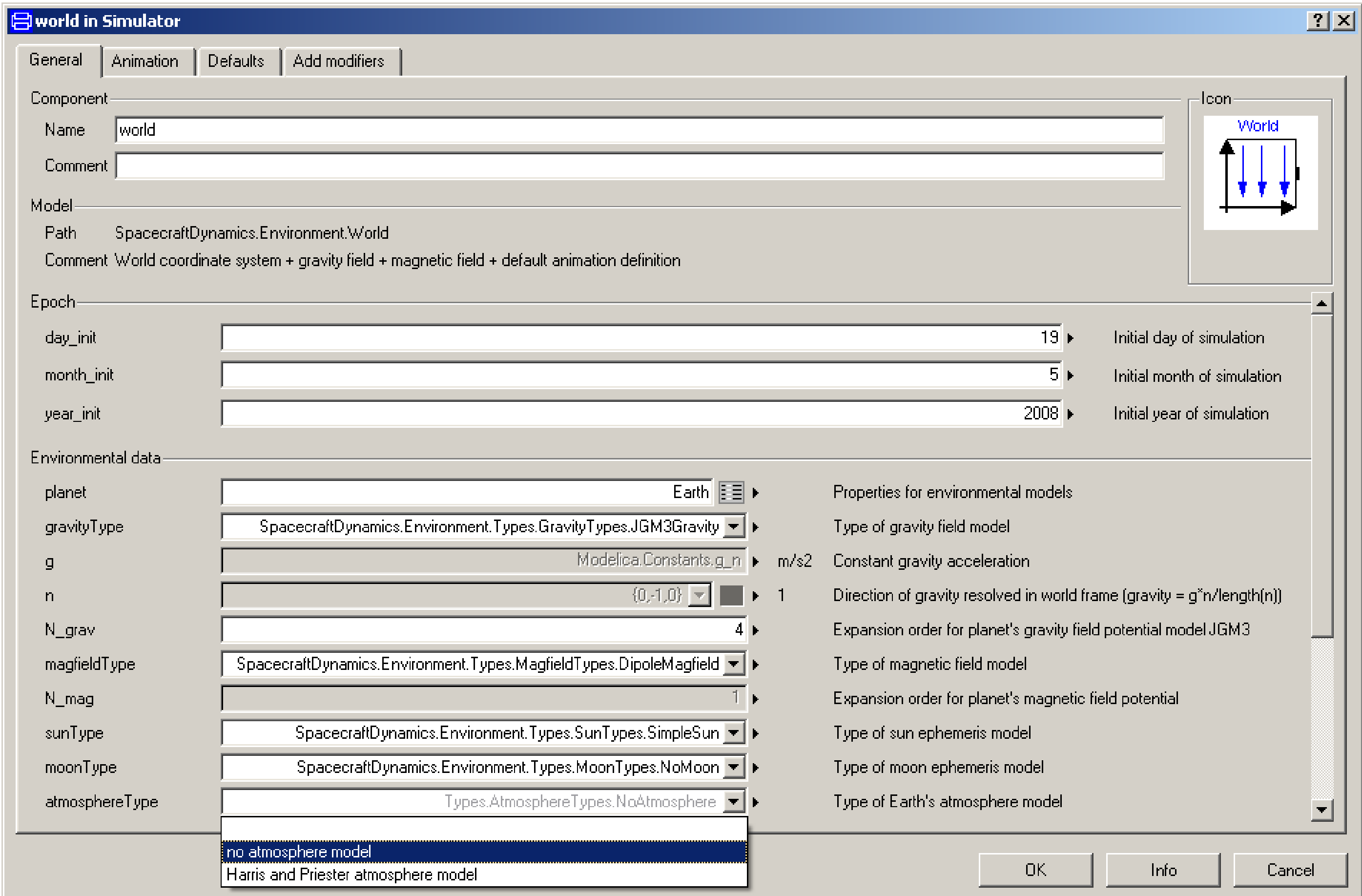
  - Atmospheric mode
- Systematic use of inheritance and replaceable classes to achieve maximum flexibility of detail

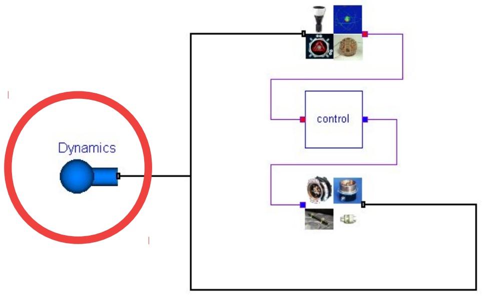
Spacecraft Model Architecture (Top View)



Choice of Environmental Model Parameters



Spacecraft Dynamics



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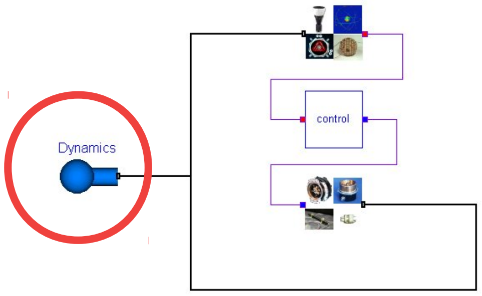
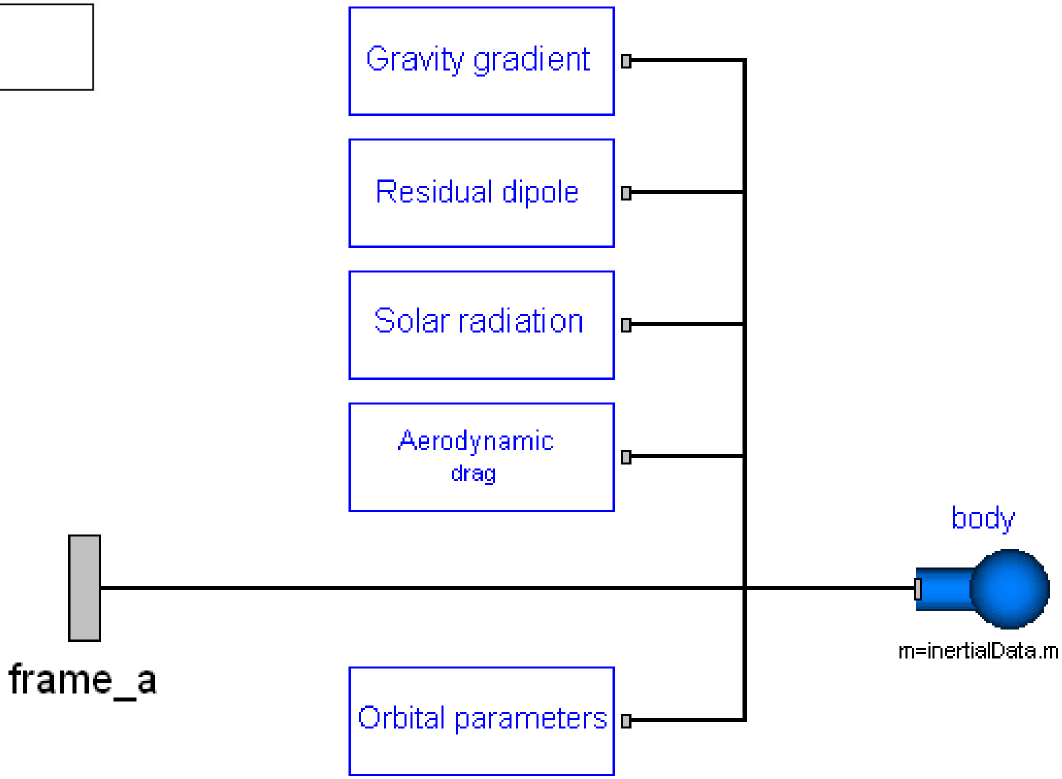
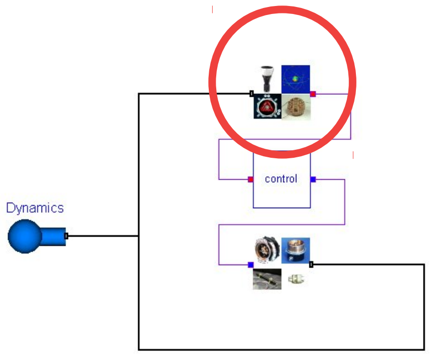




Sensor Block



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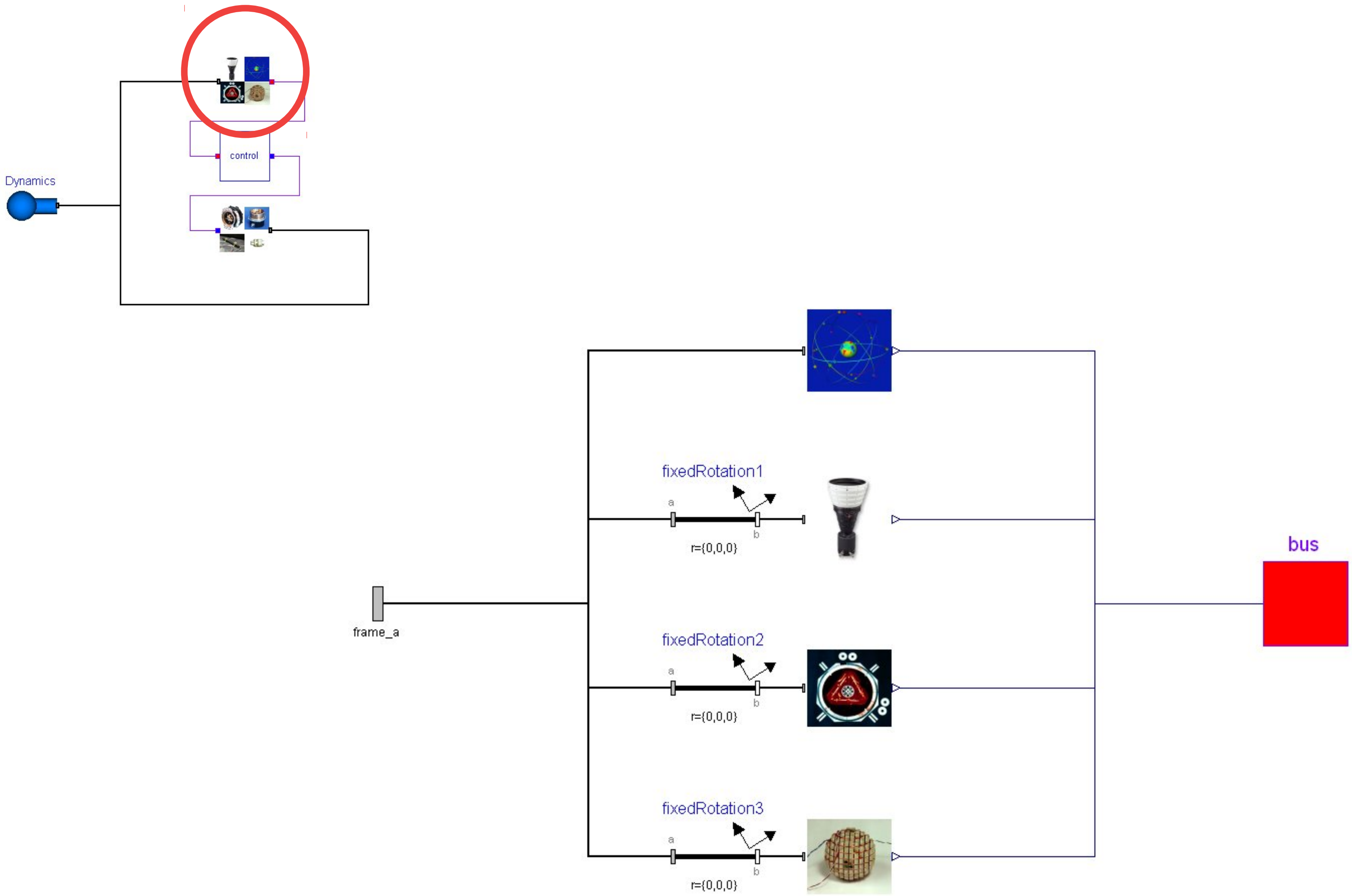
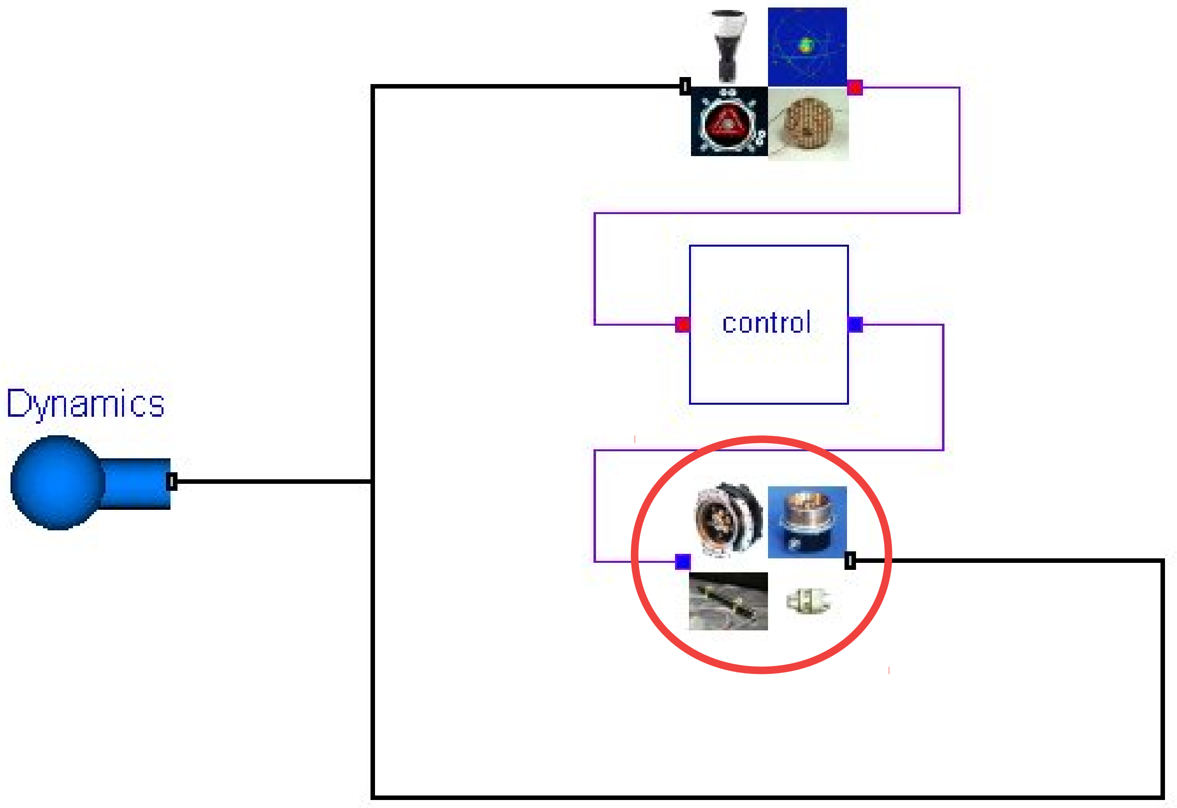
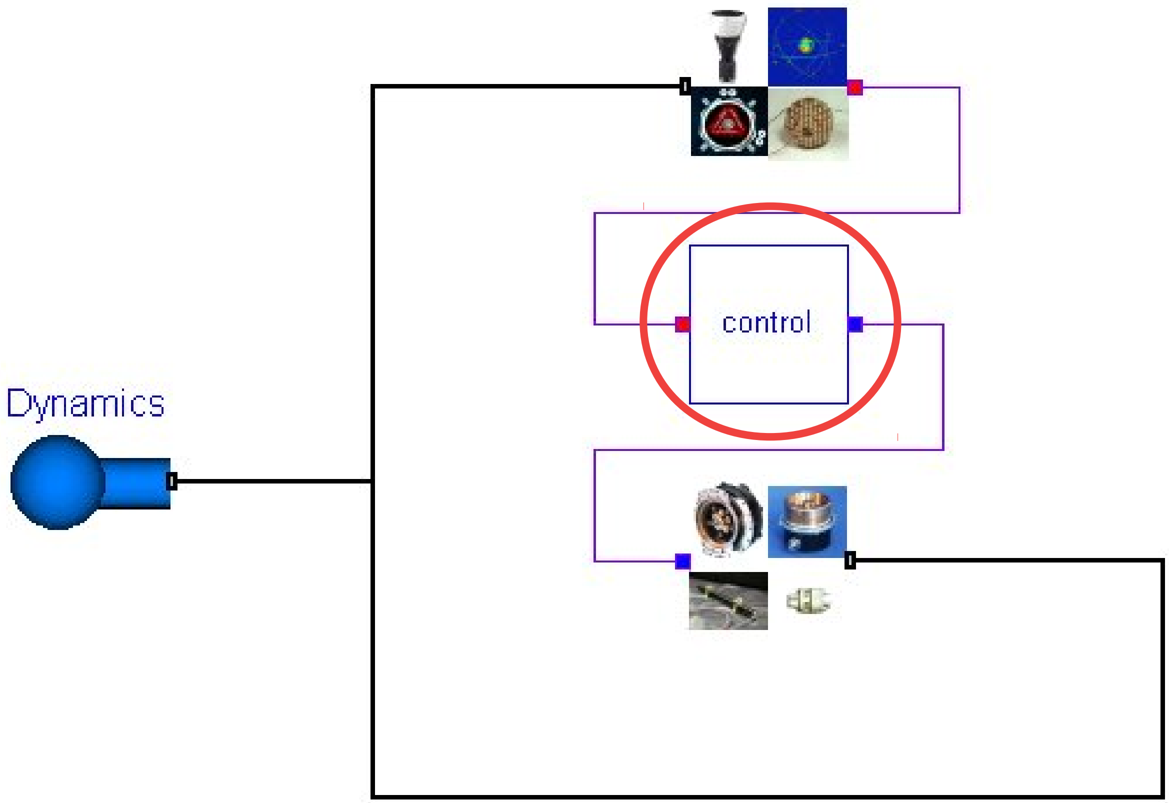


Actuator and Control Blocks



Actuator and Control Blocks



Use of Replaceable Objects

- All the components of the SensorBlock, ActuatorBlock, and ControlBlock models are *replaceable*
  - The base model defines empty interfaces with connectors
  - When instantiating a specific spacecraft model, the empty interfaces can be replaced with any of their child models
    - Idealized models (e.g. ideal torque or force generation)
    - More realistic models (with some non-ideal effects)
    - Actual engineering models of commercial units
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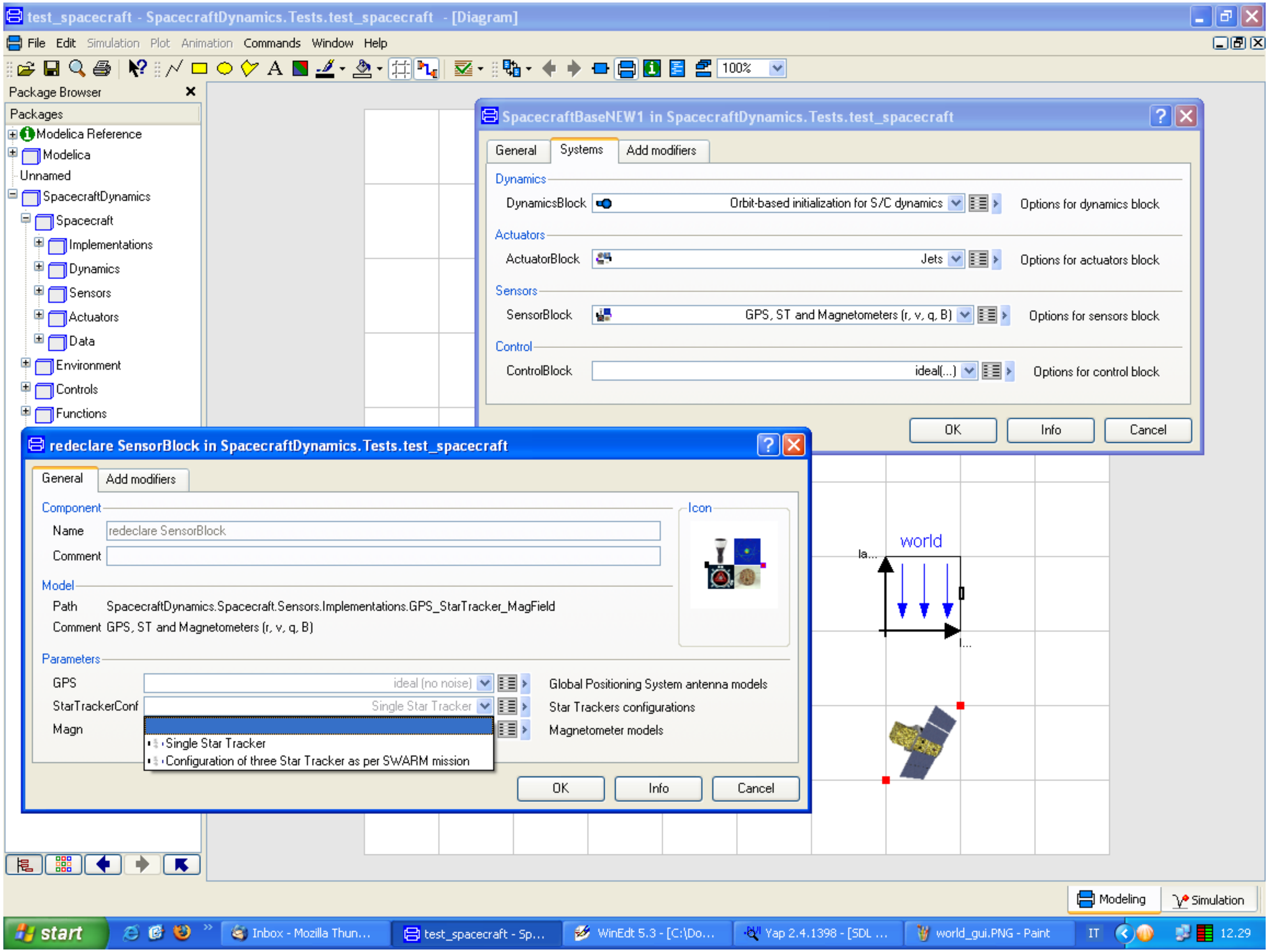
- Compare with classical copy-paste-modify approach...

Example: Textual Code View

```
model Example
  import SpacecraftDynamics.Spacecraft.* ;
  inner Environment.World world;
  Implementations.SpacecraftBase spacecraft(
    redeclare model SensorBlock =
      Sensors.Implementations.GPS_StarTracker_MagField(
        redeclare model StarTrackerConf =
          Sensors.Components.StarTrackers.Assemblies.SingleST_conf(
            redeclare model StarTracker =
              Sensors.Components.StarTrackers.StarTrackerBase(
                data=Sensors.Components.StarTrackers.Datasheets.ESA2006_prj)))
    redeclare model ActuatorBlock =
    ...
    redeclare model ControlBlock =
    ...
  );
end Example;
```

Example: Setup via GUI



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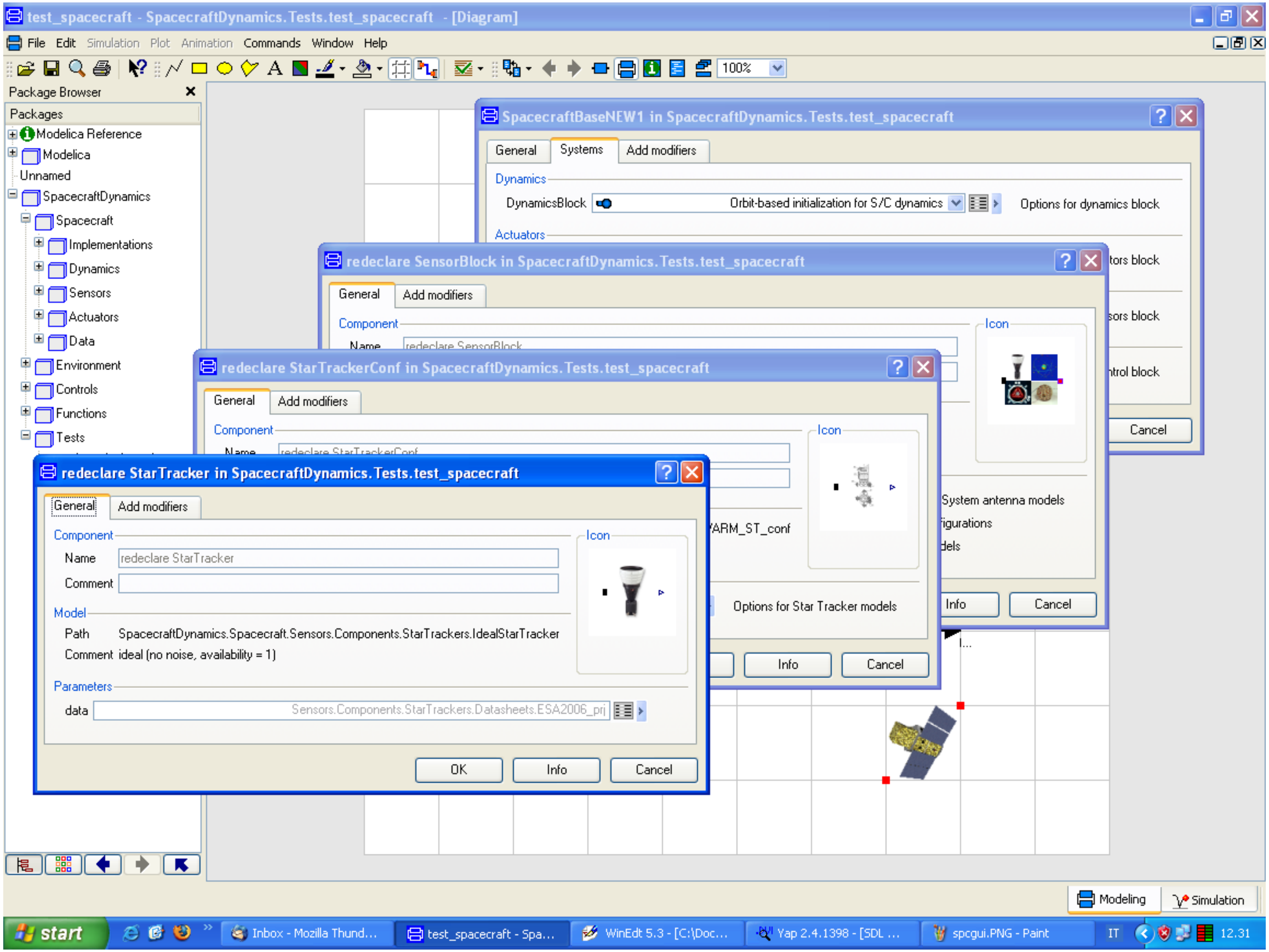

Use for Actuator Sizing

- Ideal SensorBlock
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- Equations in ControlBlock
  prescribe the exact pointing of the target
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➡ Unified & Consistent modelling framework

Use for Idealized Control Law Validation

- Ideal SensorBlock and ActuatorBlock
- Equations in ControlBlock implement textbook-version of control law

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➡ First assessment of control performance

➡ Very fast simulation (low detail)

Use for Accurate Control Performance Validation

- Detailed SensorBlock and ActuatorBlock
- Equations in ControlBlock implement detailed version of control law, possibly in discrete time

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⇨ Assessment of control performance in realistic conditions

Use for SW/HW-in-the-Loop Controller Validation

- Empty ControlBlock with top level inputs/outputs for sensor/actuator signals
- ControlBlock inputs/outputs propagated to top model inputs/outputs
- Overal model exported as FMU

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➡ Closed-loop simulation on actual control sw

➡ Closed-loop simulation on real-time control hw

The Communities

The Modelica Association

- Non-profit association developing
  Open Standards for Dynamic System Simulation
- Established in 1997
- Brings together
  - Modelica/FMI tool developers
  - Scientists and researchers from academia
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- Activity organized in coordinated Modelica Association Projects (MAPs)

The Modelica Association Projects

- MAP-LANG:
Develops the Modelica Language Specification
- MAP-LIB:
Develops the Modelica Standard Library
- MAP-FMI:
Develops the FMI standard
- MAP-SSP
Develops the SSP standard
- MAP-DCP:
Develops the DCP standard

- Other projects can be added if they are consistent with the overall goals of the Modelica Association
(Open Standards for System Simulation)

The Open Source Modelica Consortium (OSMC)

- Non-profit organization developing
  the Open Modelica Compiler (OMC) suite of tools
- Established in 2007
- 22 Companies and Institutes
  - ABB
  - Bosch-Rexroth
  - Siemens Turbo Machinery
  - Saab
  - EDF
  - RTE
  - ...
- 28 Universities

The OpenModelica Toolkit

- OpenModelica Compiler (OMC)
  - Full-fledged Modelica 3.4 compiler
  - Dual licensing: GPL v3 and OSMC-PL
  - Current release: 1.14.0
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- OMSimulator
  - Simulation environment for FMI/SSP system models
  - Integrated with OMEdit
- And many others

Development of the OpenModelica tools

- Core functionality
  - OSMC developers paid by the Consortium
- New features (also experimental):
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  - ITEA2 and ITEA3 projects
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- About 60 contributors so far
- Development hosted on GitHub https://github.com/OpenModelica
- Continuous Integration testing on each commit, online coverage reports available
- Nightly builds available
- Bug tracking infrastructure, about 250 tickets fixed per year

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- The investment in Modelica model development is guaranteed by the whole tool-vendor ecosystem, including at least another open-source tool (JModelica)

⇨ Low-risk + no vendor lock-in

Thank you
for you kind attention!

Any questions?