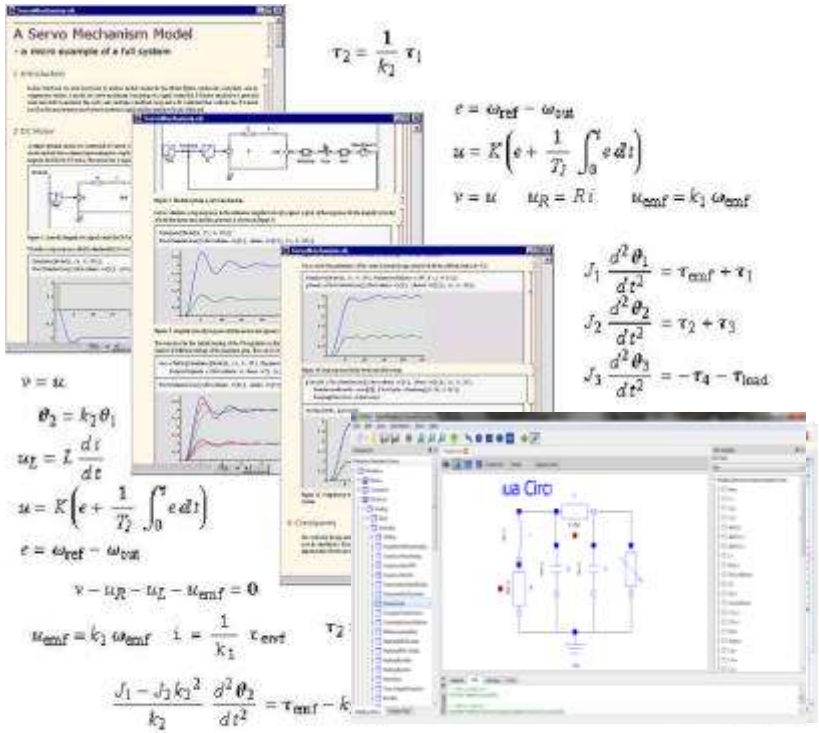
Introduction to Object-Oriented Modeling and Simulation with Modelica and OpenModelica



Lecture 1

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Vice Director of the Open Source Modelica Consortium
Vice Director of the MODPROD Center for Model-based Development

Slides

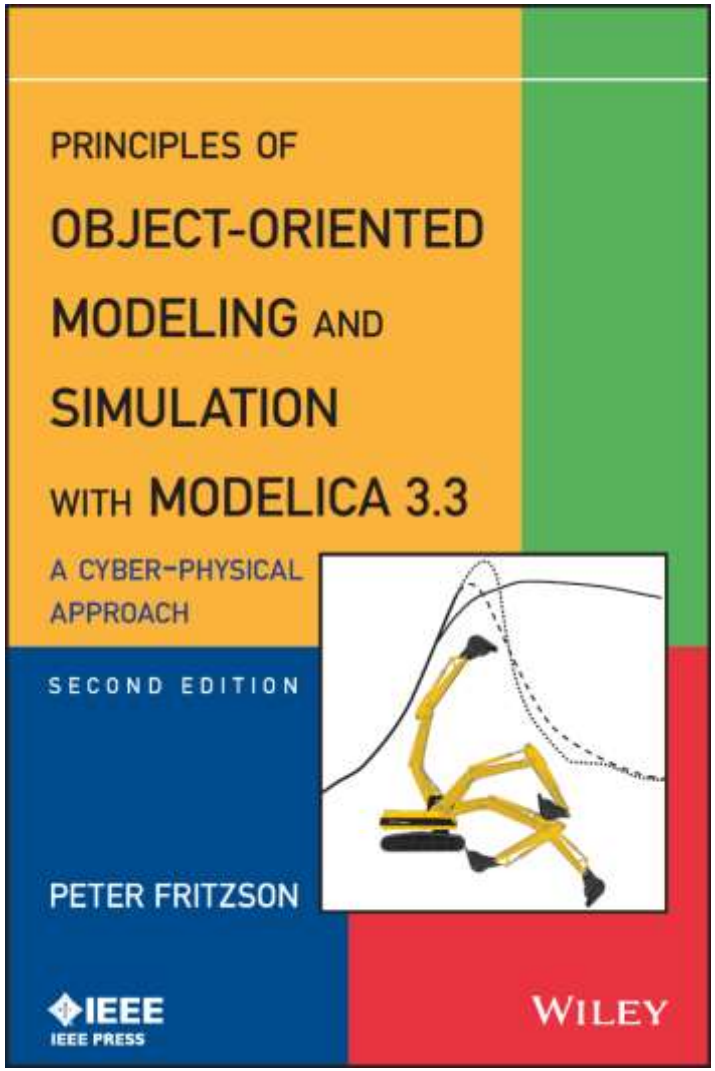
Based on book and lecture notes by Peter Fritzson
Contributions 2004-2005 by Emma Larsdotter Nilsson, Peter Bunus
Contributions 2006-2018 by Adrian Pop and Peter Fritzson
Contributions 2009 by David Broman, Peter Fritzson, Jan Brugård, and Mohsen Torabzadeh-Tari
Contributions 2010 by Peter Fritzson
Contributions 2011 by Peter F., Mohsen T,. Adeel Asghar,
Contributions 2012-2018 by Peter Fritzson, Lena Buffoni, Mahder Gebremedhin, Bernhard Thiele, Lennart Ochel
Contributions 2019-2023 by Peter Fritzson, Arunkumar Palanisamy, Bernt Lie, Adrian Pop

LINKÖPING UNIVERSITY

2023-03-14 at Swegon

MODELICA

Tutorial Based on Book, December 2014
Download OpenModelica Software



Peter Fritzson

Principles of Object Oriented Modeling and Simulation with Modelica 3.3

A Cyber-Physical Approach

Can be ordered from Wiley or Amazon

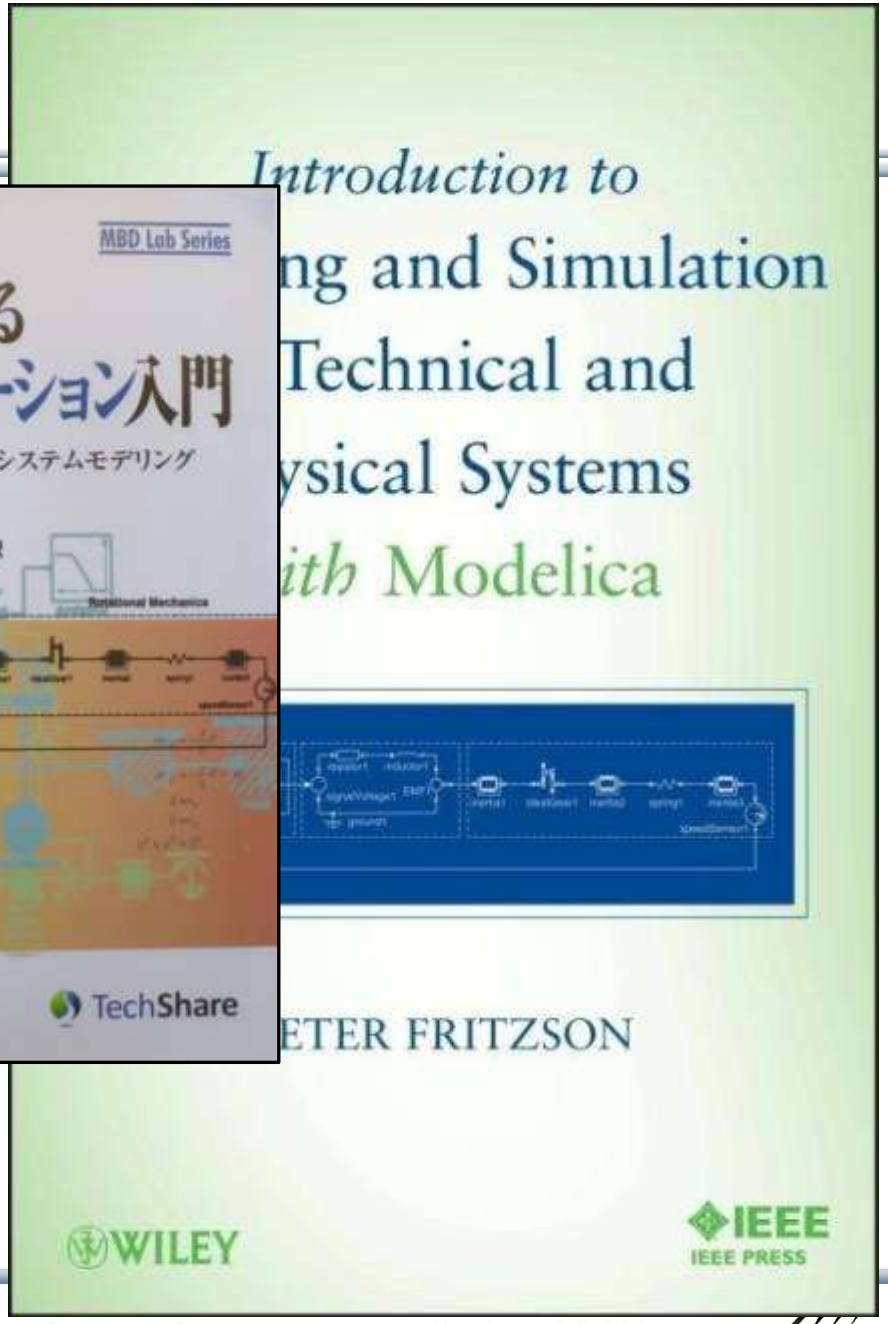
Wiley-IEEE Press, 2014, 1250 pages

- OpenModelica
  - www.openmodelica.org
- Modelica Association
  - www.modelica.org

Introductory Modelica Book

September 2011
232 pages

Translations available in **Chinese**, **Japanese**, **Spanish**



Wiley
IEEE Press

For Introductory Short Courses on Object Oriented Mathematical Modeling

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- OpenModelica: www.openmodelica.org

Detailed Schedule Day 1

Day 1, 9.00-16.00 (including lunch and short breaks)
12.00 -13.15 lunch break.
10.00 -10.15; 11.00 -11.15 and 14.00 -14.15, 15-15.15 small breaks.
Lecturers: Peter Fritzson

Lecture 1 Introduction to Modeling and Simulation with Modelica and OpenModelica
Lecture Introduction to Modelica and OpenModelica

- Demo+short exercise: Graphic modeling with OMEdit
- OpenModelica OMNotebook and OMWebbook usage
- Introduction to textual modeling
- Demo+Exercise: OMNotebook, DrModelica, OMWebbook, Spokentutorial

Lecture Modelica Classes, Inheritance and Equations

- Lecture+Exercises: classes and inheritance
- Exercise01-classes-simple-textual.onb
- Lecturing on Modelica equation s.

Lecture Debugging and Performance Analysis

- Lecture and exercises

Lecture – Modelica Connectors, Packages and Libraries

- Lecturing+Exercises: Component connectors and connections, graphical modeling
- Exercise02-graphical-modeling.onb
- Lecturing on Modelica packages and libraries

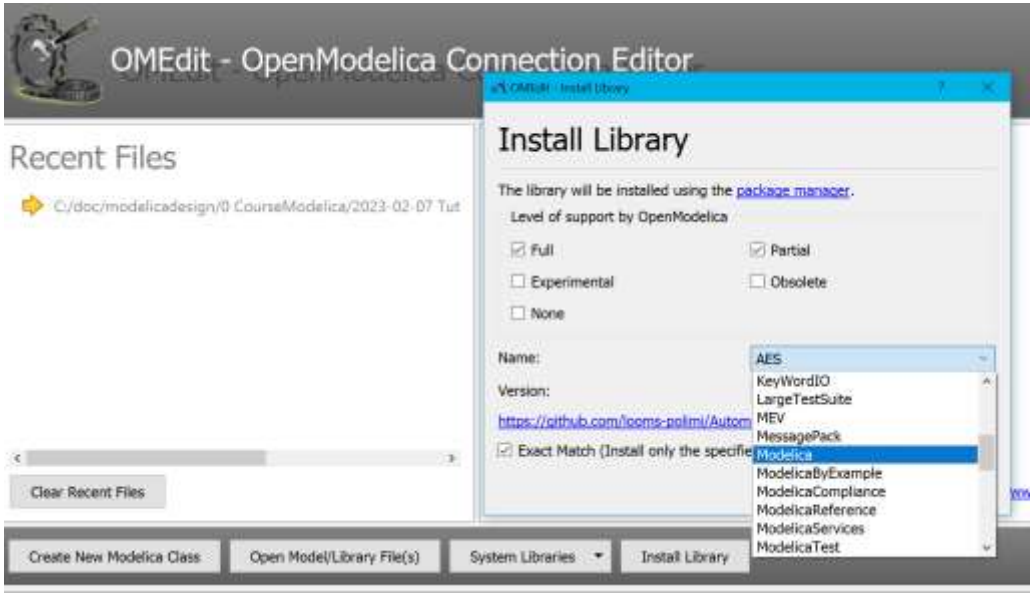
Lecture – 3D Visualization and animation

- Lecturing+Exercises: MSL Multi-Body 3D visualization using OMEdit

Software Installation - Windows

- Start the software installation
- Install OpenModelica-1.20.0 or later Download from www.openmodelica.org (takes about 20min)

- You also need to load the Modelica standard library if not already loaded:
  (push the load library button and select Modelica)



Software Installation – Linux (requires internet connection)

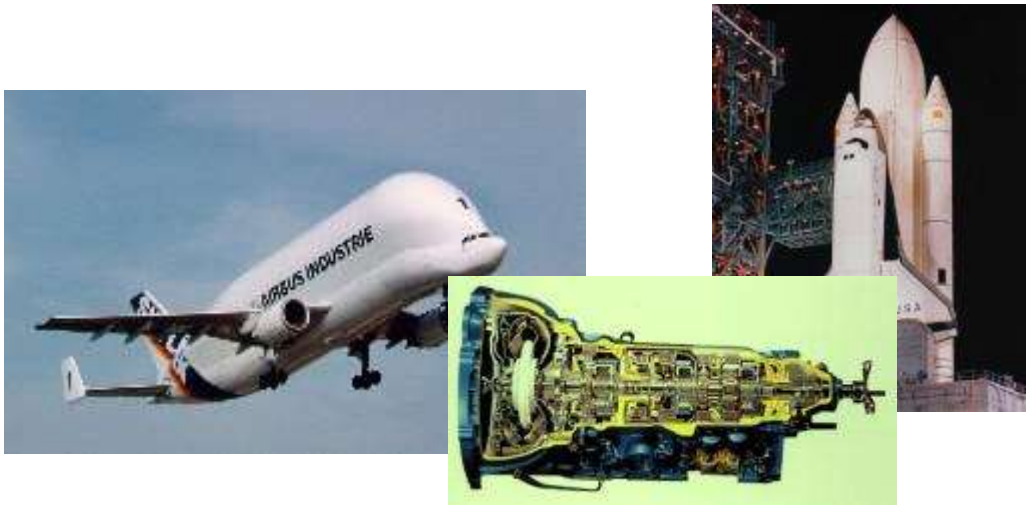
- Go to https://openmodelica.org/index.php/download/download-linux and follow the instructions.

Software Installation – MAC (requires internet connection)

- Go to https://openmodelica.org/index.php/download/download-mac and follow the instructions or follow the instructions written below.
- The installation uses MacPorts. After setting up a MacPorts installation, run the following commands on the terminal (as root):
  - *echo rsync://build.openmodelica.org/macports/ >> /opt/local/etc/macports/sources.conf # assuming you installed into /opt/local*
  - *port selfupdate*
  - *port install openmodelica-devel*

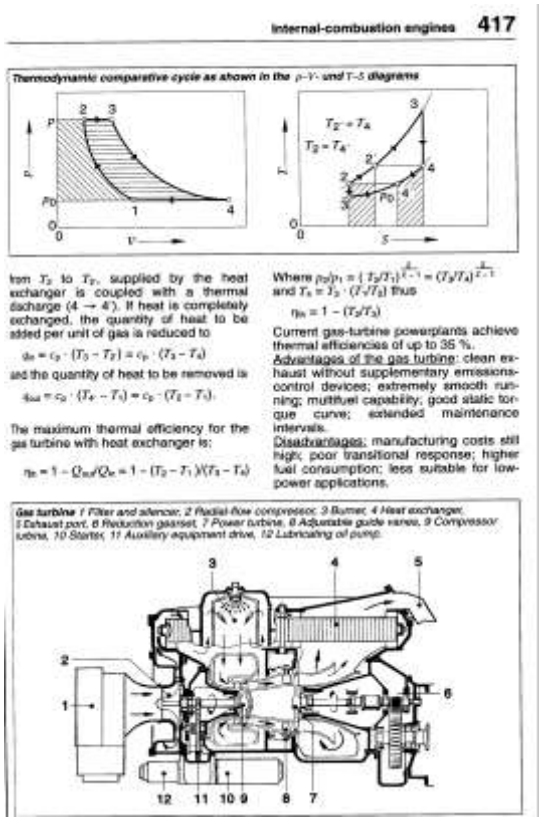
Part I

Introduction to Modelica and a demo example



Modelica Background: Stored Knowledge

Model knowledge is stored in books and human minds which computers cannot access



internal-combustion engines 417

Thermodynamic comparative cycle as shown in the p–V- und T–S diagrams

from T_2 to $T_{2'}$ supplied by the heat exchanger is coupled with a thermal discharge (4 → 4'). If heat is completely exchanged, the quantity of heat to be added per unit of gas is reduced to

$$q_{zu} = c_p \cdot (T_3 - T_{2'}) = c_p \cdot (T_3 - T_4)$$

and the quantity of heat to be removed is

$$q_{ab} = c_p \cdot (T_{4'} - T_1) = c_p \cdot (T_4 - T_1).$$

The maximum thermal efficiency for the gas turbine with heat exchanger is:

$$\eta_{th} = 1 - Q_{ab}/Q_{zu} = 1 - (T_2 - T_1)/(T_3 - T_4)$$

Where $(p_2/p_1) = (T_2/T_1)^{\frac{\kappa}{\kappa-1}} = (T_3/T_4)^{\frac{\kappa}{\kappa-1}}$ and $T_4 = T_3 \cdot (T_1/T_2)$ thus

$$\eta_{th} = 1 - (T_2/T_3)$$

Current gas-turbine powerplants achieve thermal efficiencies of up to 35 %.

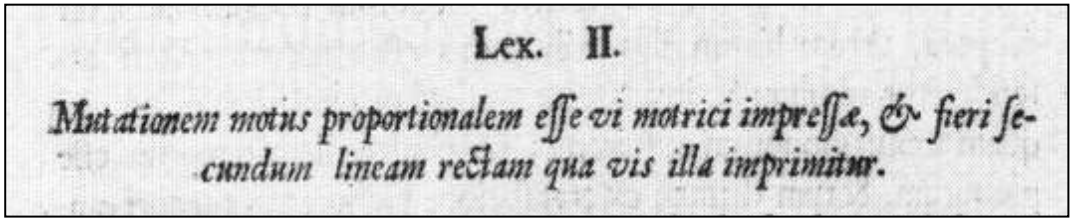
Advantages of the gas turbine: clean exhaust without supplementary emissions-control devices; extremely smooth running; multifuel capability; good static torque curve; extended maintenance intervals.

Disadvantages: manufacturing costs still high; poor transitional response; higher fuel consumption; less suitable for low-power applications.

Gas turbine 1 Filter and silencer, 2 Radial-flow compressor, 3 Burner, 4 Heat exchanger, 5 Exhaust port, 6 Reduction gearset, 7 Power turbine, 8 Adjustable guide vanes, 9 Compressor turbine, 10 Starter, 11 Auxiliary-equipment drive, 12 Lubricating oil pump

"The change of motion is proportional to the motive force impressed"

– Newton

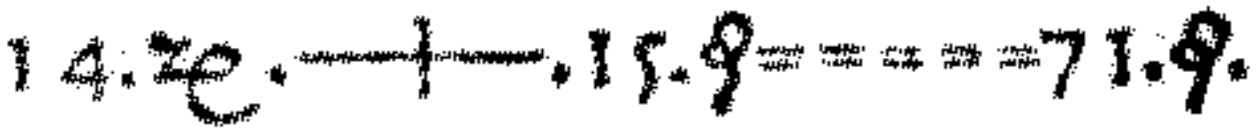


Lex. II.

Mutationem motus proportionalem esse vi motrici impressæ, & fieri secundum lineam rectam qua vis illa imprimitur.

Modelica Background: The Form – Equations

- Equations were used in the third millennium B.C.
- Equality sign was introduced by Robert Recorde in 1557



Newton still wrote text (Principia, vol. 1, 1686)

"*The change of motion is proportional to the motive force impressed*"

CSSL (1967) introduced a special form of "equation":

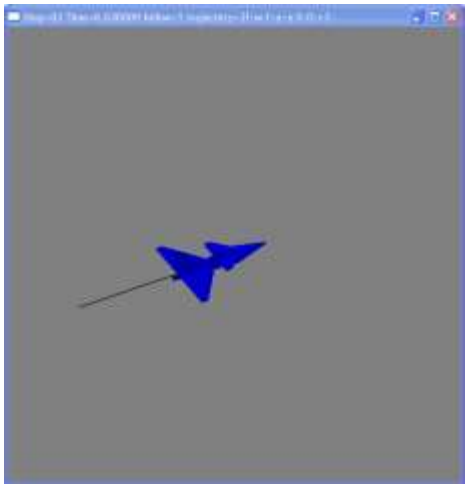
```
variable = expression
v = INTEG(F)/m
```

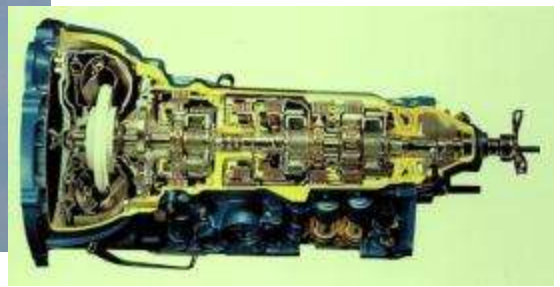
Programming languages usually do not allow equations!

What is Modelica?

A language for modeling of complex cyber-physical systems

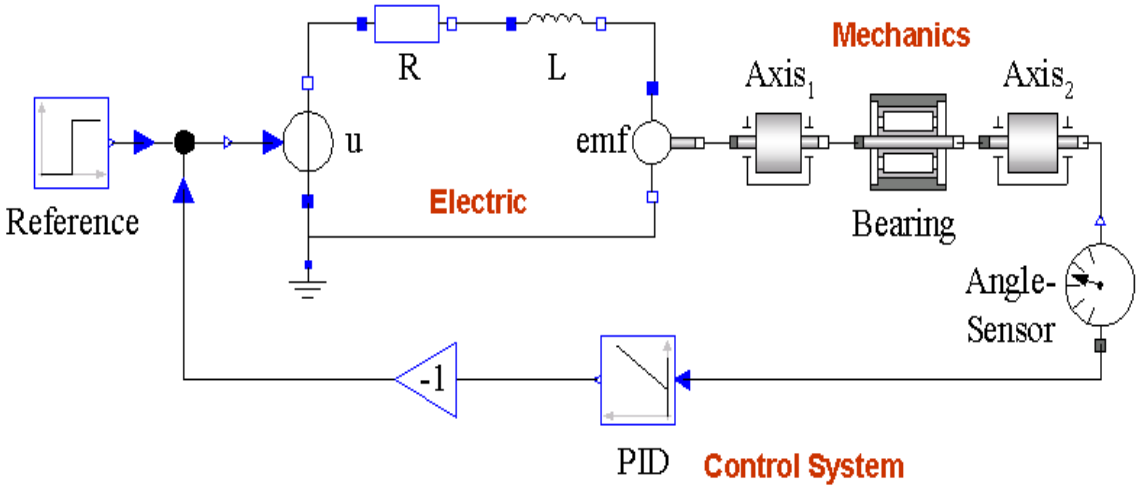
- Robotics
- Automotive
- Aircrafts
- Satellites
- Power plants
- Systems biology





What is Modelica?

A language for modeling of complex cyber-physical systems



Primary designed for **simulation**, but there are also other usages of models, e.g. optimization.

What is Modelica?

A language for modeling of complex cyber-physical systems

i.e., Modelica is **not** a tool

Free, open language specification:

Available at: www.modelica.org

Developed and standardized by Modelica Association

There exist one free and several commercial tools, for example:

- **OpenModelica from OSMC**
  (in ABB Optimax, Bosch-Rexr Control Edge Designer, Mike DHI)
- Dymola from Dassault systems
- Wolfram System Modeler from Wolfram MathCore
- SimulationX from ITI, part of ESI Group
- MapleSim from MapleSoft
  (also in Altair solidThinking Activate)
- AMESIM from LMS
- Optimica Toolkit from Modelon
  (also in ANSYS Simplorer, Rickardo tool, etc.)
- MWORKS from Tongyang Sw & Control
- IDA Simulation Env, from Equa
-

Modelica – The Next Generation Modeling Language

Declarative language

Equations and mathematical functions allow acausal modeling, high level specification, increased correctness

Multi-domain modeling

Combine electrical, mechanical, thermodynamic, hydraulic, biological, control, event, real-time, etc...

Everything is a class

Strongly typed object-oriented language with a general class concept, Java & MATLAB-like syntax

Visual component programming

Hierarchical system architecture capabilities

Efficient, non-proprietary

Efficiency comparable to C; advanced equation compilation, e.g. 300 000 equations, ~150 000 lines on standard PC

Modelica Acausal Modeling

What is *acausal* modeling/design?

Why does it increase *reuse*?

> The acausality makes Modelica library classes *more reusable* than traditional classes containing assignment statements where the input-output causality is fixed.

Example: a resistor *equation*:

R*i = v;

can be used in three ways:

i := v/R;

v := R*i;

R := v/i;

What is Special about Modelica?

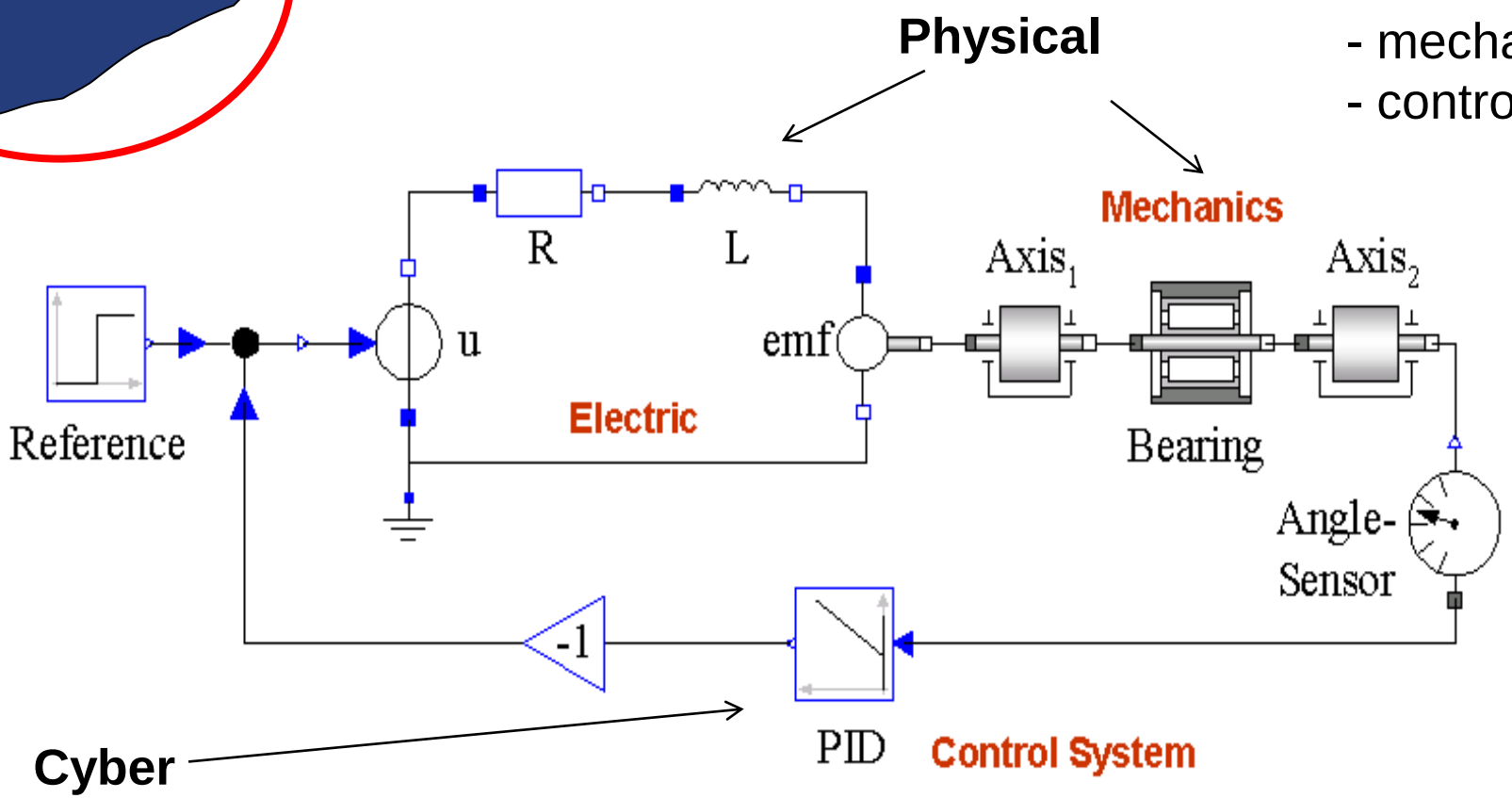
- Multi-Domain Modeling
- Visual acausal hierarchical component modeling
- Typed declarative equation-based textual language
- Hybrid modeling and simulation

What is Special about Modelica?

Multi-Domain Modeling

Cyber-Physical Modeling

3 domains
- electric
- mechanics
- control



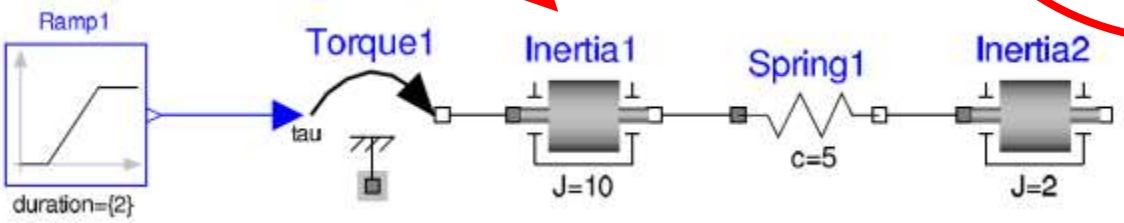
What is Special about Modelica?

Multi-Domain Modeling

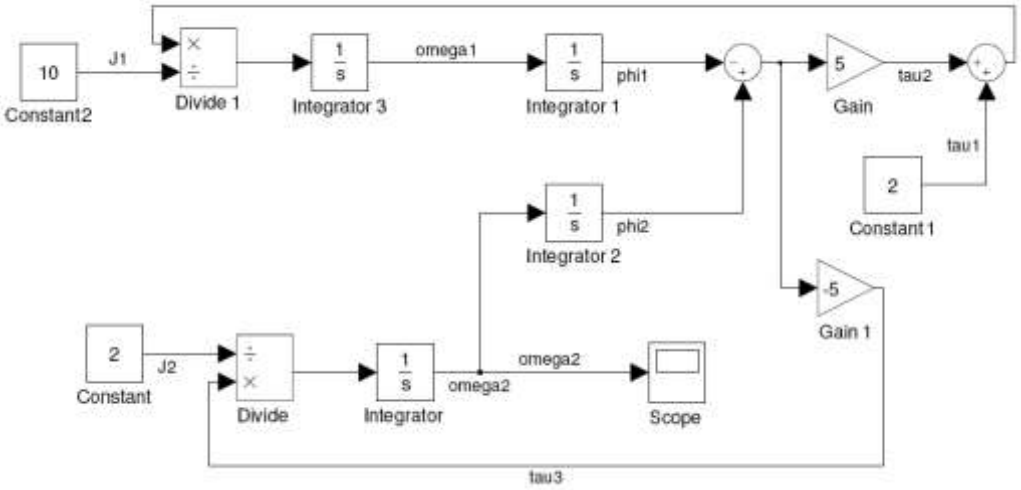
Visual Acausal Hierarchical Component Modeling

Keeps the physical structure

Acausal model (Modelica)



Causal block-based model (Simulink)

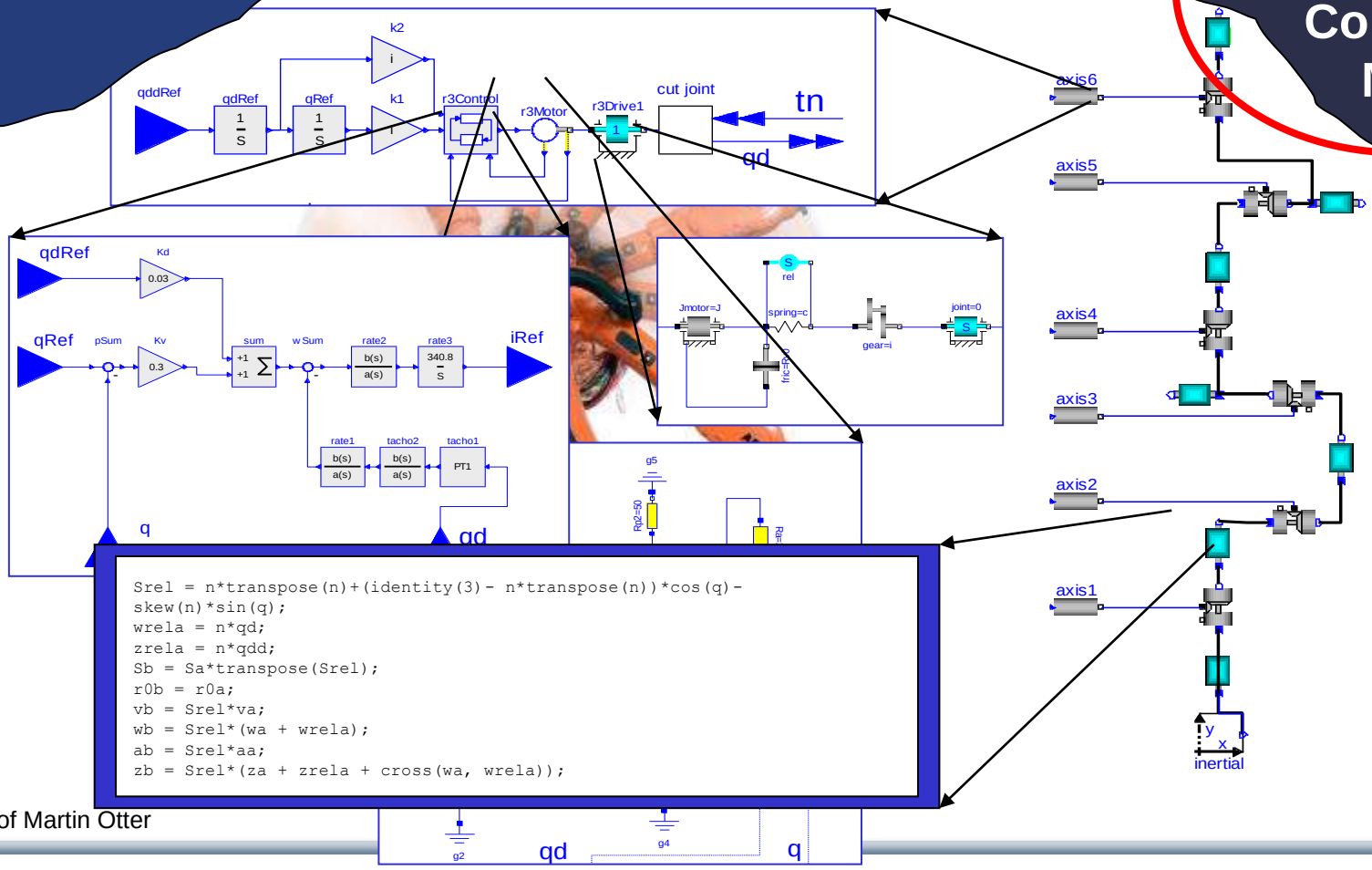


What is Special about Modelica?

Multi-Domain Modeling

Hierarchical system modeling

Visual Acausal Hierarchical Component Modeling



Courtesy of Martin Otter

What is Special about Modelica?

Multi-Domain Modeling

Visual Acausal Hierarchical Component Modeling

A textual *class-based* language
OO primary used for as a structuring concept

Behaviour described declaratively using

- Differential algebraic equations (DAE) (continuous-time)
- Event triggers (discrete-time)

Typed Declarative Equation-based Textual Language

Variable declarations

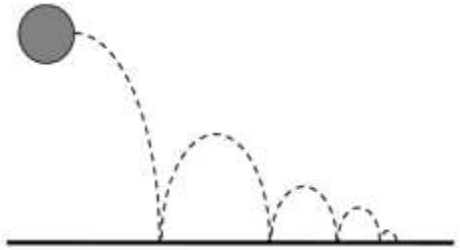
```
class VanDerPol  "Van der Pol oscillator model"
  Real x(start = 1)  "Descriptive string for x";
  Real y(start = 1)  "y coordinate";
  parameter Real lambda = 0.3;
equation
  der(x) = y;
  der(y) = -x + lambda*(1 - x*x)*y;
end VanDerPol;
```

Differential equations

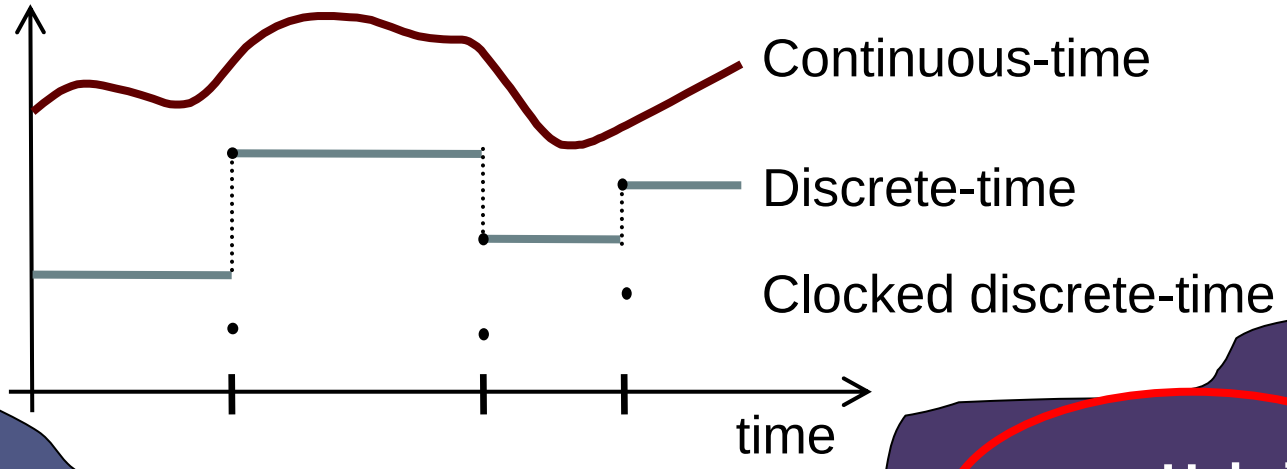
What is Special about Modelica?

Multi-Domain Modeling

Visual Acausal Component Modeling



Hybrid modeling =
continuous-time + discrete-time modeling

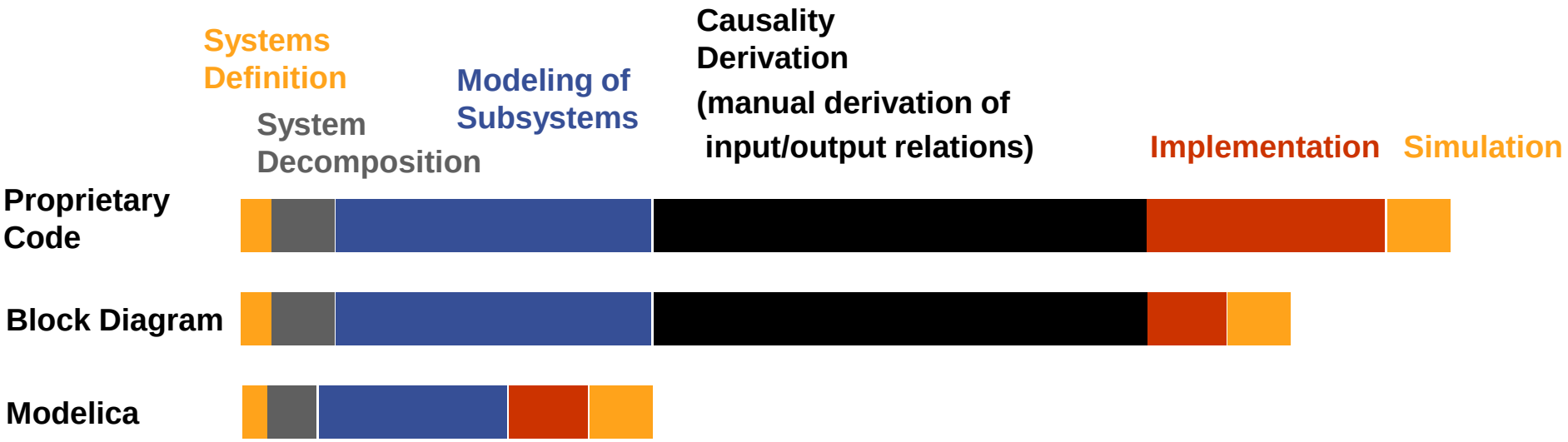


Typed
Declarative
Equation-based
Textual Language

Hybrid Modeling

Modelica – Faster Development, Lower Maintenance than with Traditional Tools

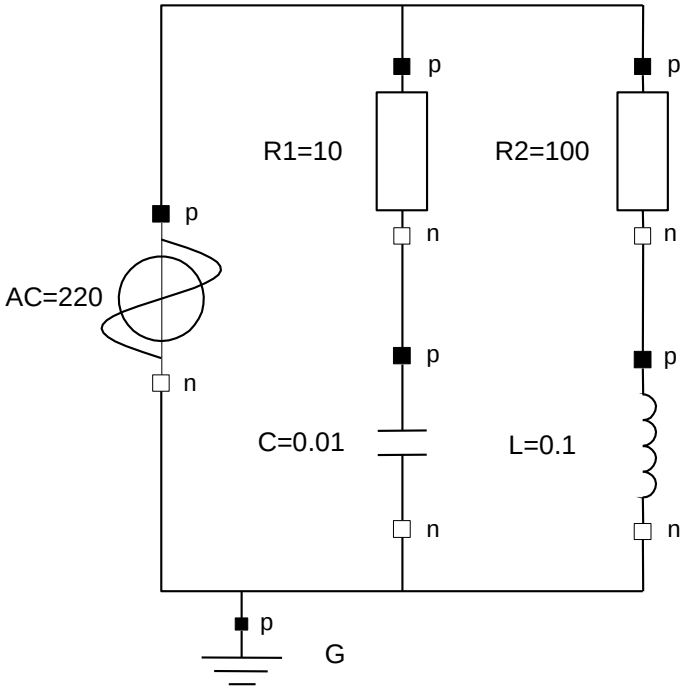
Block Diagram (e.g. Simulink, ...) or
Proprietary Code (e.g. Ada, Fortran, C,...)
vs Modelica



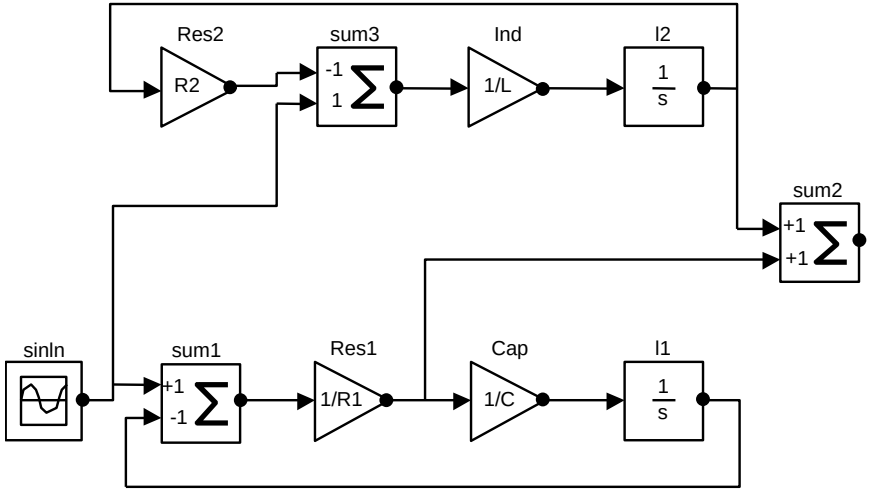
Modelica vs Simulink Block Oriented Modeling Simple Electrical Model

Modelica:
Physical model – easy to understand

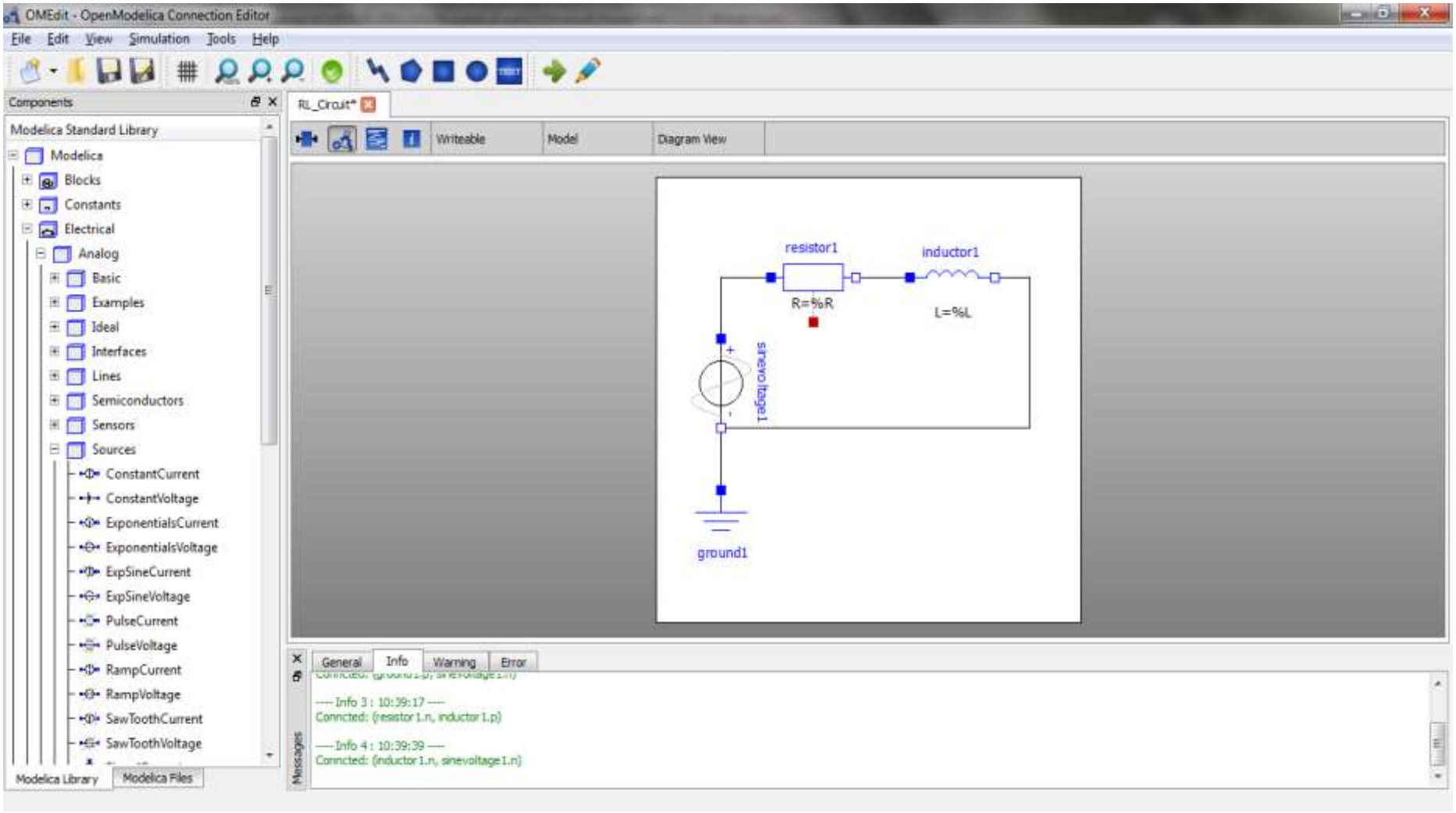
Keeps the physical structure



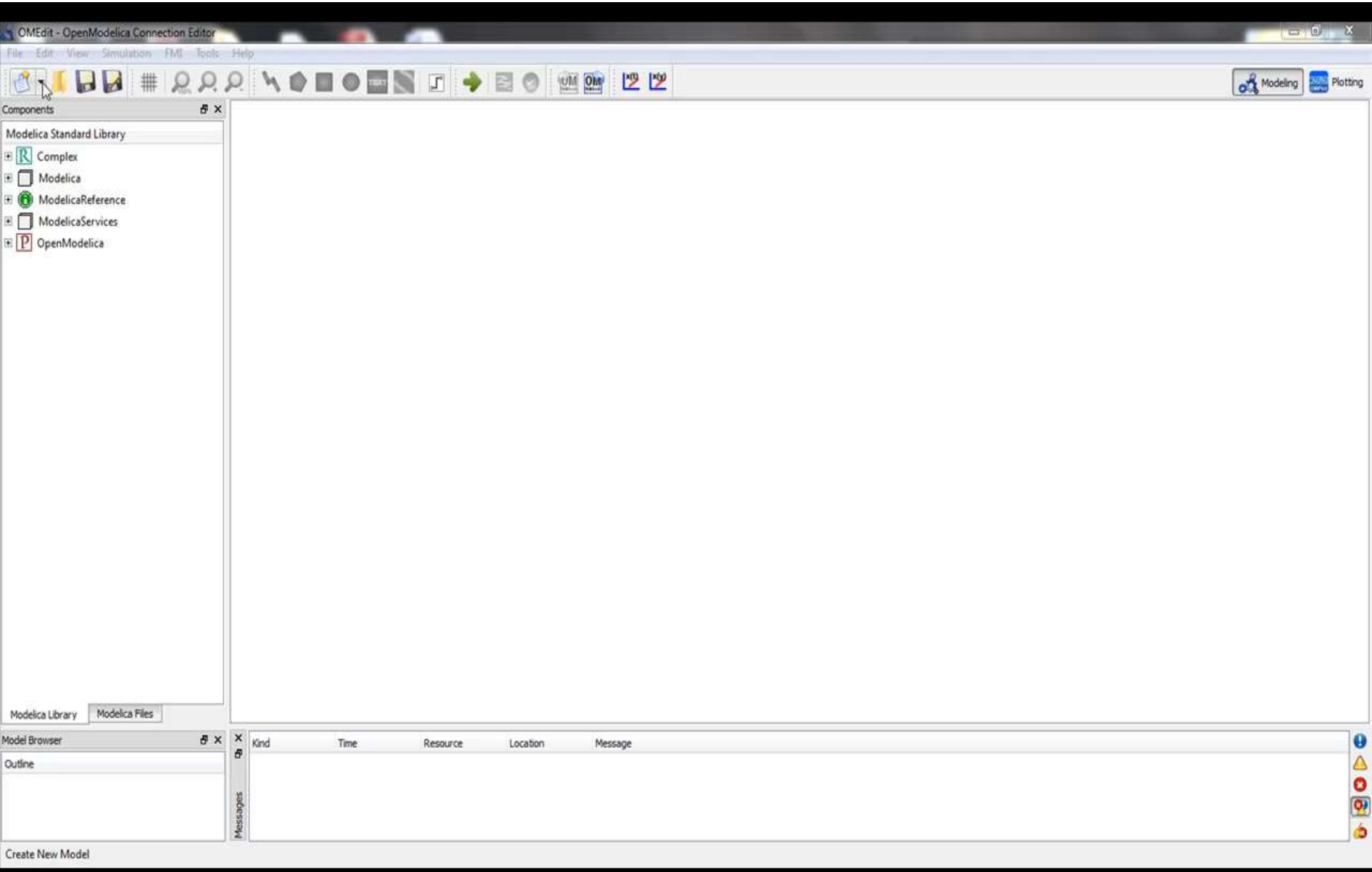
Simulink:
Signal-flow model – hard to understand



Graphical Modeling - Using Drag and Drop Composition



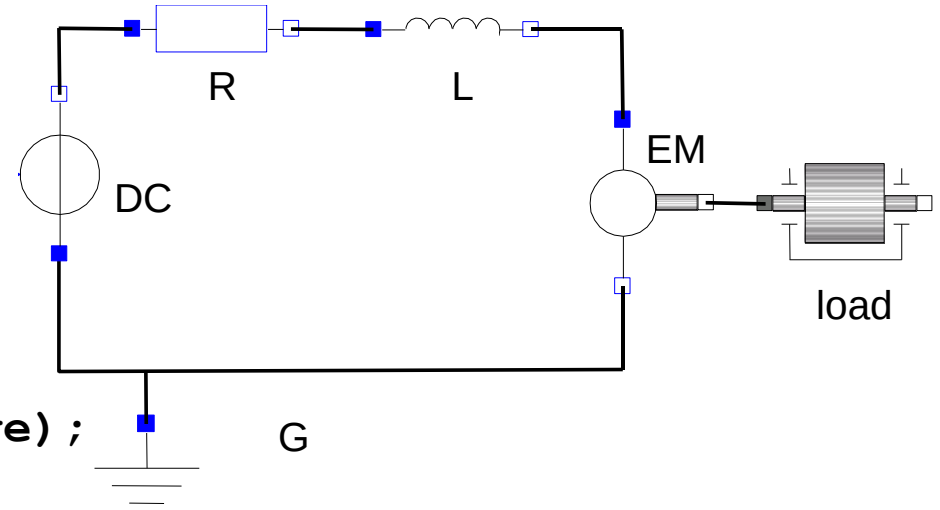
Graphical Modeling with OpenModelica Environment



Multi-Domain (Electro-Mechanical) Modelica Model

- A DC motor can be thought of as an electrical circuit which also contains an electromechanical component

```
model DCMotor
   Resistor R(R=100);
   Inductor L(L=100);
   VsourceDC DC(f=10);
   Ground G;
   ElectroMechanicalElement EM(k=10,J=10, b=2);
   Inertia load;
equation
   connect(DC.p,R.n);
   connect(R.p,L.n);
   connect(L.p, EM.n);
   connect(EM.p, DC.n);
   connect(DC.n,G.p);
   connect(EM.flange,load.flange);
end DCMotor
```



Corresponding DCMotor Model Equations

The following equations are automatically derived from the Modelica model:

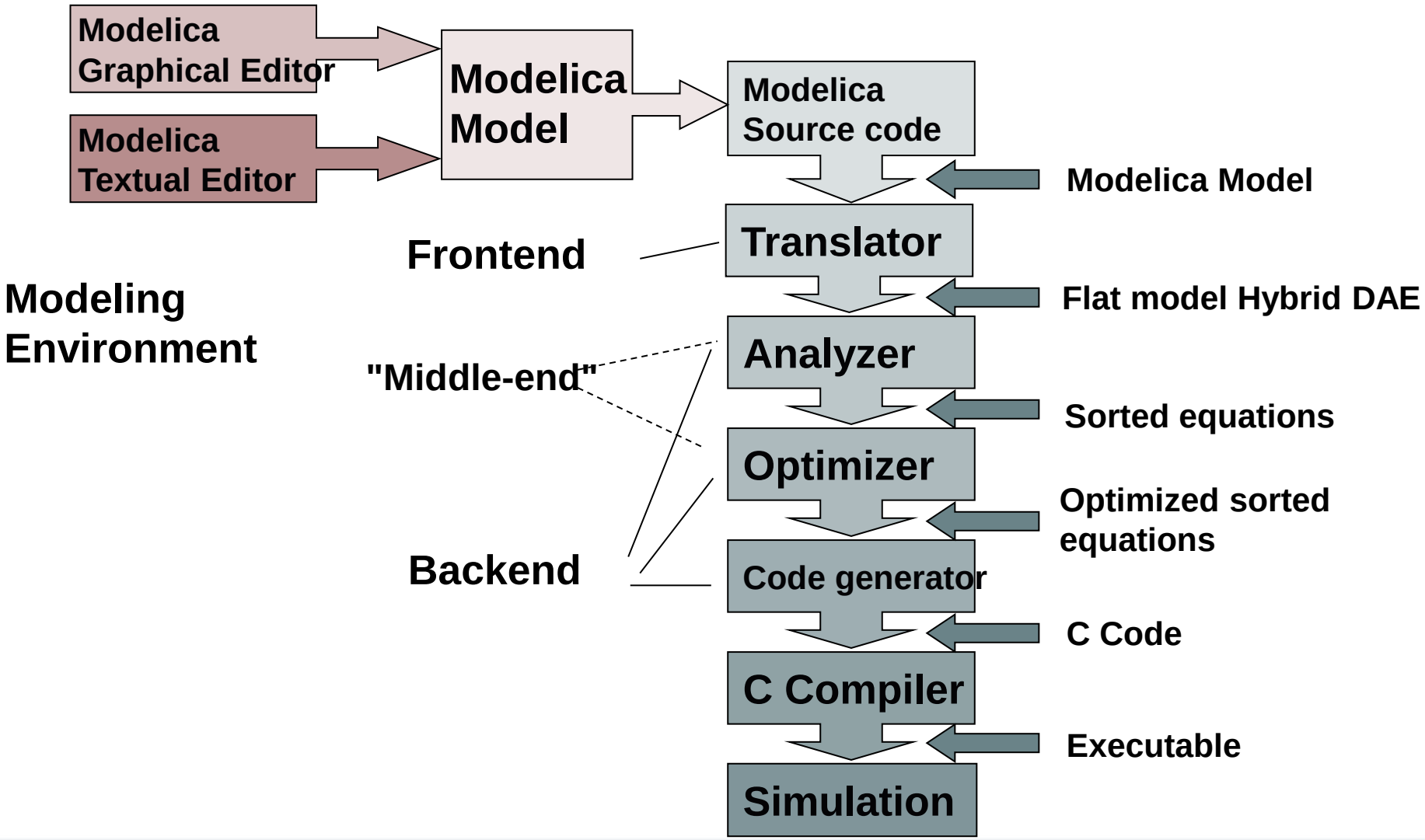
```
0 == DC.p.i + R.n.i
DC.p.v == R.n.v

0 == R.p.i + L.n.i
R.p.v == L.n.v

0 == L.p.i + EM.n.i
L.p.v == EM.n.v

0 == EM.p.i + DC.n.i
EM.p.v == DC.n.v

0 == DC.n.i + G.p.i
DC.n.v == G.p.v

EM.u == EM.p.v - EM.n.v
0 == EM.p.i + EM.n.i
EM.i == EM.p.i
EM.u == EM.k * EM.ω
EM.i == EM.M / EM.k
EM.J * EM.ω == EM.M - EM.b * EM.ω

DC.u == DC.p.v - DC.n.v
0 == DC.p.i + DC.n.i
DC.i == DC.p.i
DC.u == DC.Amp * Sin[2 π DC.f * t]

R.u == R.p.v - R.n.v
0 == R.p.i + R.n.i
R.i == R.p.i
R.u == R.R * R.i

L.u == L.p.v - L.n.v
0 == L.p.i + L.n.i
L.i == L.p.i
L.u == L.L * L.i'
```

(`load` component not included)

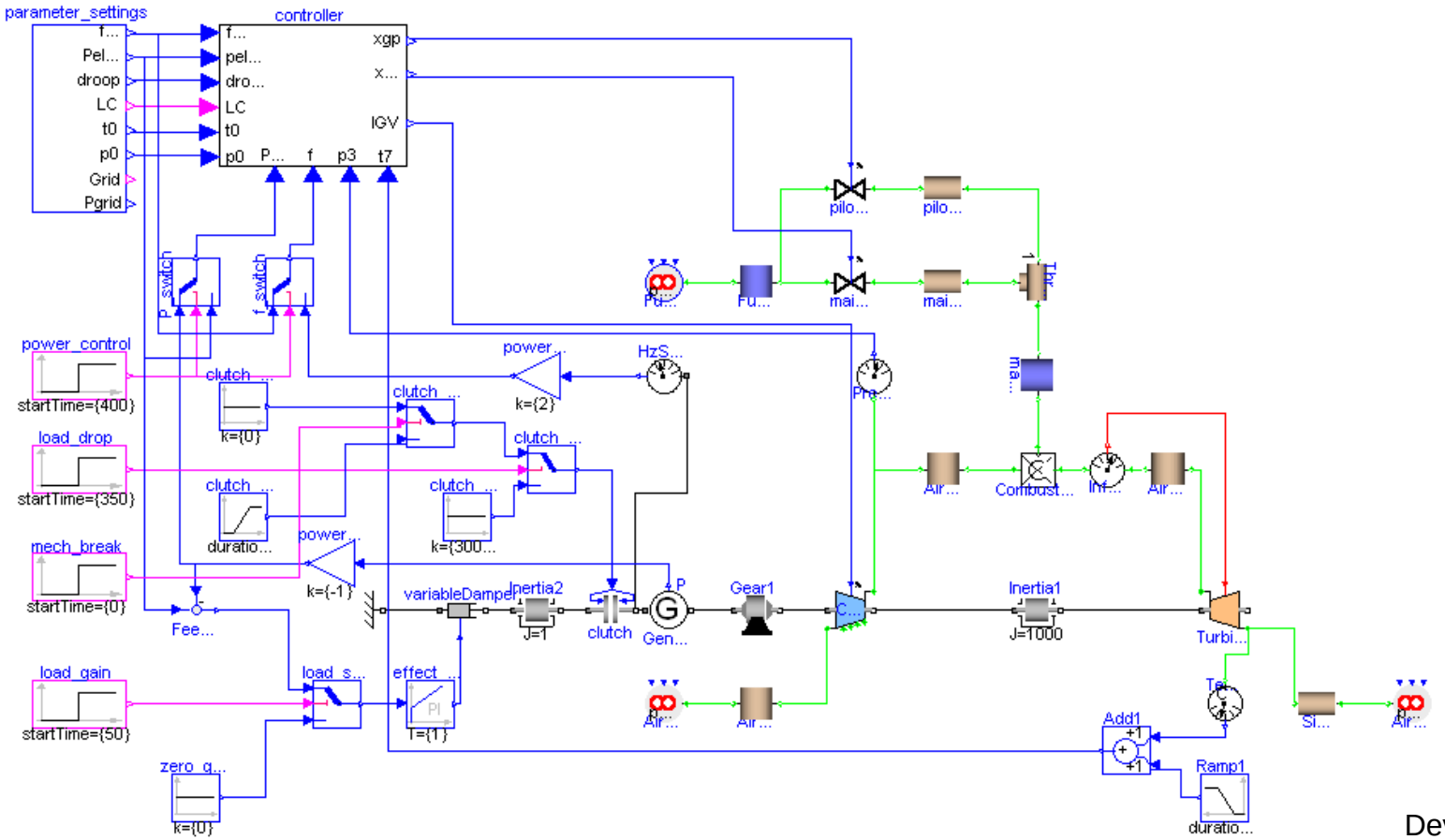
Automatic transformation to ODE or DAE for simulation:

$$\frac{dx}{dt} == f[x, u, t] \qquad g\left[\frac{dx}{dt}, x, u, t\right] == 0$$

Model Translation Process to Hybrid DAE to Code



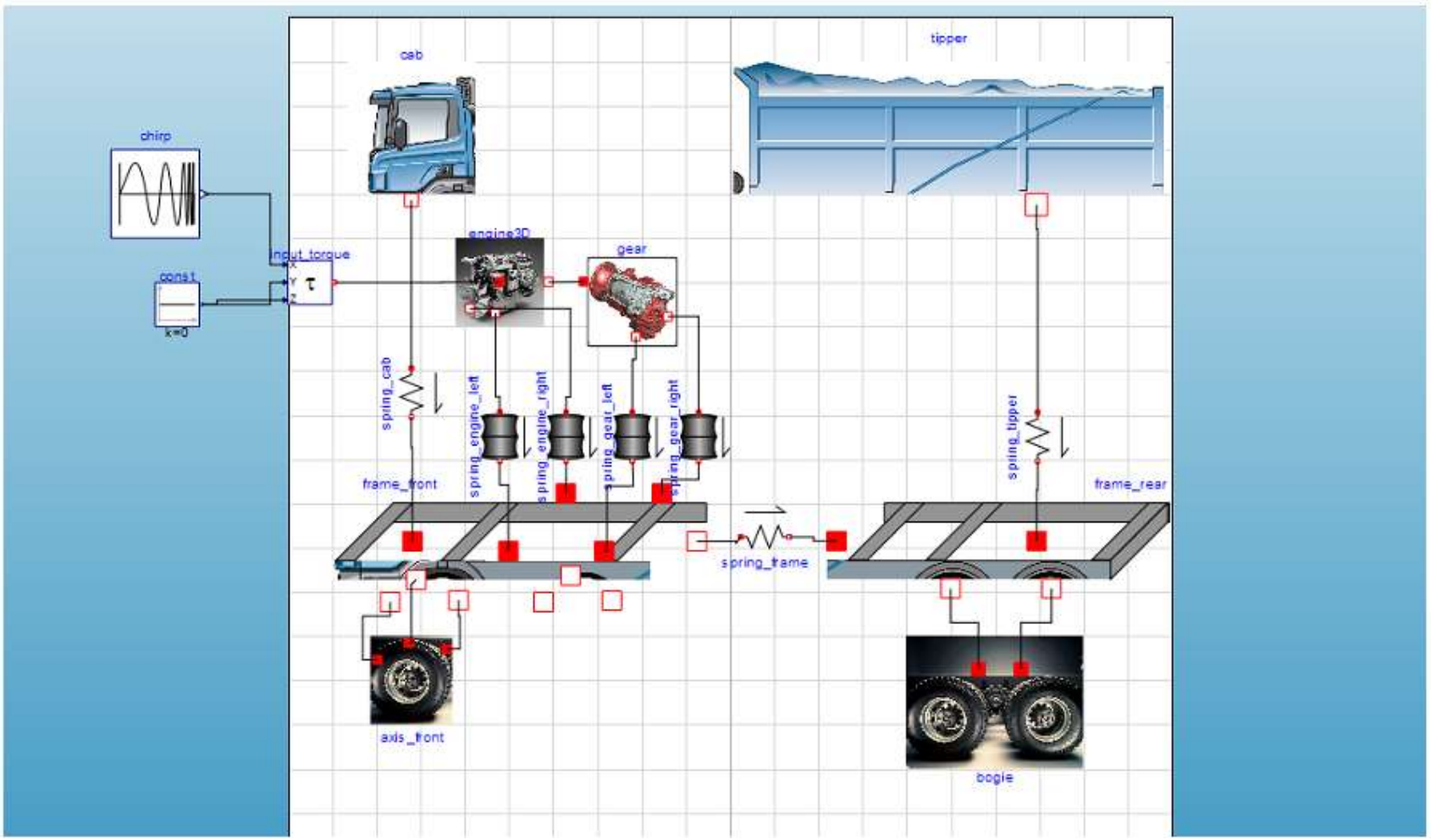
Modelica in Power Generation
GTX Gas Turbine Power Cutoff Mechanism



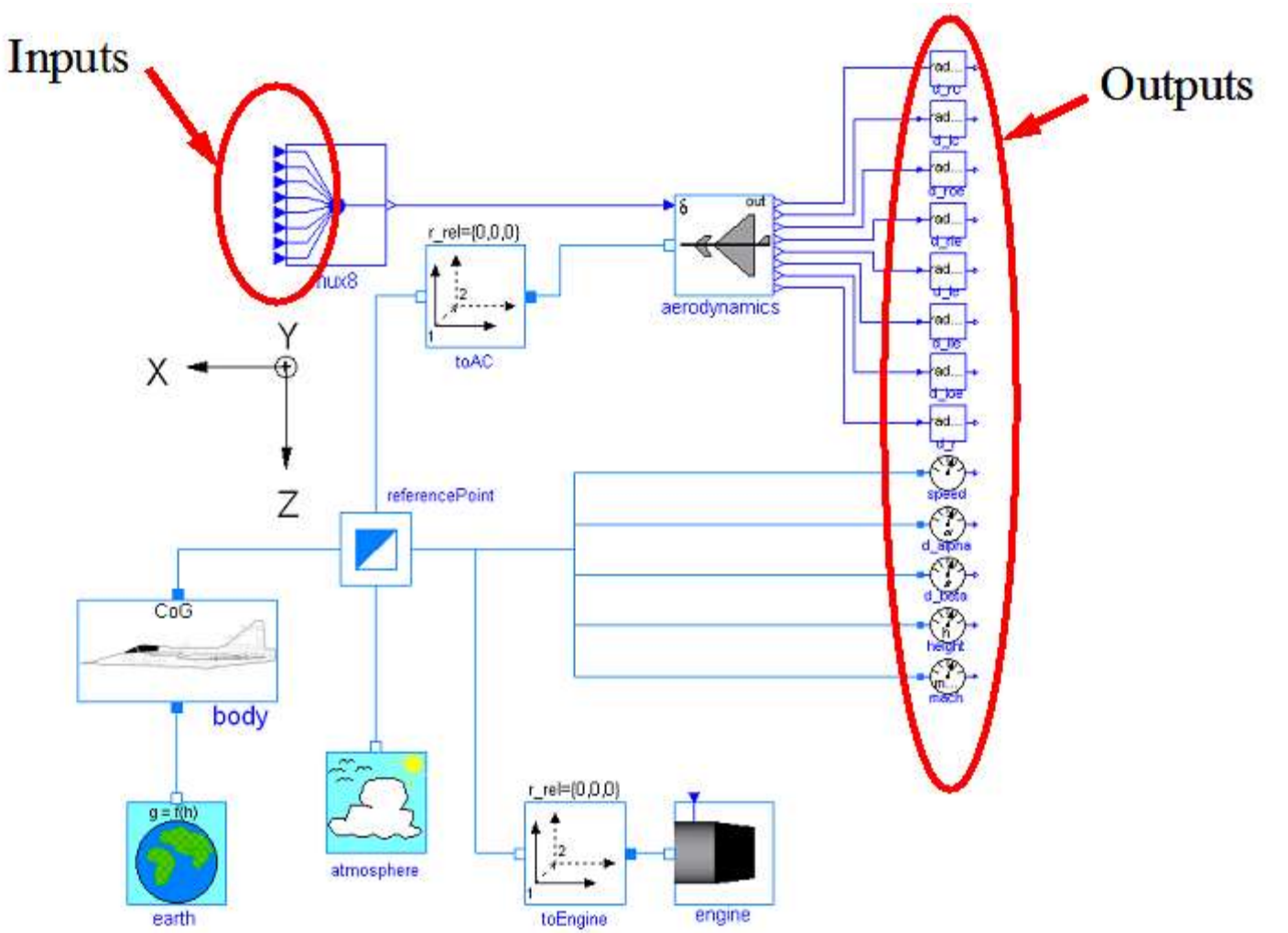
Developed by MathCore for Siemens

Courtesy of Siemens Energy AB

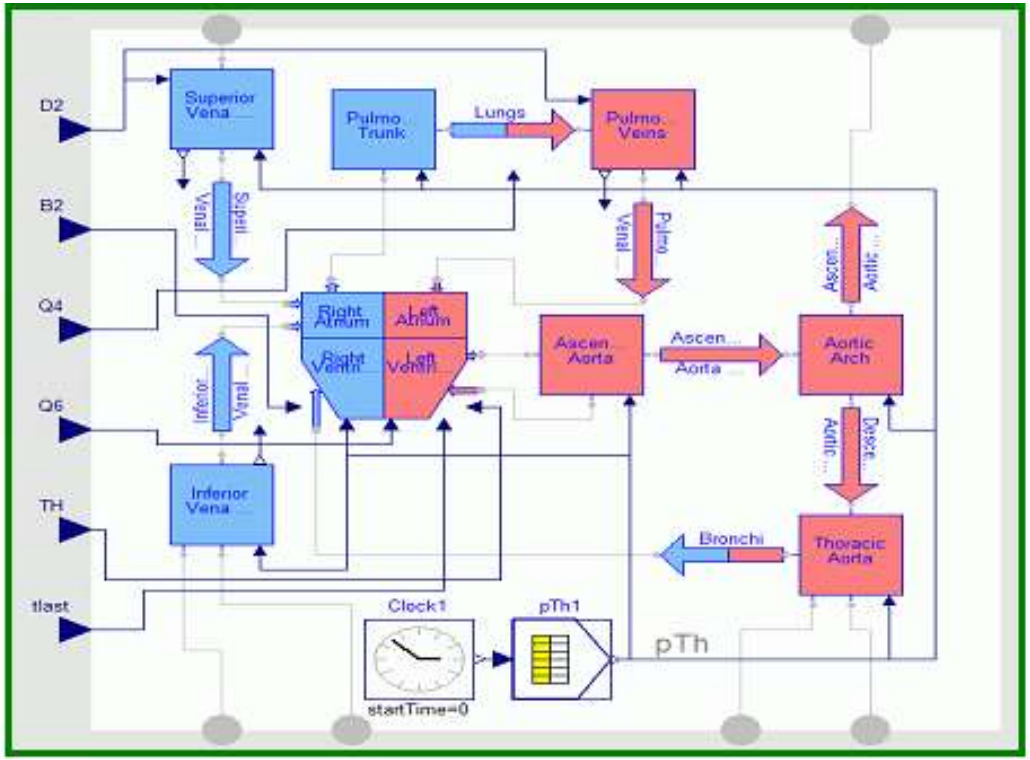
Modelica in Automotive Industry



Modelica in Avionics



Modelica in Biomechanics



Application of Modelica in Robotics Models Real-time Training Simulator for Flight, Driving

- Using Modelica models generating real-time code
- Different simulation environments (e.g. Flight, Car Driving, Helicopter)
- Developed at DLR Munich, Germany
- Dymola Modelica tool

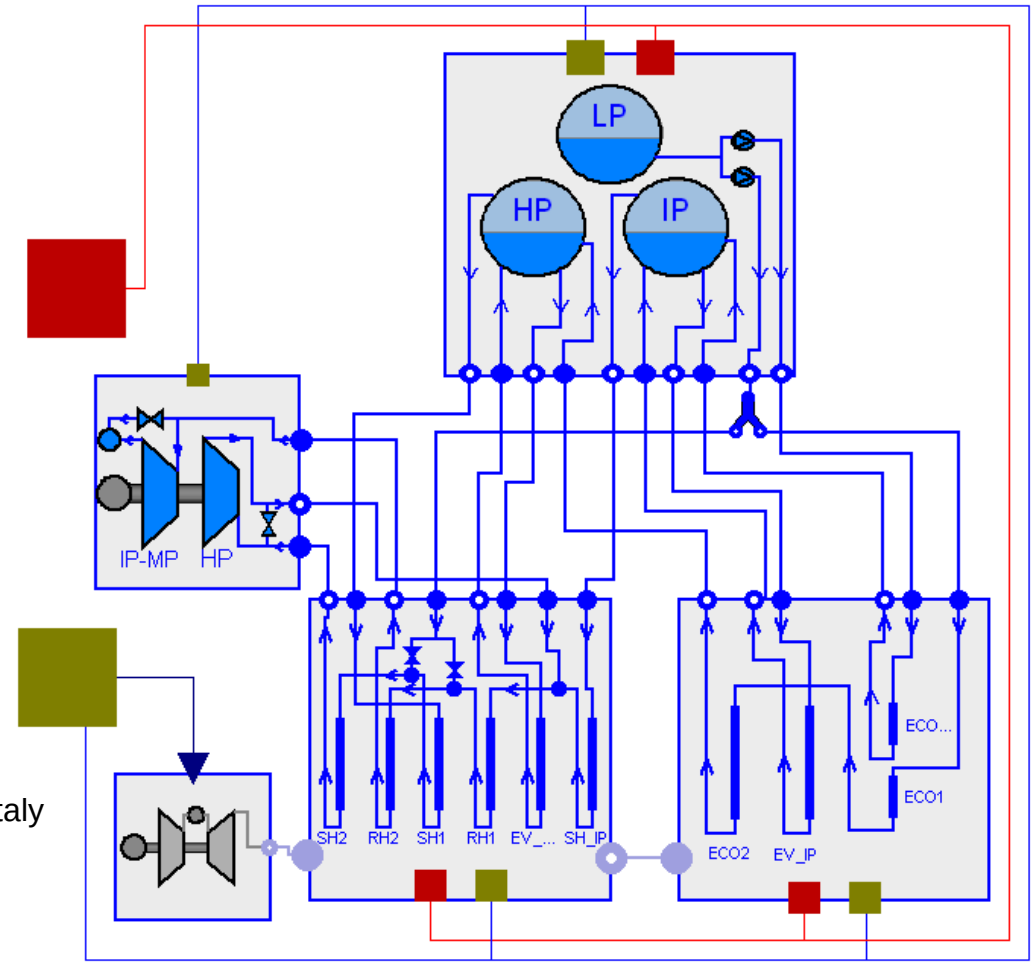
(Movie demo next page)

Courtesy of Tobias Bellmann, DLR, Oberphaffenhofen, Germany

DLR Real-time Training Simulator Movie Demo

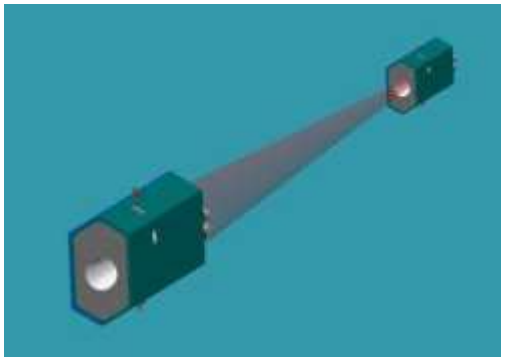
Combined-Cycle Power Plant
Plant model – system level

- GT unit, ST unit, Drum boilers unit and HRSG units, connected by thermo-fluid ports and by signal buses
- Low-temperature parts (condenser, feedwater system, LP circuits) are represented by trivial boundary conditions.
- GT model: simple law relating the electrical load request with the exhaust gas temperature and flow rate.



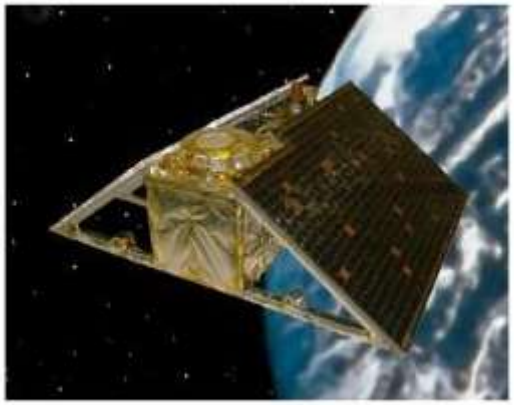
Courtesy Francesco Casella, Politecnico di Milano – Italy and Francesco Pretolani, CESI SpA - Italy

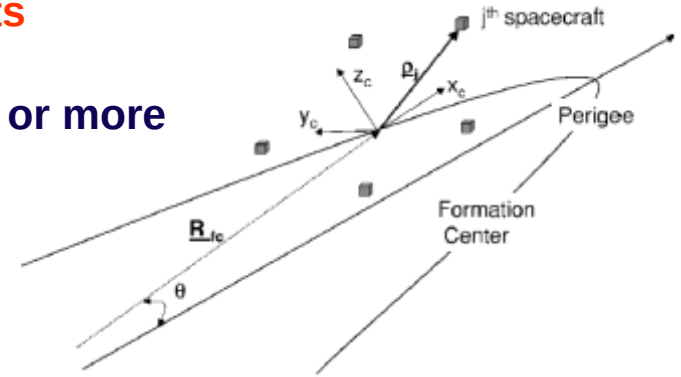
Modelica Spacecraft Dynamics Library



Formation flying on elliptical orbits

Control the relative motion of two or more spacecraft





Attitude control for satellites using magnetic coils as actuators

Torque generation mechanism: interaction between coils and geomagnetic field

Courtesy of Francesco Casella, Politecnico di Milano, Italy

Large-scale ABB OpenModelica Application
Generate code for controlling 7.5 to 10% of German Power Production

ABB OPTIMAX PowerFit

- Real-time optimizing control of large-scale virtual power plant for system integration
- **Software including OpenModelica** now used in managing more than 2500 renewable plants, total up to 1.5 GW

High scalability supporting growth

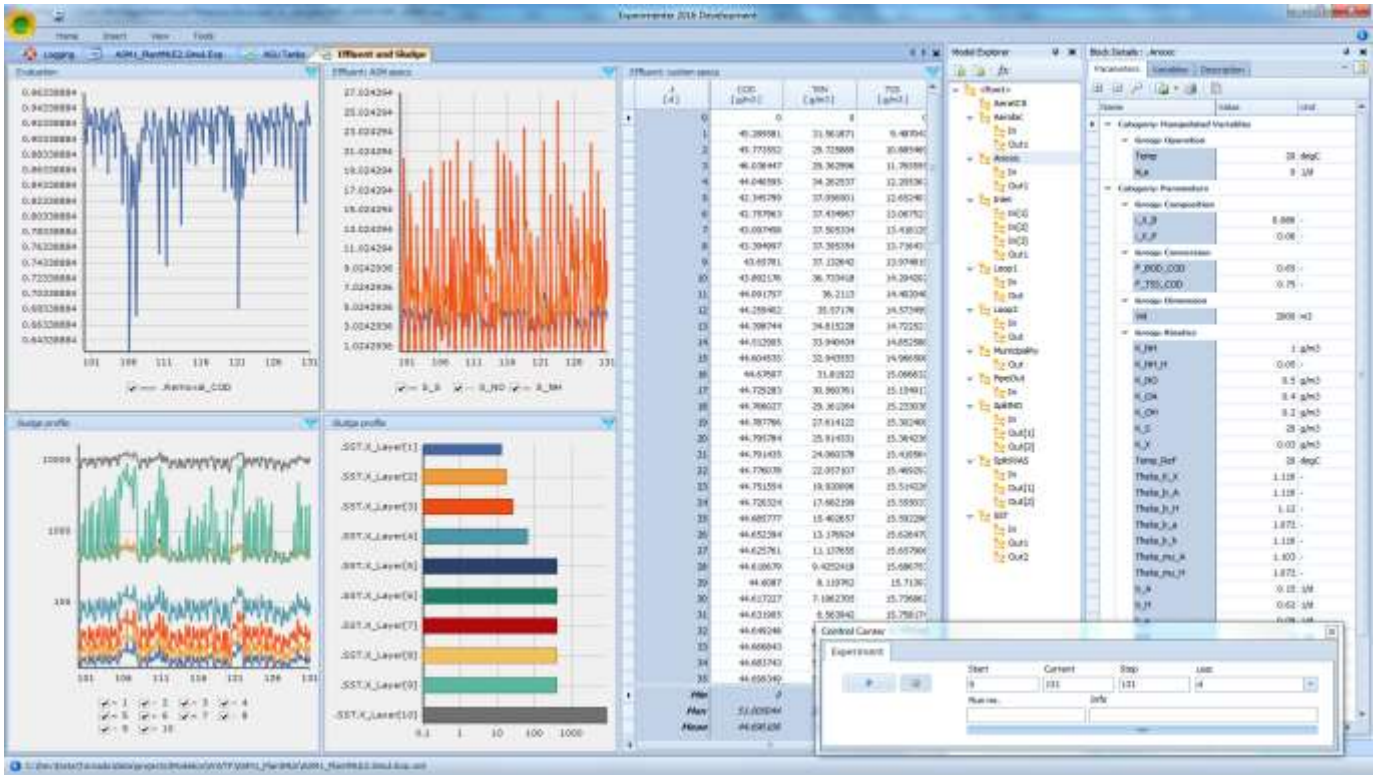
- 2012: initial delivery (for 50 plants)
- 2013: SW extension (500 plants)
- 2014: HW+SW extension (> 2000)
- 2015: HW+SW extension, incl. OpenModelica generating optimizing controller code in FMI 2.0 form

Manage 7.5% - 10% of German Power

- 2015, Aug: OpenModelica Exports FMUs for real-time optimizing control (seconds) of about **5.000 MW (7.5%) of power in Germany**

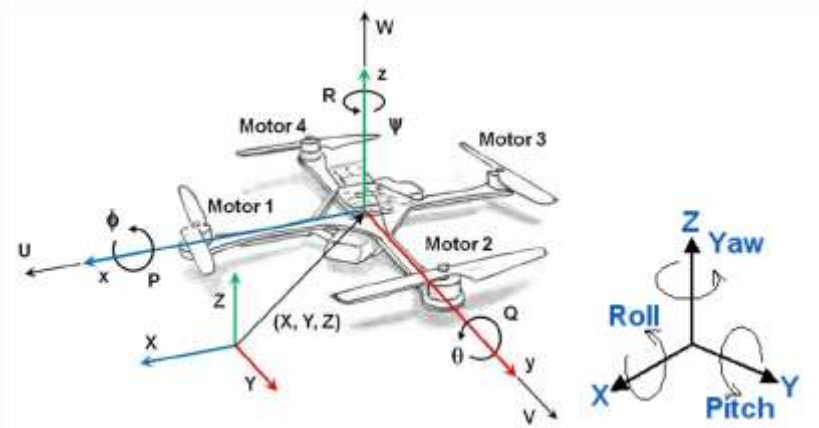
Industrial Product with OEM Usage of OpenModelica –
MIKE by DHI, WEST Water Quality, Water Treatment and Sludge

- **MIKE by DHI**, www.mikebydhi.com, **WEST Water Quality** modeling and simulation environment
- Includes a large part of the OpenModelica compiler using the OEM license.
- Here a water treatment effluent and sludge simulation.



Digital Twin OpenModelica Applications by Modelicon
Model-based Control of UAVs and Walking Robots

- UAV control and simulation
- Walking 2-wheel robot



UAV
Movie demo

All models and control software done using OpenModelica!

Walking 2-wheel Robot,

Movie demo

More Sustainable Foestry – Digital Twin of Balloon-Assisted UAV – Collaboration with GI-LIFT AB and Modelicon

Avoid clear-cut damage

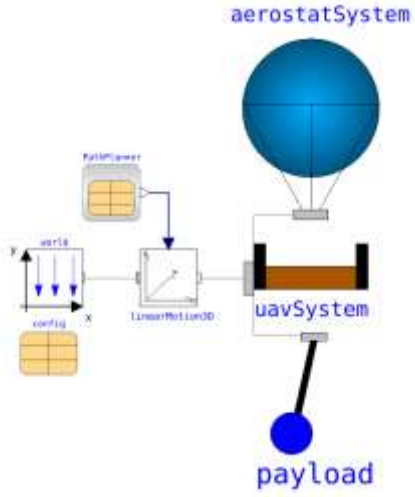
Instead high-powered Electric Ballon-assisted UAV lifting system
(patent pending, GI-LIFT)

Timber

Branches

Whole tree

Digital Twin Using OpenModelica



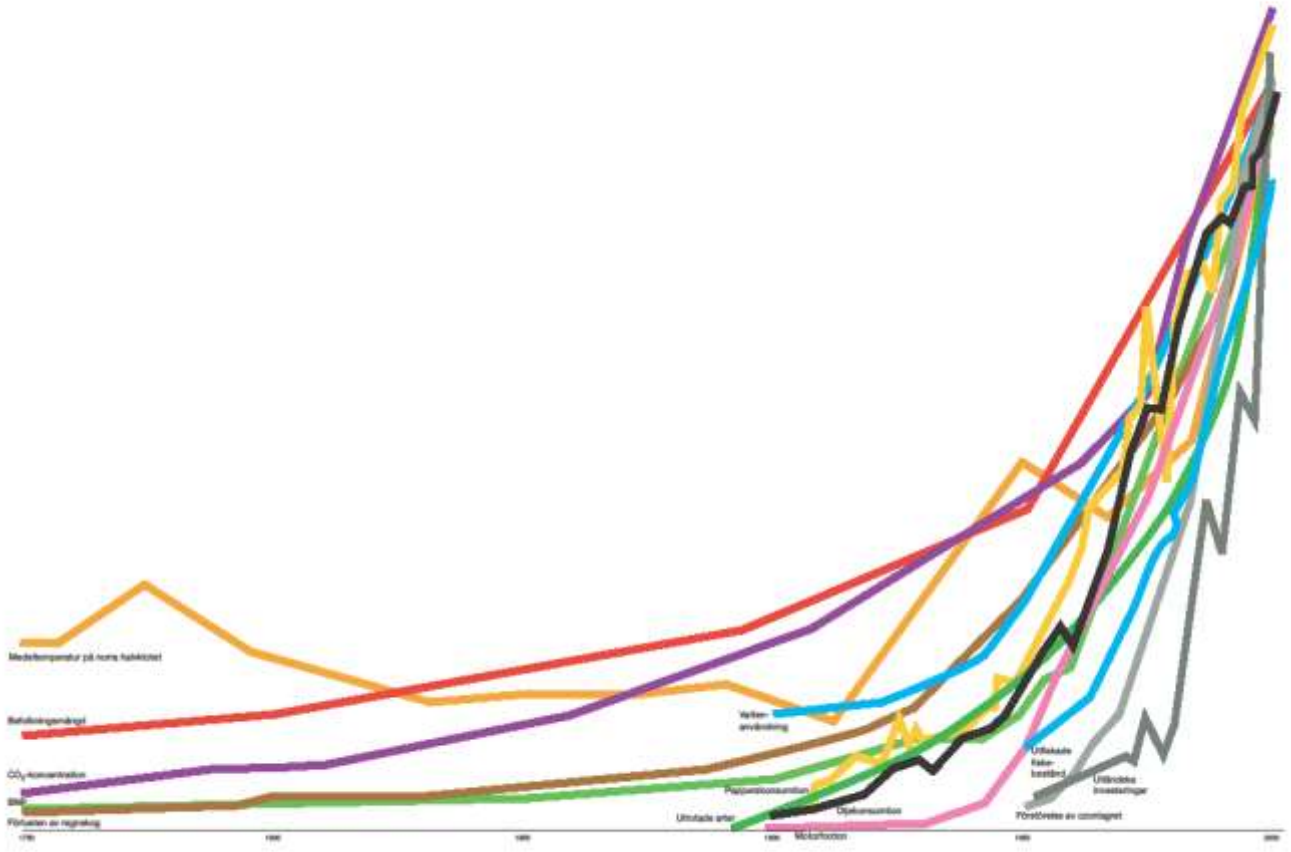
MODELICA pelab

Most important challenge for humanity - Develop a sustainable society!

Use **Modelica** in to model and optimize **sustainable technical innovations**, and a sustainable circular economy

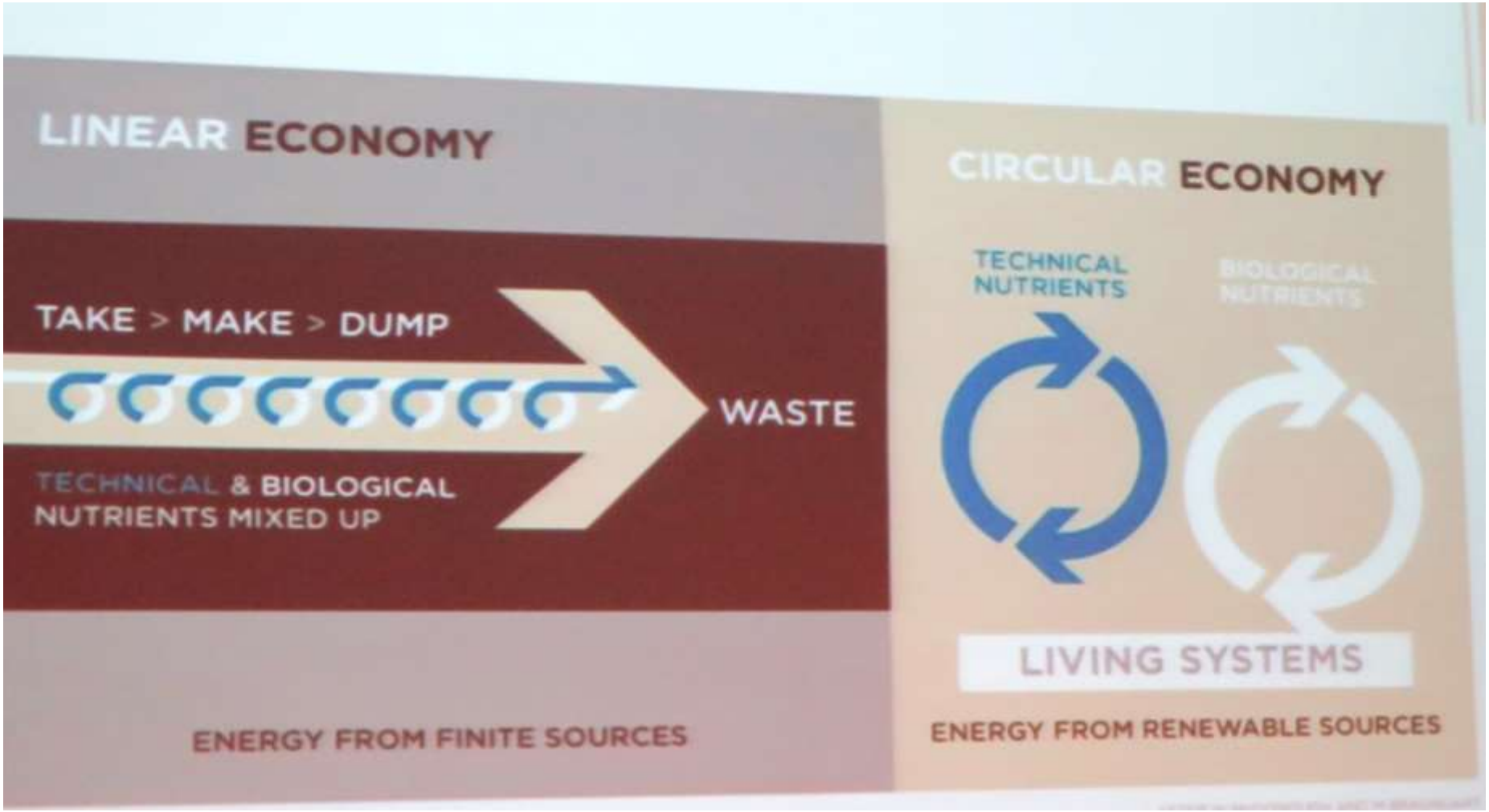
A Unique Point in History – Exponential Trends Approaches Planet Earth Boundaries

Year 1750-2000:



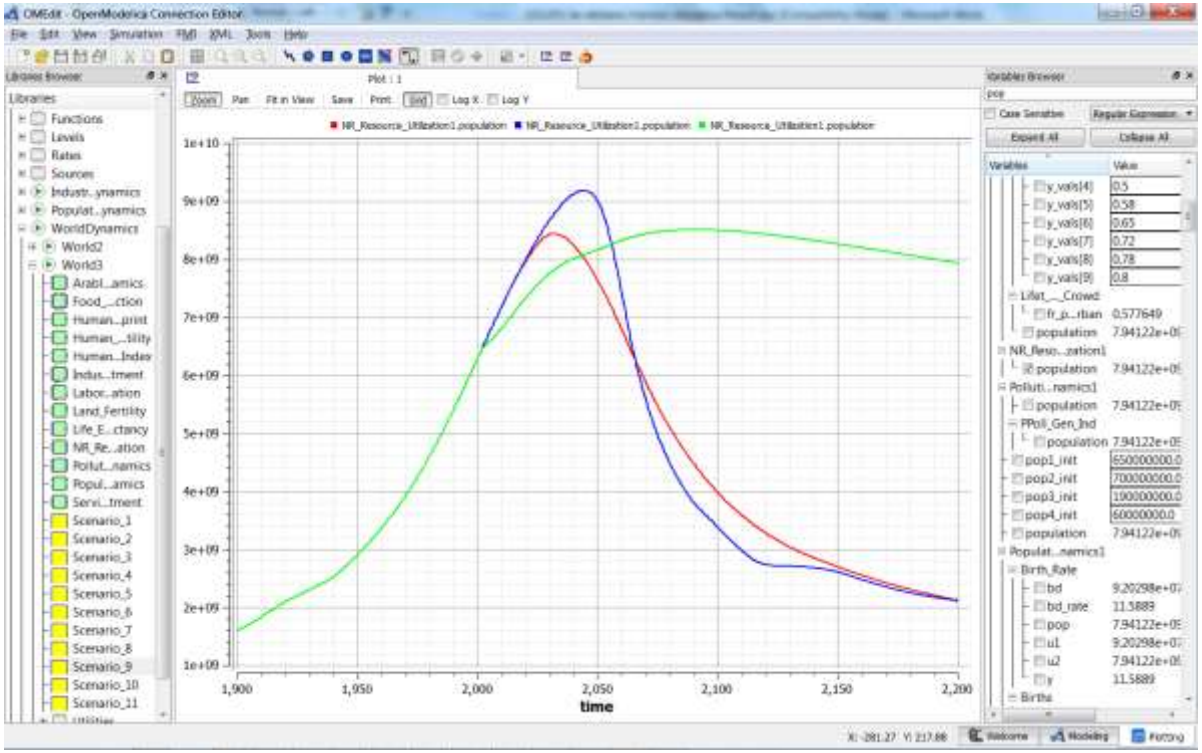
- Mean temperature north hemisphere,
- Population,
- CO_2-concentration,
- BNP,
- Loss av rain forest,
- Water usage
- Paper consumption,
- Exterminated species
- Oil consumtion,
- Motor vehicles
- Destroyed fish populations
- Destruction of ozon layer
- Foreign investments

Challenge: Use Modeling and Simulation Technology to Support Circular Economy – for a Sustainable World



System Dynamics – World Society Simulation

Limits to Material Growth; Population, Energy and Material flows



Left. **World3 simulation** with OpenModelica

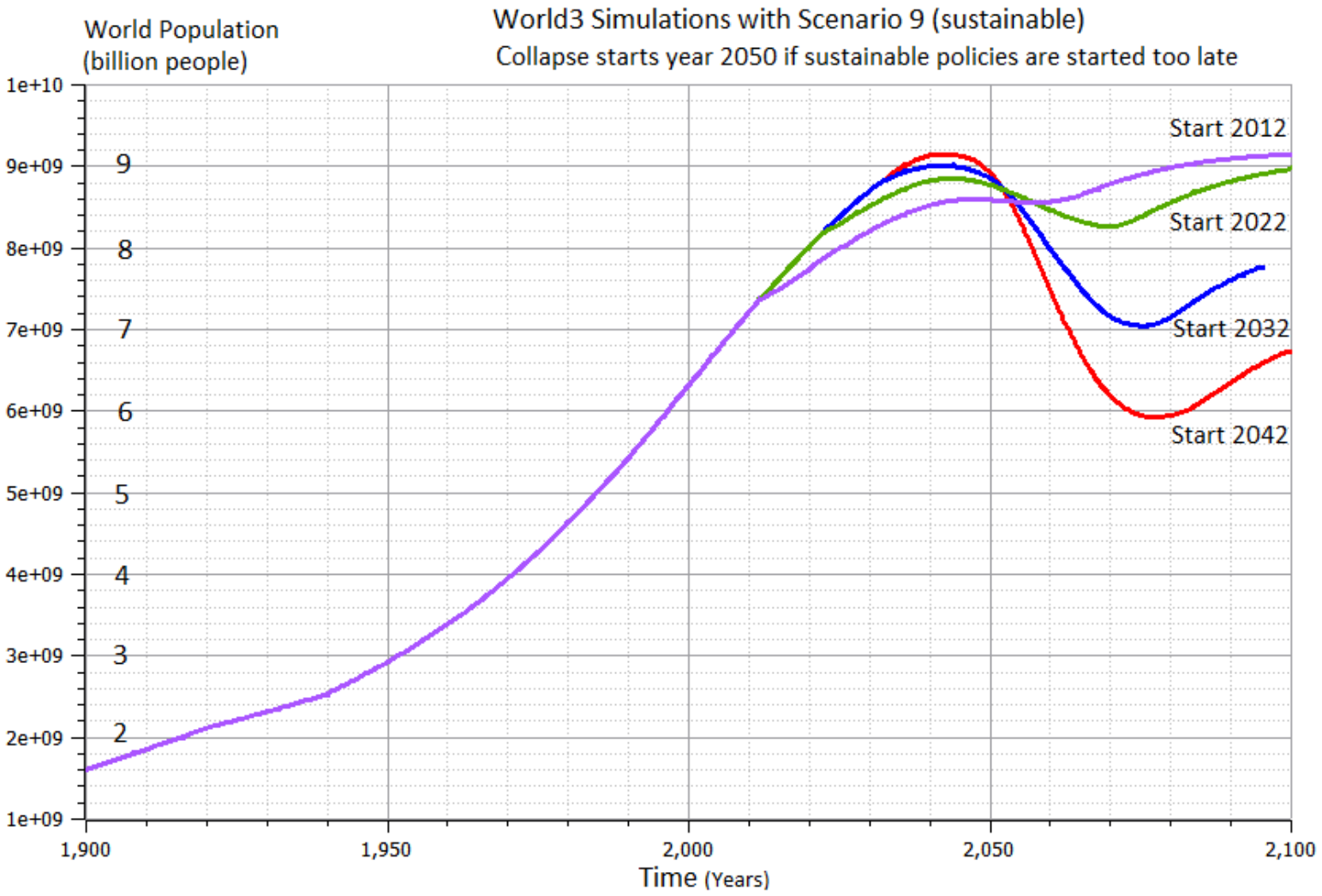
- 2 collapse scenarios (close to current developments)
- 1 sustainable scenario (green).

CO_2 Emissions per person**:**

- USA 17 ton/yr
- Sweden 7 ton/yr
- India 1.4 ton/yr
- Bangladesh 0.3 ton/yr

- **System Dynamics Modelica library** by Francois Cellier (ETH), et al in OM distribution
- Warming converts many agriculture areas to deserts (USA, Europe, India, Amazonas)
- Ecological breakdown around 2080-2100, drastic reduction of world population
- To **avoid** this: Need for massive investments in sustainable technology and renewable energy sources

World3 Simulations with Different Start Years for Sustainable Policies – Collapse if starting too late



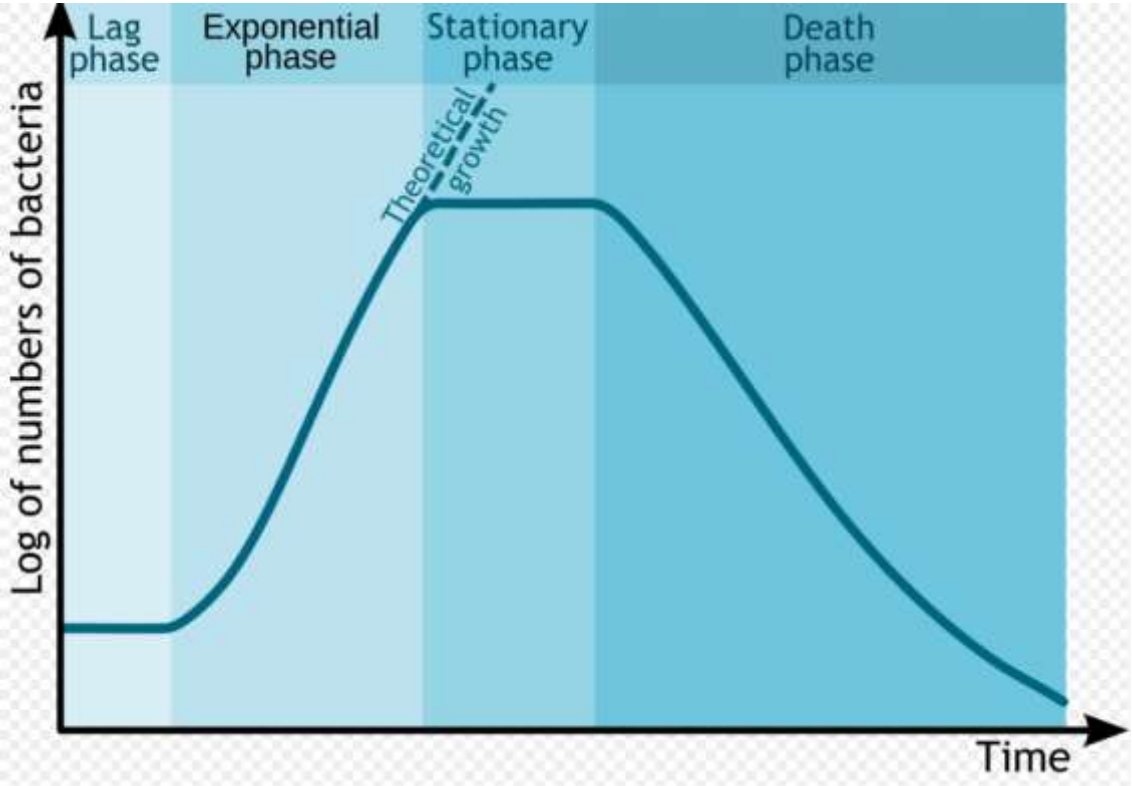
Are Humans More Intelligent than Bacteria?

Not yet evident!

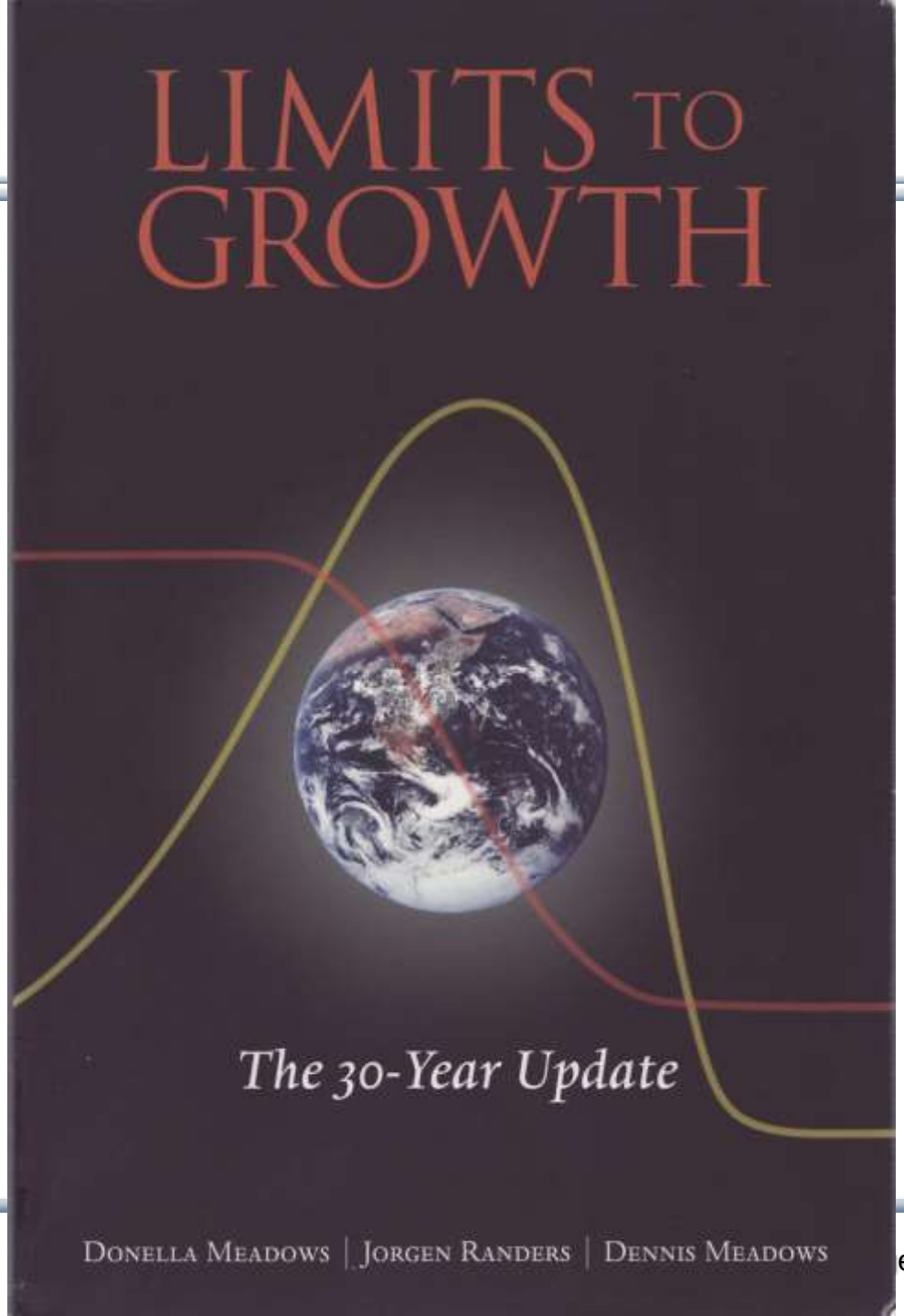
Humans on a **finite Earth**

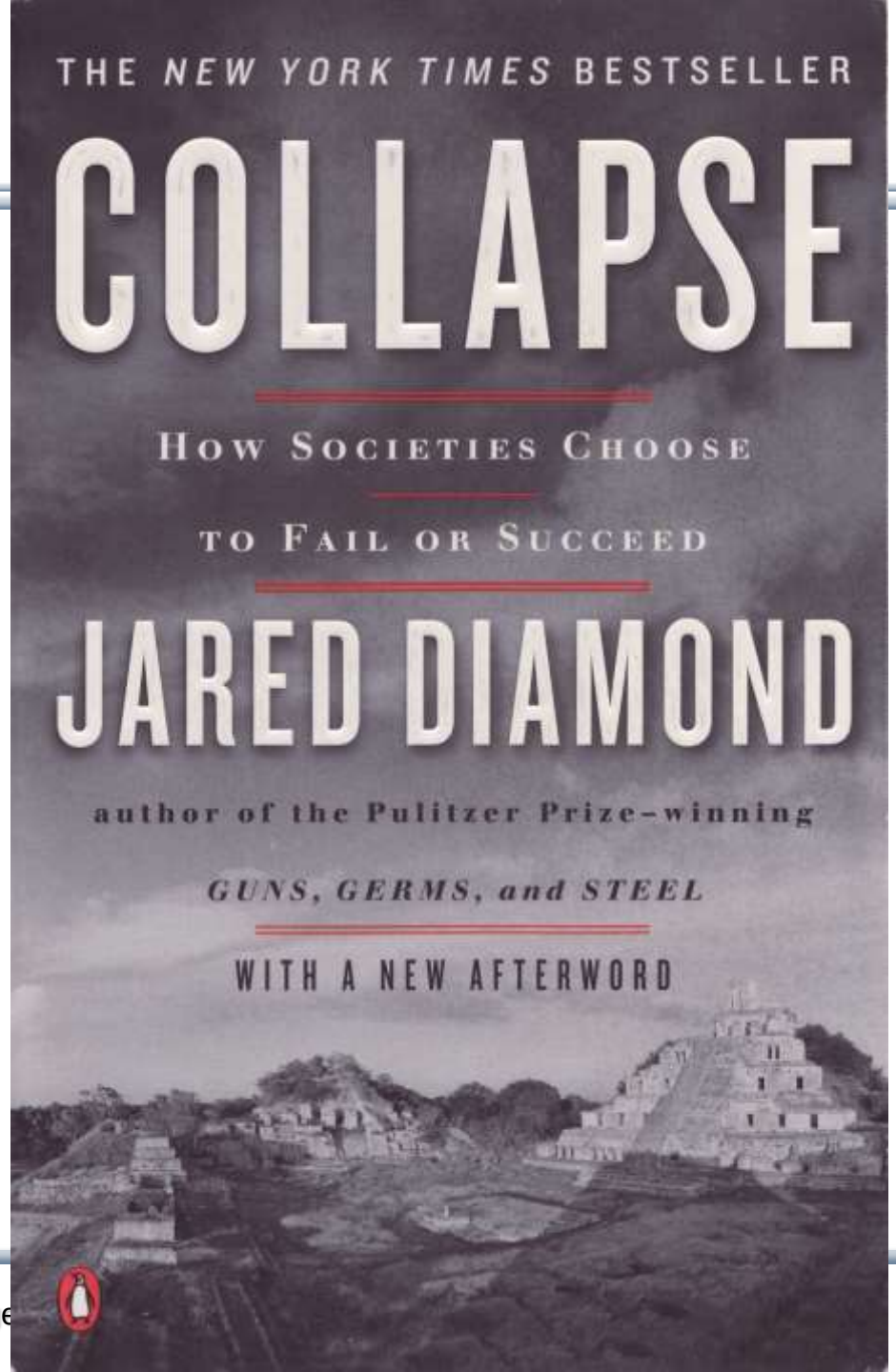
vs

Bacteria on a **finite substrate**



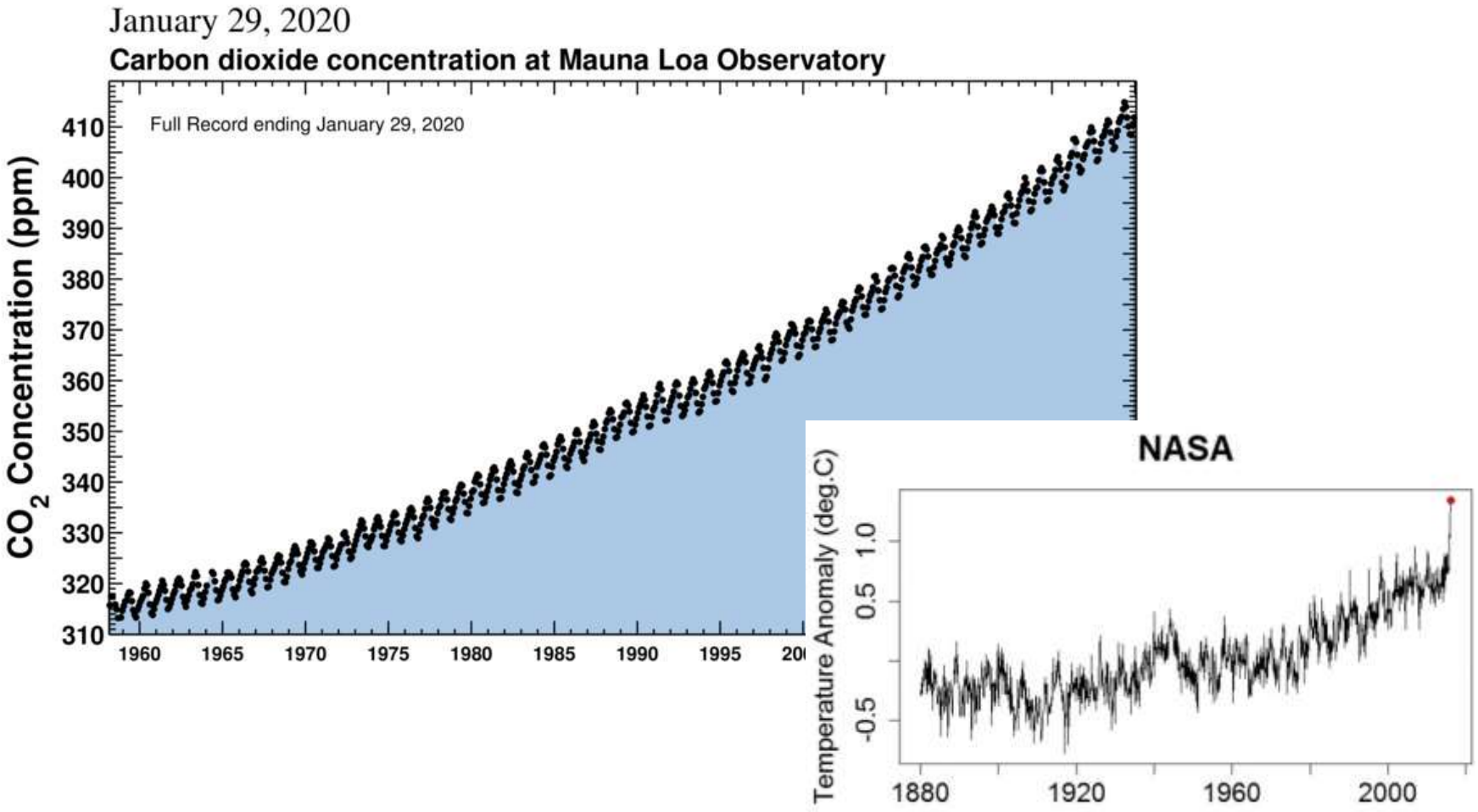
Bacterial growth curve /kinetic curve (Wikipedia)


LIMITS TO GROWTH
The 30-Year Update
DONELLA MEADOWS | JORGEN RANDERS | DENNIS MEADOWS

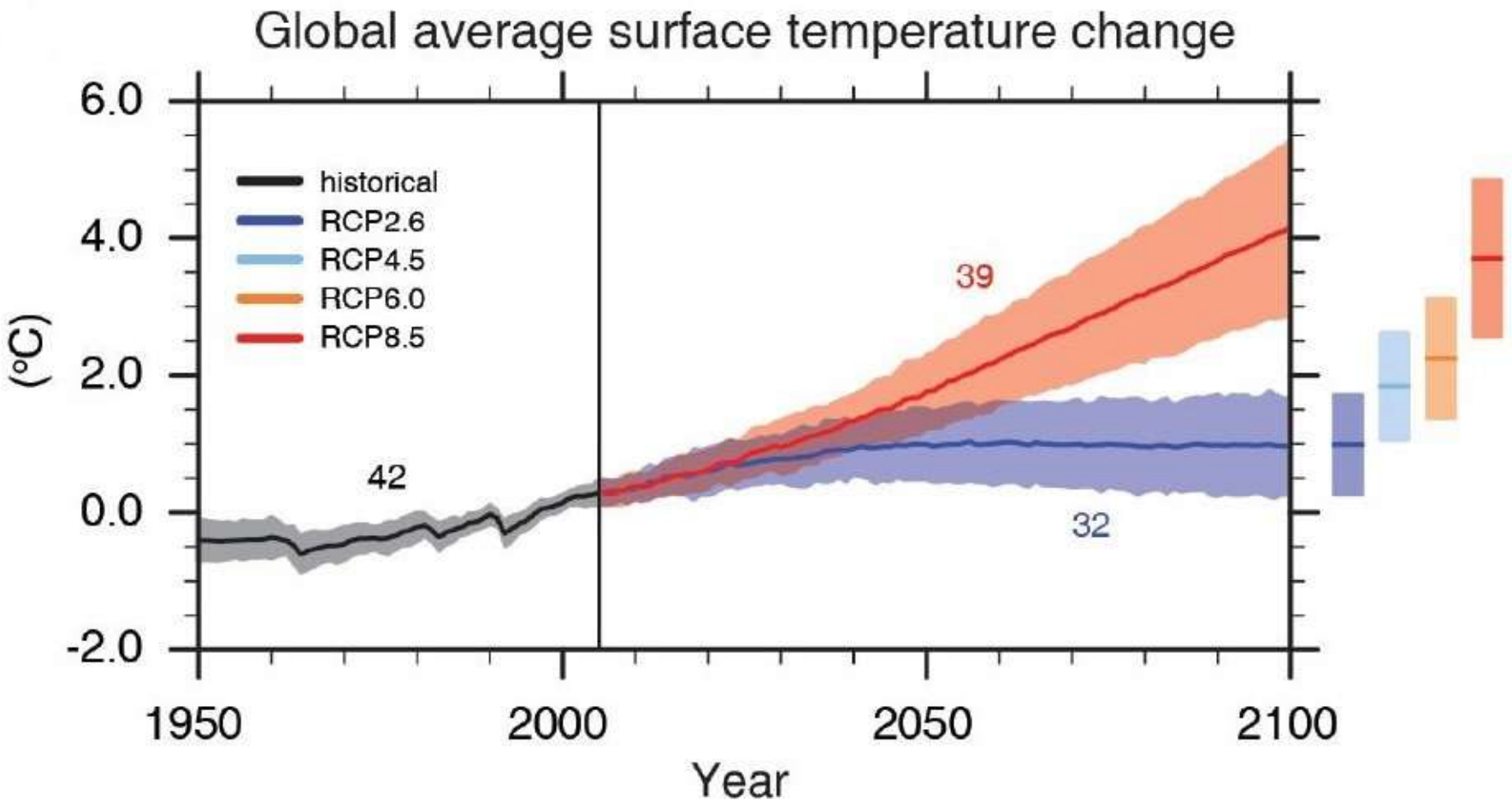

THE NEW YORK TIMES BESTSELLER
COLLAPSE
HOW SOCIETIES CHOOSE
TO FAIL OR SUCCEED
JARED DIAMOND
author of the Pulitzer Prize–winning
GUNS, GERMS, and STEEL
WITH A NEW AFTERWORD

The Keeling Curve on CO2 Concentrations until 2020

Temperatures 1880 - 2016

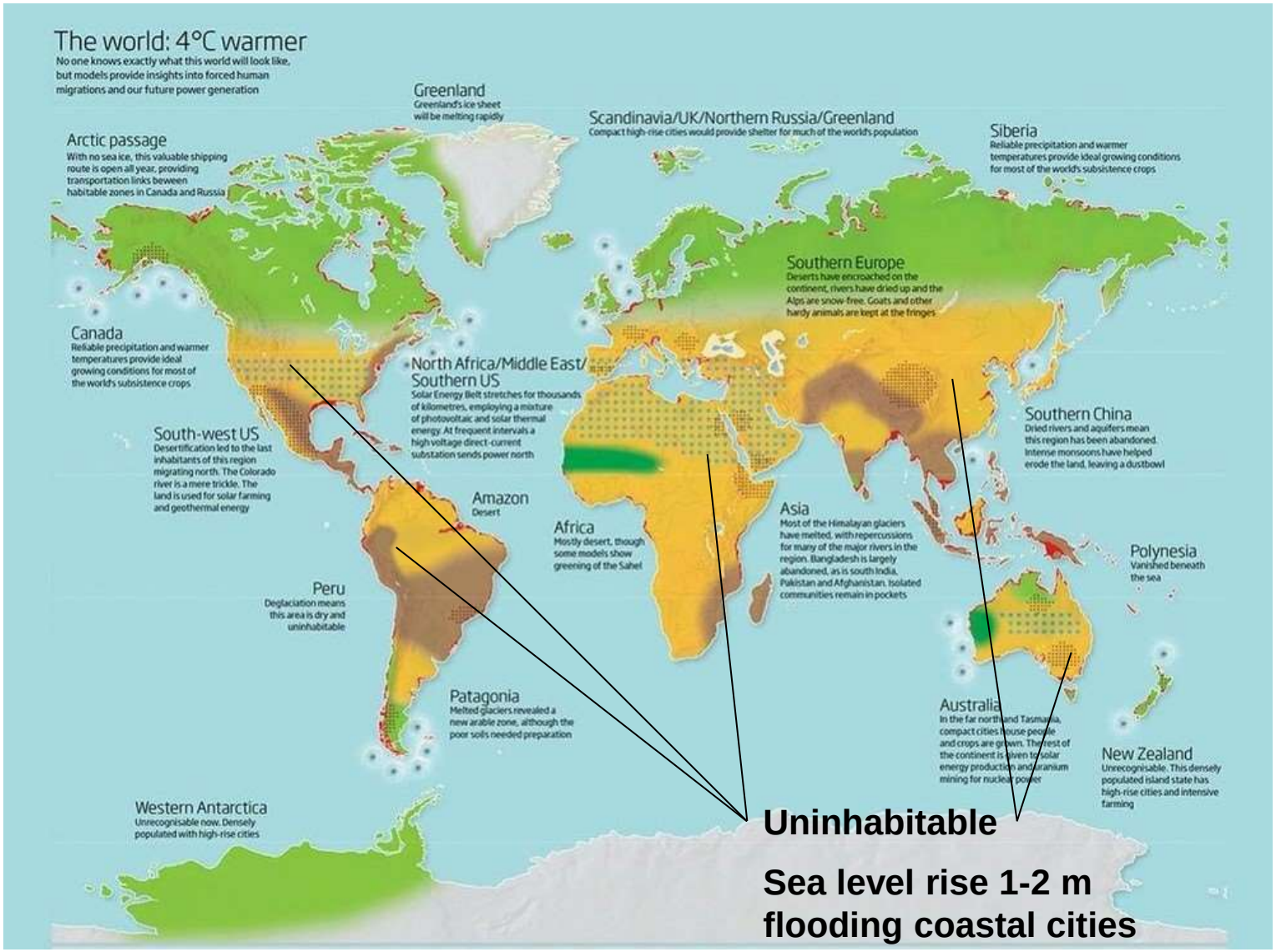


Global Temperature Rise Scenarios (IPCC 2013)



How the world could be in 80-100 years at a global warming of 4 degrees

Business-as-usual scenario, IPCC



- Cities, agriculture
- Uninhabitable desert
- Uninhabitable due to extreme weather
- Flooded

Massive migration to to northern Europe, Russia, and Canada

Example Emissions CO2e / person
- Earth can handle 2 ton/yr
- Flight Spain – 1 ton
- Flight Canaryisl – 2 ton
- Flight Thailand – 4 ton

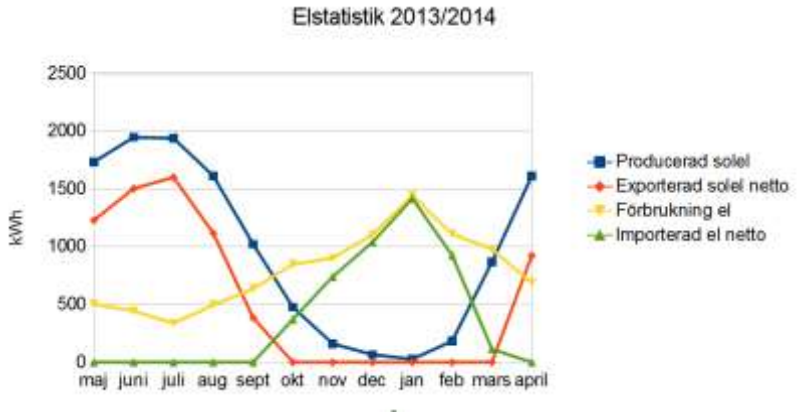
References

New Scientist, 28 february 2009
IPCC, business as usual scenario
www.climate-lab-book.ac.uk
www.atmosfair.de

What Can You Do?
Need Global Sustainability Mass Movement

- Develop smart Cyber-Physical systems for reduced energy and material footprint
- Model-based circular economy for re-use of products and materials
- Promote sustainable lifestyle and technology
- Install electric solar PV panels
- Buy shares in cooperative wind power

20 sqm solar panels on garage roof, Nov 2012
Generated 2700 W at noon March 10, 2013



Expanded to 93 sqm, 12 kW, March 2013
House produced 11600 kwh, used 9500 kwh
Avoids 10 ton CO_2 emission per year

Example Electric Cars

Can be charged by electricity from own solar panels

Renault ZOE; 5 seat; Range:
22kwh (2014) vs 51 kwh battery (2019)

- **Realistic Swedish drive cycle:**
- **Summer: 160 km, 2019 385 km**
- **Winter: 110 km, 2019 290 km**

2018, Tesla Model 3 LR, range 560 km

DLR ROboMObil

- **experimental electric car**
- **Modelica models**

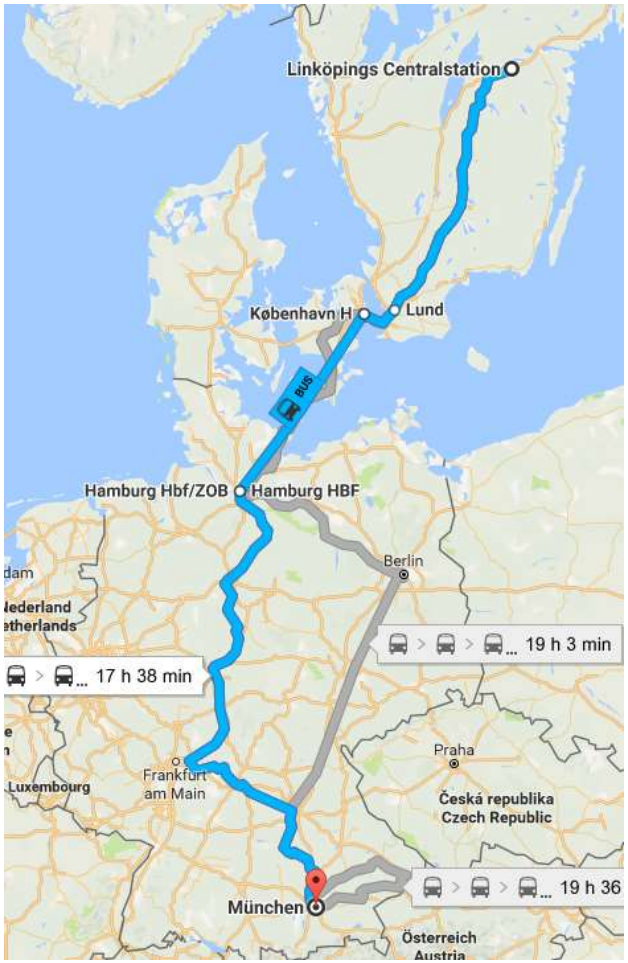
2020, Volvo XC40 recharge, range 400 km

What Can You Do?
More Train Travel – Less Air Travel

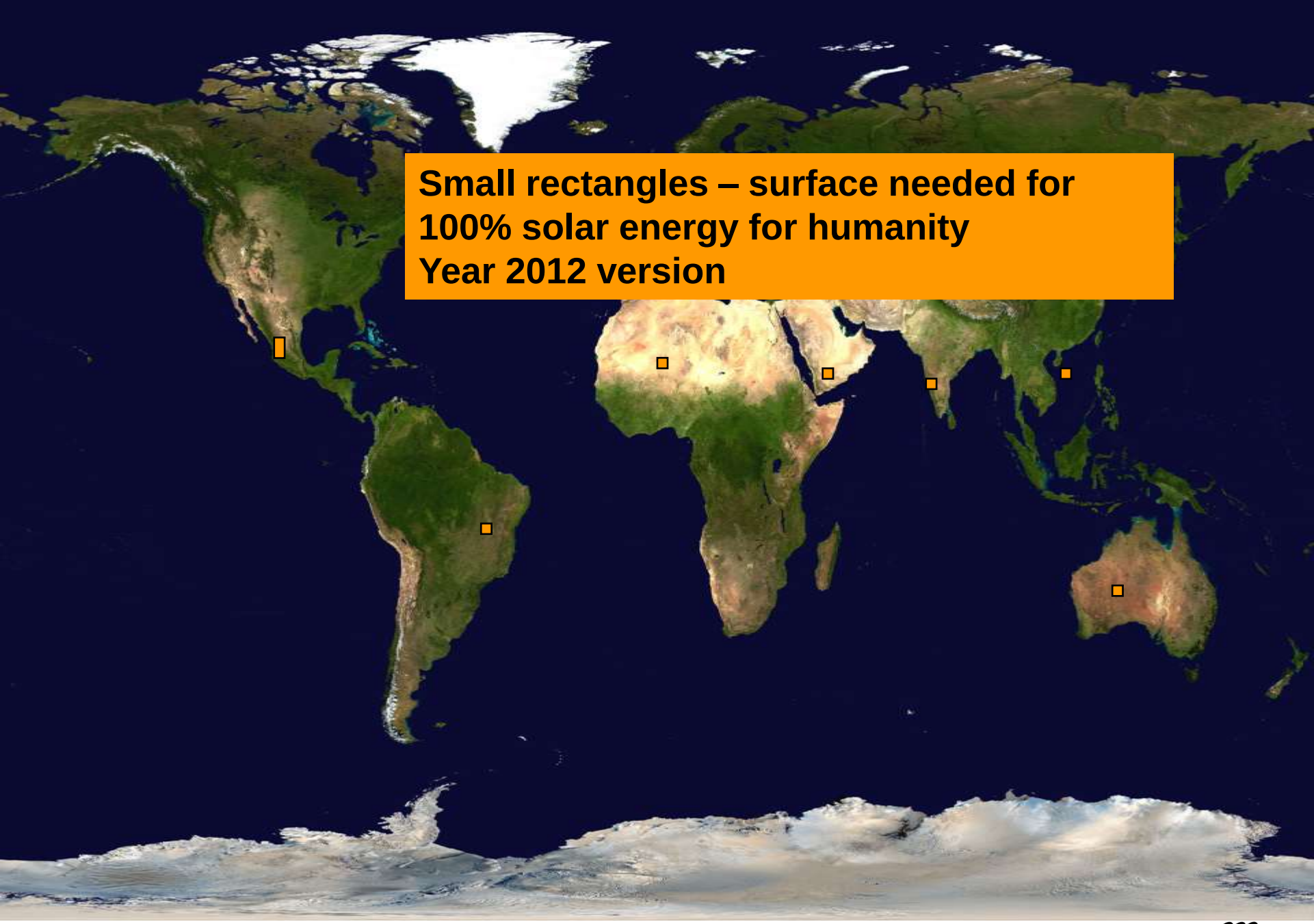
- Air travel by Swedish Citizens – about the same emissions as all personal car traffic in Sweden!
- By train from Linköping to Munich and back – saves almost 1 ton of CO2e emissions compared to flight
- Leave Linköping 07.00 in Munich 23.14

More Examples, PF travel 2016:

- Train Linköping-Paris, Dec 3-6, EU project meeting
- Train Linköping-Dresden, Dec 10-16, 1 week workshop

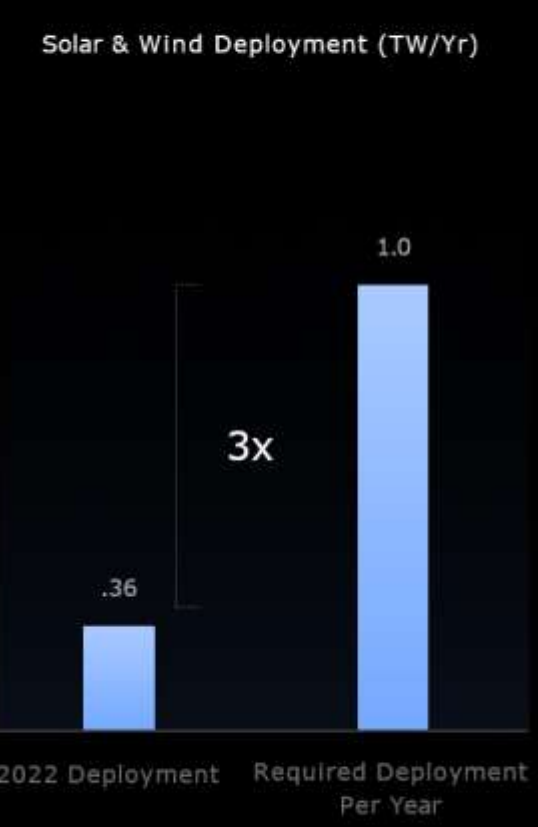


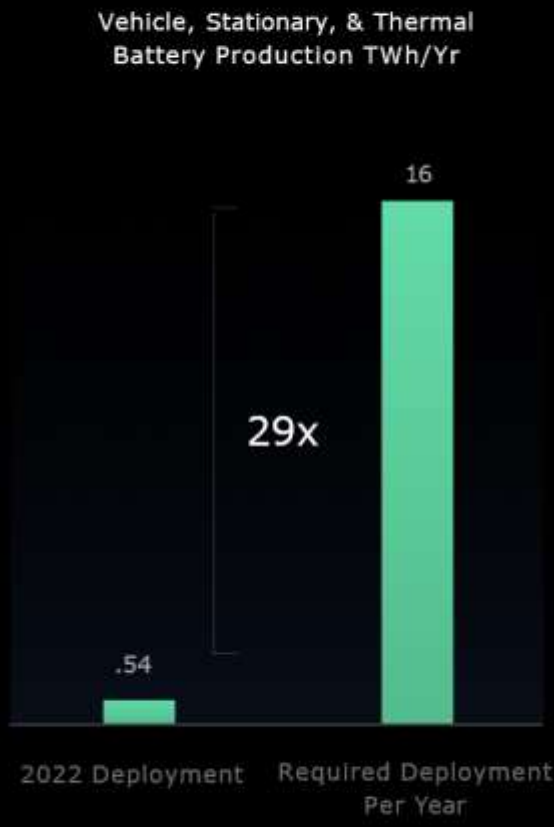
Train travel Linköping - Munich

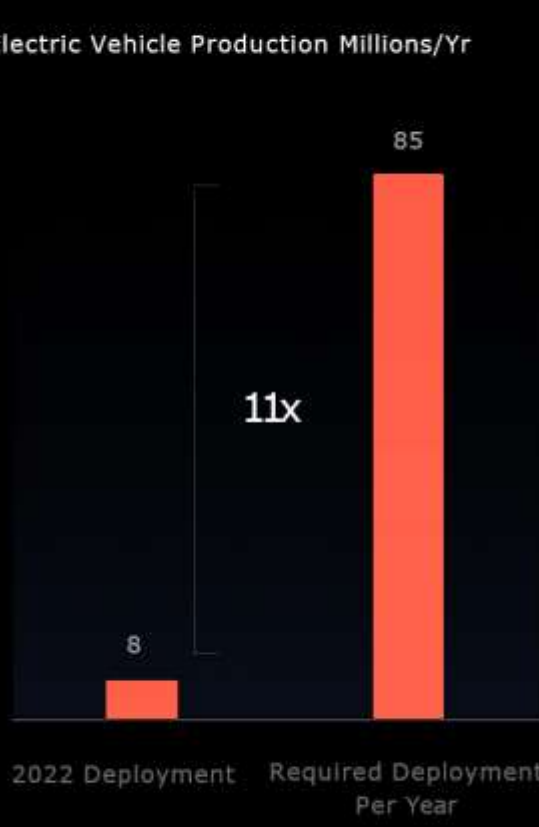


More Than Enough Renewable Resources Available (Tesla Master Plan, Investor days, March 1, 2023)

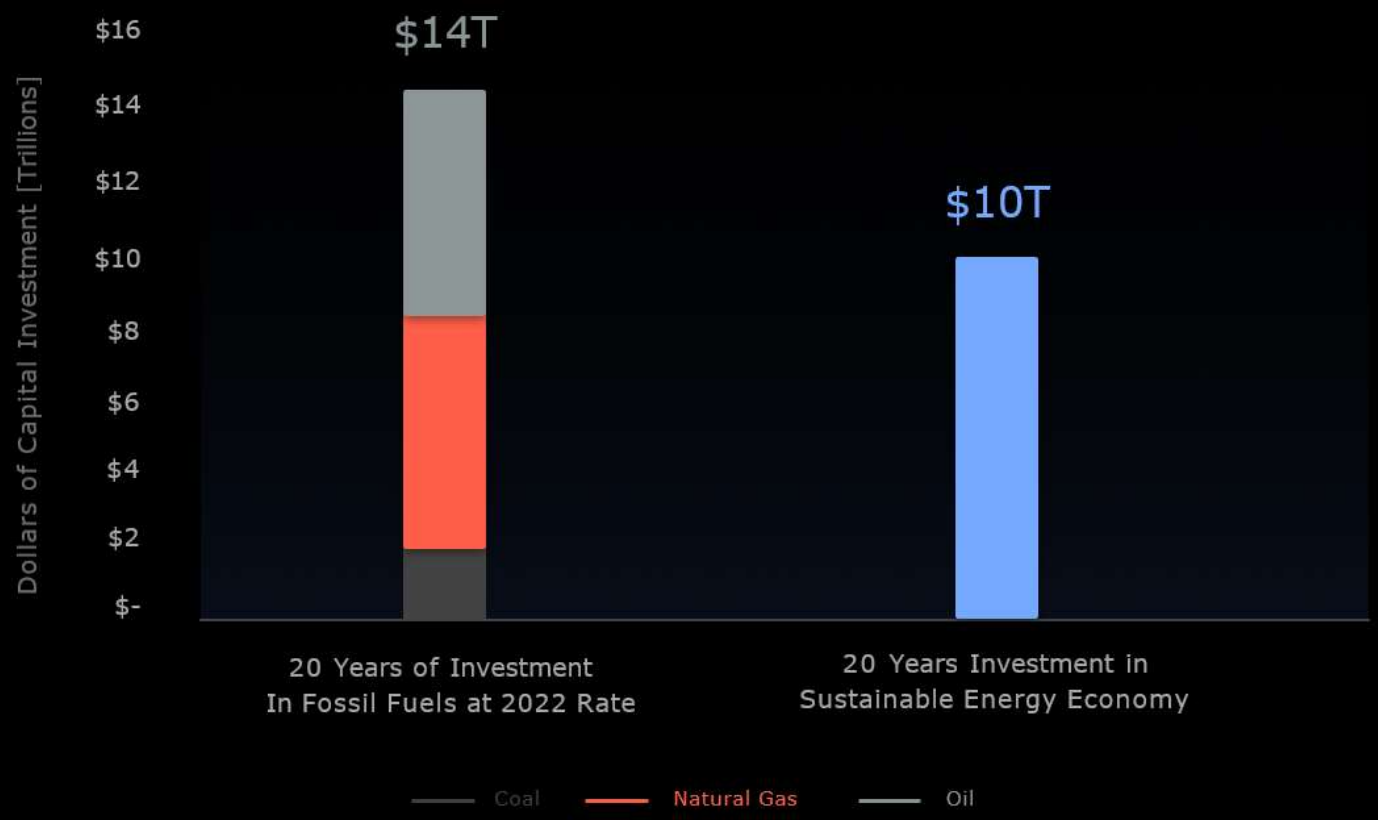
If We Grow our Production Capacity as Shown by 2030 We Can Be 100% Sustainable by 2050







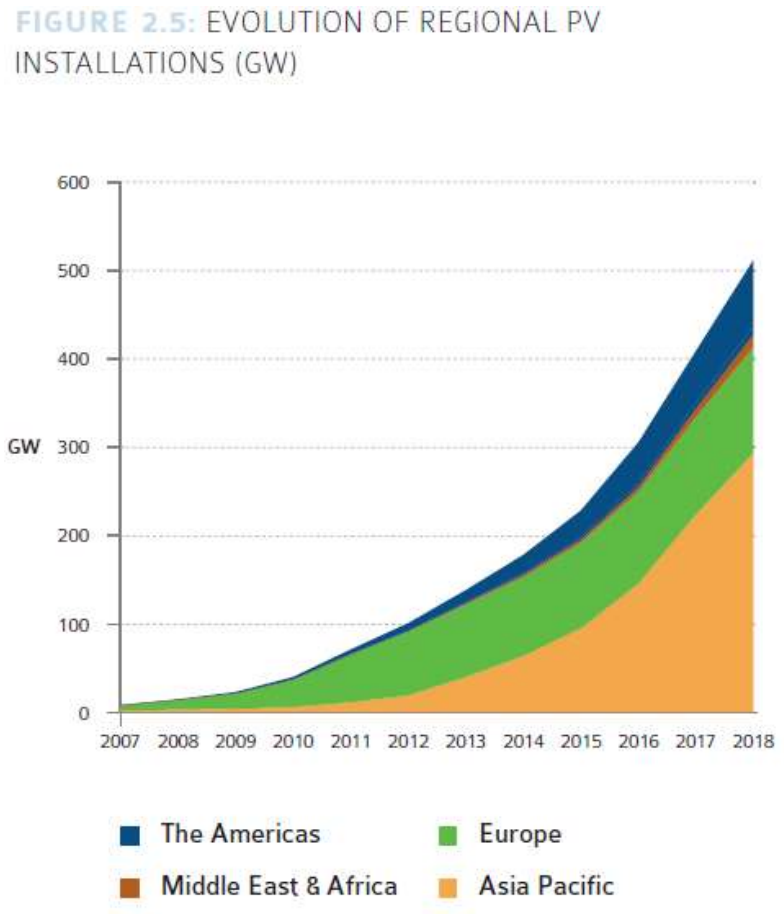
A Sustainable Energy Economy Is 60% The Cost of Continuing Fossil Fuel Investments

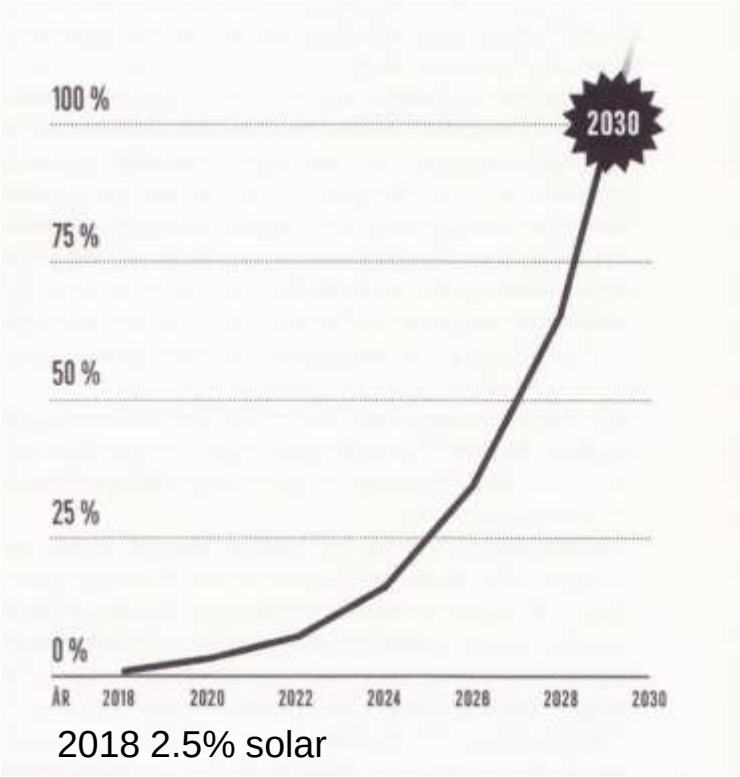


Solar Energy PhotoVoltaics Growth Trends

Almost Exponential worldwide Growth of Photovoltaics 2006 – 2018

IEA PVPS TRENDS IN PHOTOVOLTAIC APPLICATIONS 2019





2018 2.5% solar

100% of global electricity production year 2030 if strong exponential growth continues

Sustainable Society Necessary for Human Survival

Almost Sustainable

- India, recently 1.4 ton C02/person/year
- Healthy vegetarian food
- Small-scale agriculture
- Small-scale shops
- Simpler life-style (Mahatma Gandhi)

Non-sustainable

- USA 17 ton CO2, Sweden 7 ton CO2/yr
- High meat consumption (1 kg beef uses ca 4000 L water for production)
- Hamburgers, unhealthy , includes beef
- Energy-consuming mechanized agriculture
- Transport dependent shopping centres
- Stressful materialistic lifestyle

Gandhi – role model for future less materialistic life style

Brief Modelica History

- First Modelica design group meeting in fall 1996
  - International group of people with expert knowledge in both language design and physical modeling
  - Industry and academia
- Modelica Versions
  - 1.0 released September 1997
  - 2.0 released March 2002
  - 2.2 released March 2005
  - 3.0 released September 2007
  - 3.1 released May 2009
  - 3.2 released March 2010
  - 3.3 released May 2012
  - 3.2 rev 2 released November 2013
  - 3.3 rev 1 released July 2014
  - 3.4 released April 2017
  - 3.5 released February 2021
- Modelica Association was established in 2000 in Linköping
  - Open, non-profit organization

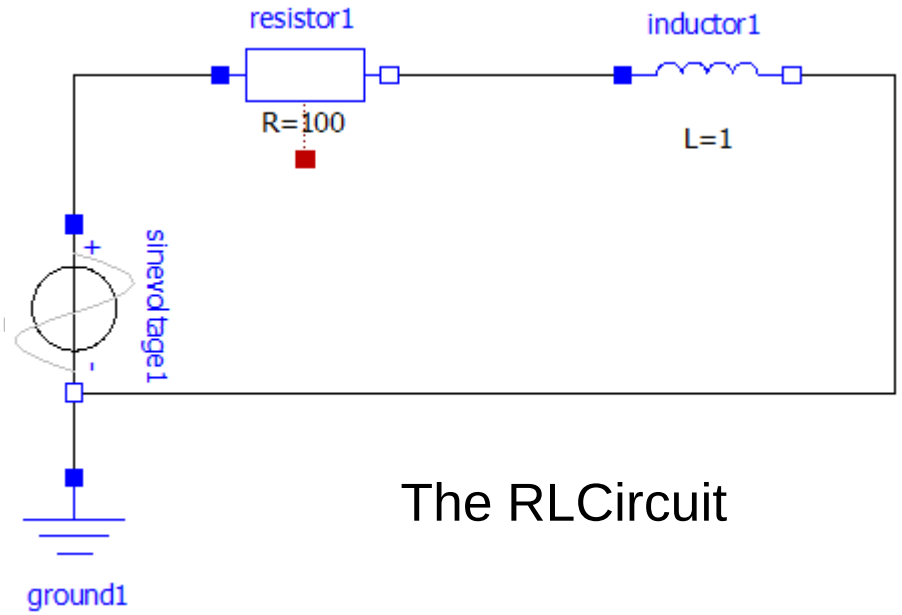
Modelica Conferences

- The 1st International Modelica conference October, 2000
- The 2nd International Modelica conference March 18-19, 2002
- The 3rd International Modelica conference November 5-6, 2003 in Linköping, Sweden
- The 4th International Modelica conference March 6-7, 2005 in Hamburg, Germany
- The 5th International Modelica conference September 4-5, 2006 in Vienna, Austria
- The 6th International Modelica conference March 3-4, 2008 in Bielefeld, Germany
- The 7th International Modelica conference Sept 21-22, 2009 in Como, Italy
- The 8th International Modelica conference March 20-22, 2011 in Dresden, Germany
- The 9th International Modelica conference Sept 3-5, 2012 in Munich, Germany
- The 10th International Modelica conference March 10-12, 2014 in Lund, Sweden
- The 11th International Modelica conference Sept 21-23, 2015 in Versailles, Paris
- The 12th International Modelica conference May 15-17, 2017 in Prague, Czech Rep
- The 13th International Modelica conference March 4-6, 2019, Regensburg, Germany
- The 14th International Modelica conference Sept 20-24, 2021, Linköping, Sweden
- Also: Asian Modelica conferences 2016, 2017, 2018, 2020, 2022
- Also: US Modelica conference 2018, 2020, 2022

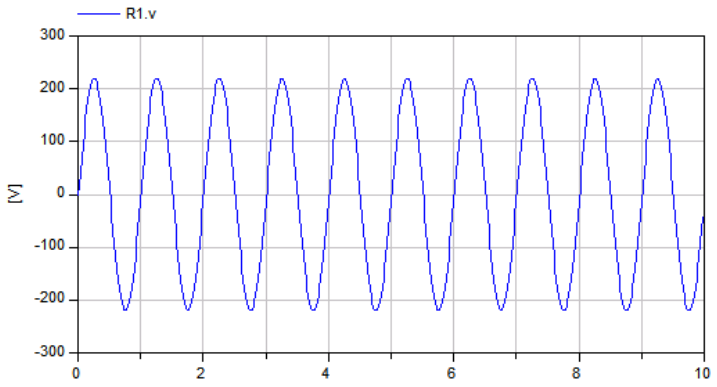
Exercises Part I
Hands-on graphical modeling
(15 minutes)

Exercises Part I – Basic Graphical Modeling

- (*See instructions on next two pages*)
- Start the OMEdit editor (part of OpenModelica)
- Draw the RLCircuit
- Simulate



The RLCircuit



Simulation

Exercises Part I – OMEdit Instructions (Part I)

- Start OMEdit from the Program menu under OpenModelica
- Go to **File** menu and choose **New**, and then select **Model**.
- E.g. write *RLCircuit* as the model name.
- For more information on how to use OMEdit, go to **Help** and choose **User Manual** or press **F1**.

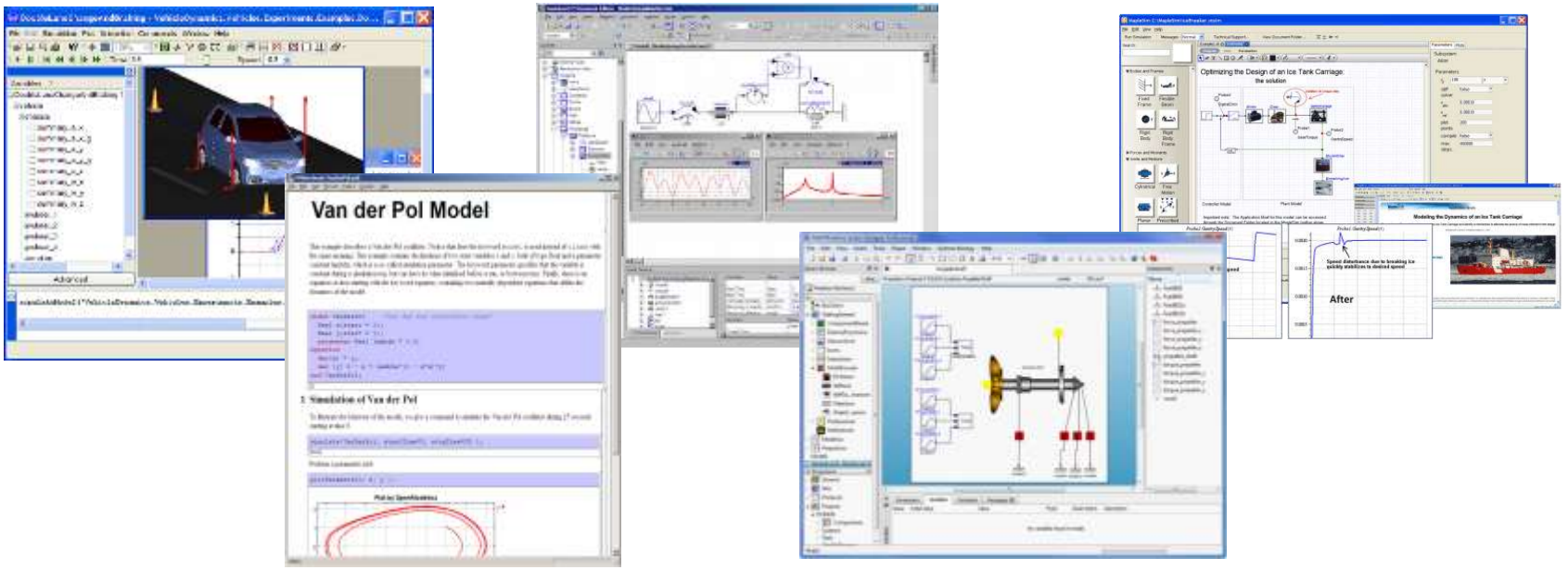
- Under the **Modelica Library:**
  - Contains The standard Modelica library components
  - The **Modelica files** contains the list of models you have created.

Exercises Part I – OMEdit Instructions (Part II)

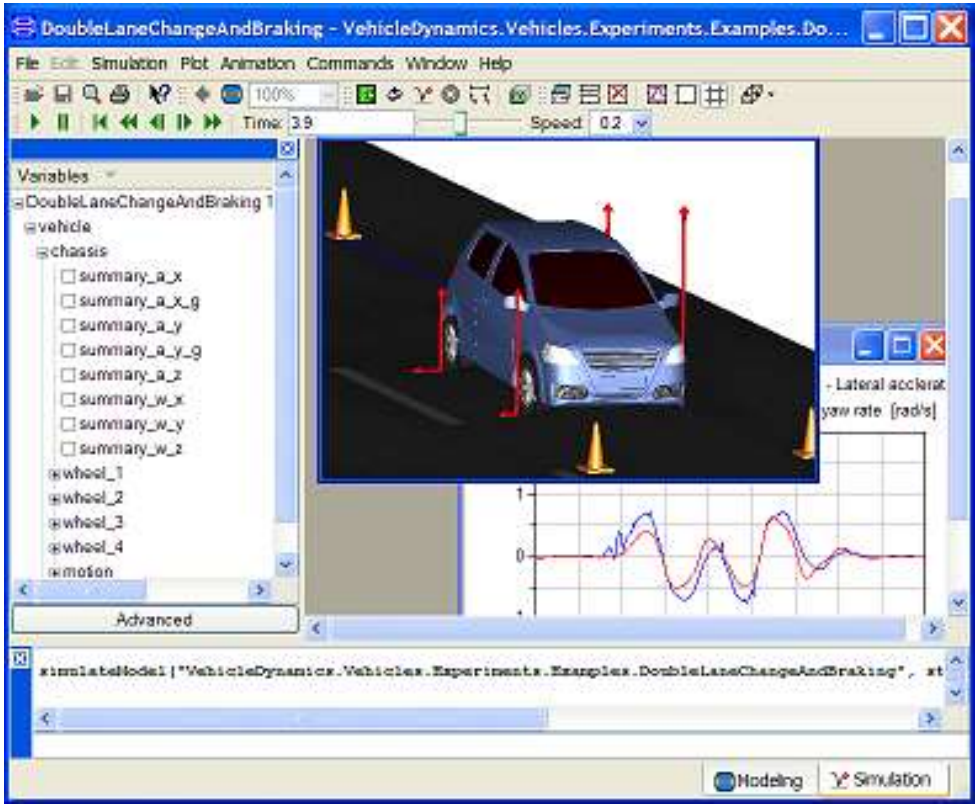
- For the RLCircuit model, **browse** the Modelica standard library and **add** the following component models:
  - Add `Ground`, `Inductor` and `Resistor` component models from Modelica.Electrical.Analog.Basic package.
  - Add SineVoltage component model from Modelica.Electrical.Analog.Sources package.
- Make the corresponding **connections** between the component models as shown in the previous slide.
- To **draw a connection line**: first single-click on a connector box; then start drawing while keeping the mouse button down; after drawing a little you can release the mouse button and continue drawing.
- **Simulate** the model
  - Go to the Simulation menu and choose simulate or click on the simulate button  in the toolbar.
- **Plot** the instance variables
  - Once the simulation is completed, a plot variables list will appear on the right side. Select the variable that you want to plot.

Part II

Modelica environments and OpenModelica

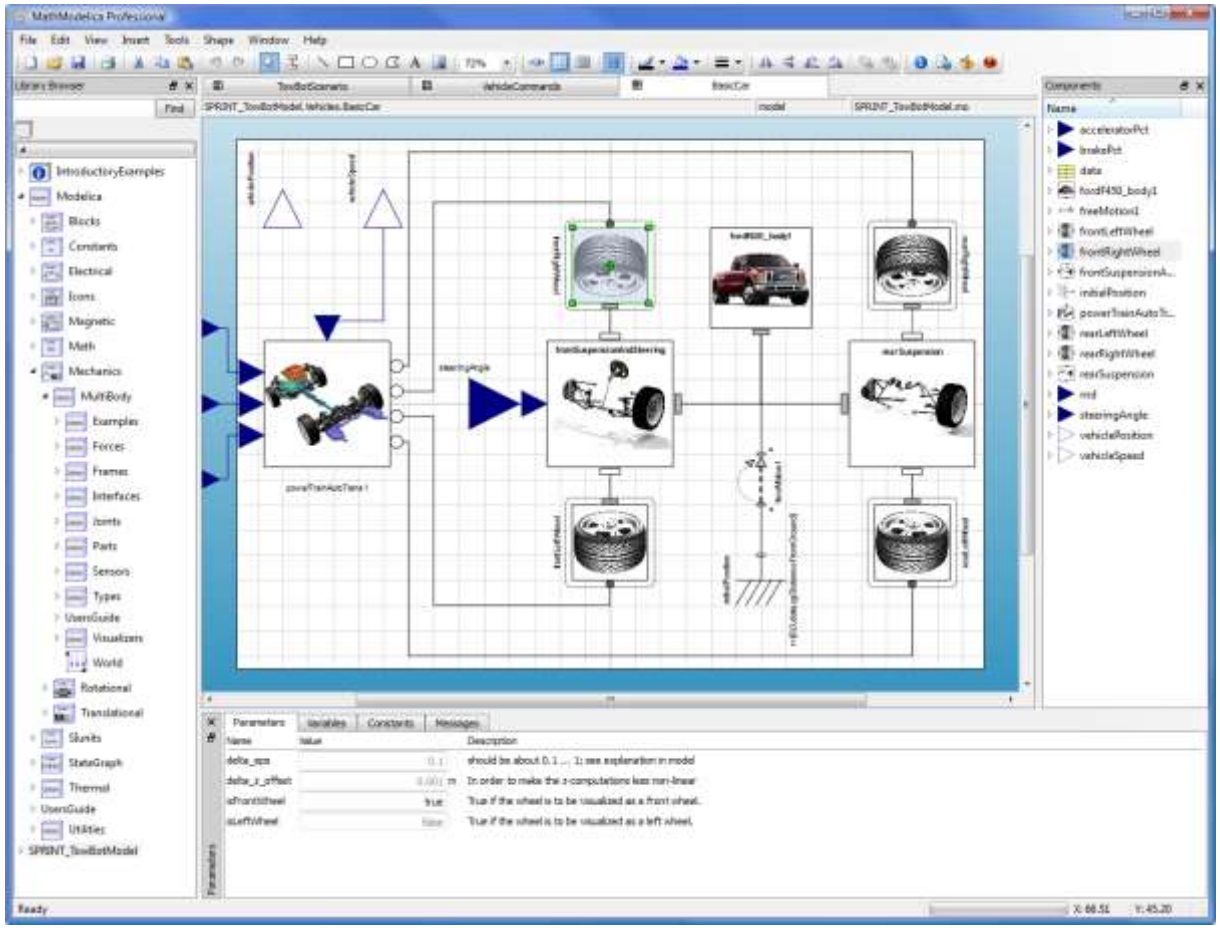


Dymola



- Dassault Systemes Sweden
- Sweden
- First Modelica tool on the market
- Initial main focus on automotive industry
- www.dymola.com

Wolfram System Modeler – Wolfram MathCore

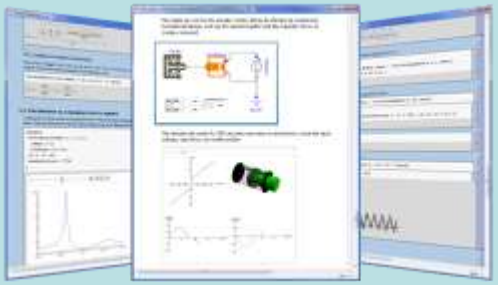


Car model graphical view

Courtesy Wolfram Research

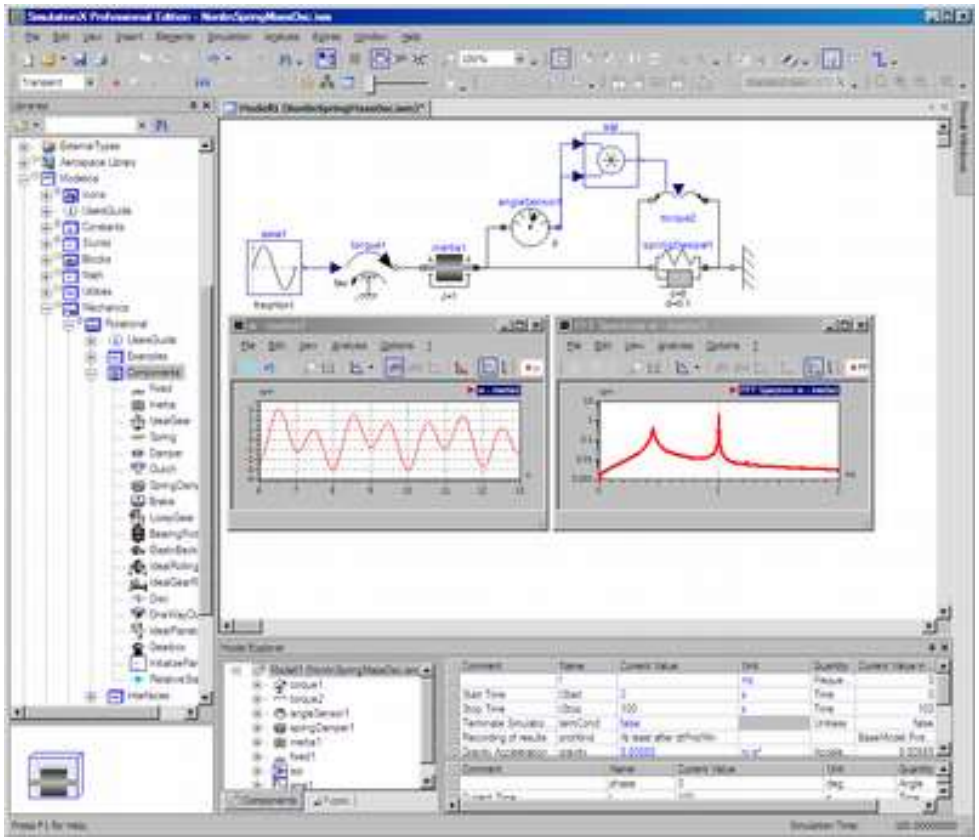
- Wolfram Research
- USA, Sweden
- General purpose
- Mathematica integration
- www.wolfram.com
- www.mathcore.com

Mathematica



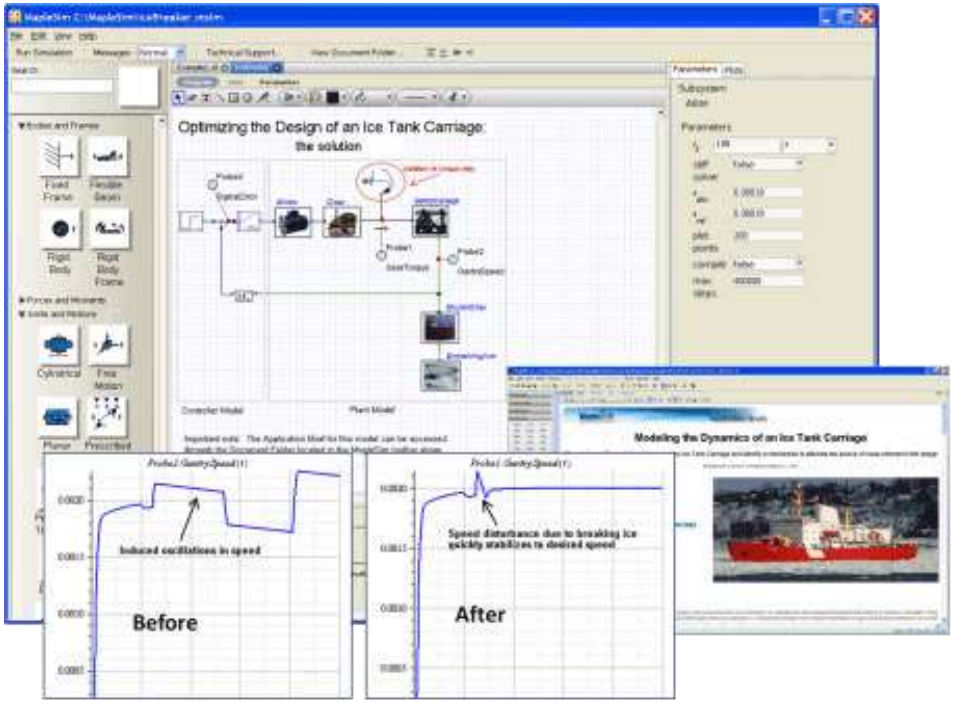
Simulation and analysis

Simulation X



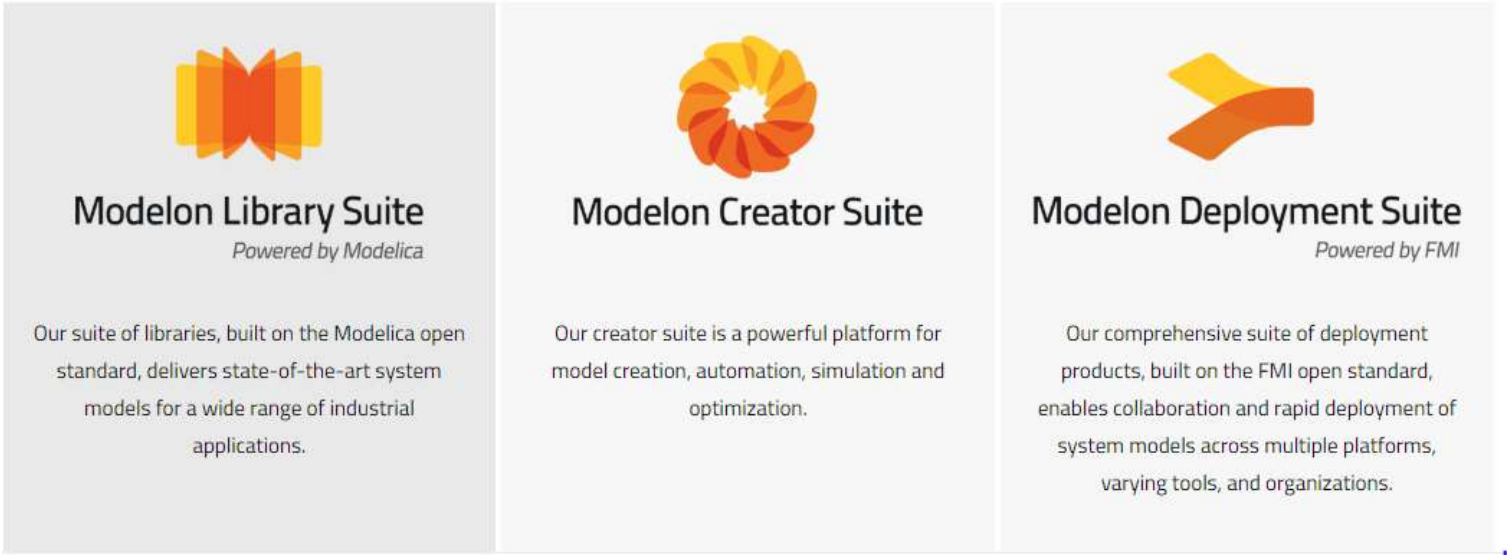
- ITI Gmbh (Part of ESI Group)
- Germany
- Mechatronic systems
- www.simulationx.com

MapleSim



- Maplesoft
- Canada
- Recent Modelica tool on the market
- Integrated with Maple
- www.maplesoft.com

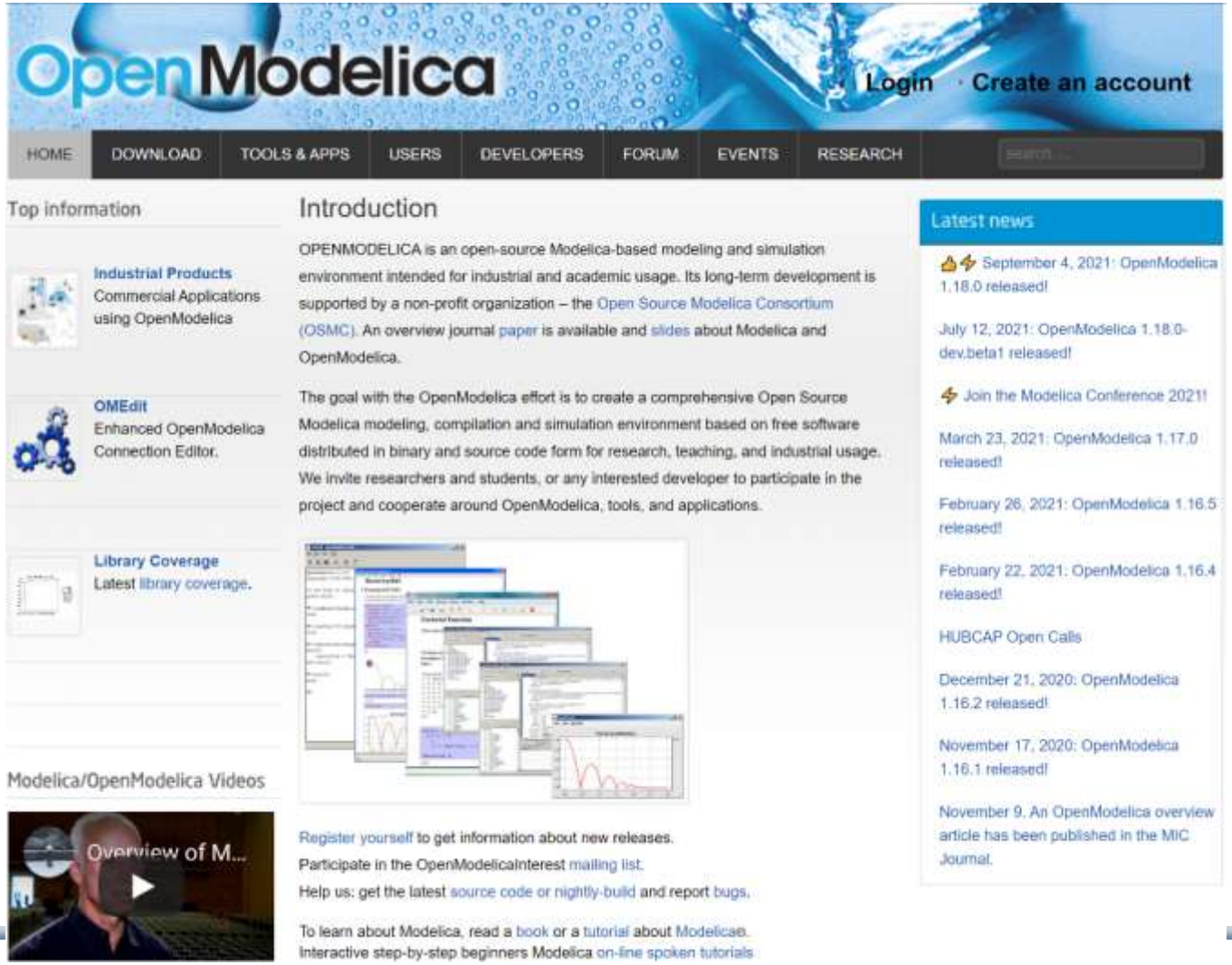
Modelon



- Modelon
- Sweden and International
- Library Suite
- Creator Suite with Impact product and Optimica Compiler Toolbox and WAMS model editor
- www.modelon.com

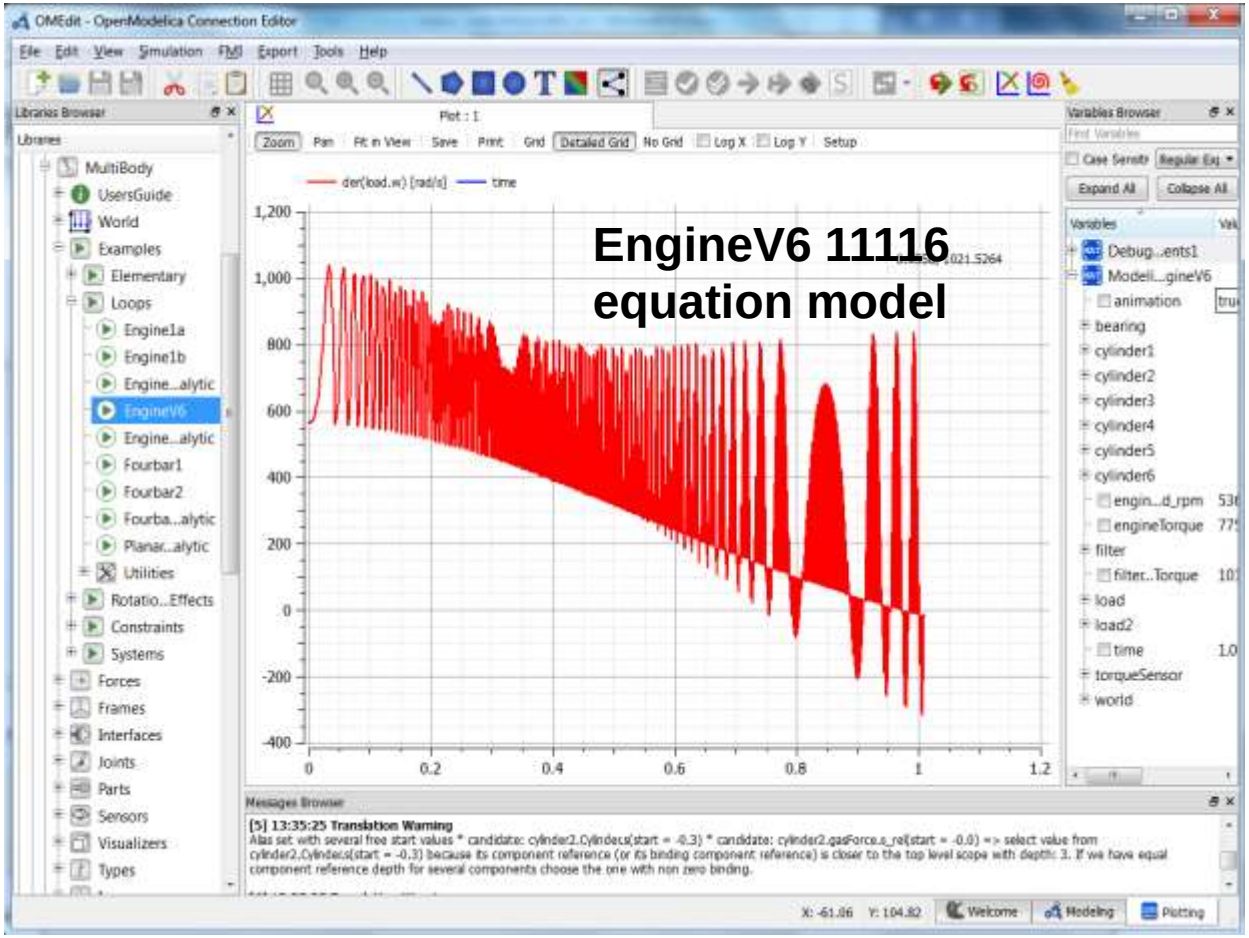
The OpenModelica Environment

www.OpenModelica.org



OpenModelica – Free Open Source Tool
developed by the Open Source Modelica Consortium (OSMC)

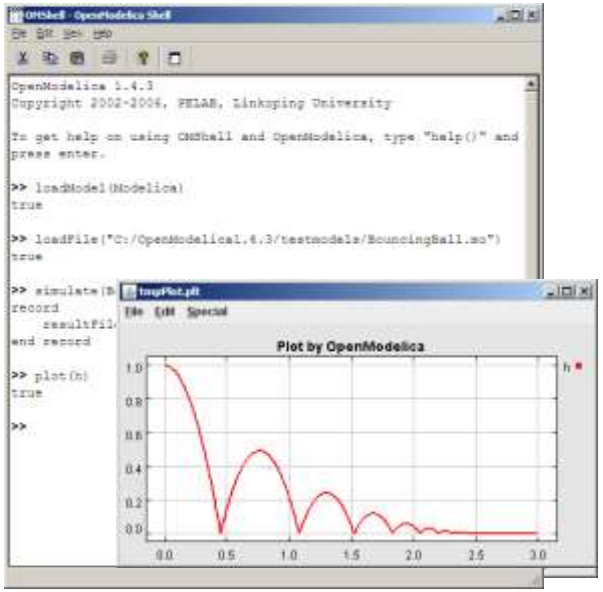
- Graphical editor
- Model compiler and simulator
- Debugger
- Performance analyzer
- Dynamic optimizer
- Symbolic modeling
- Parallelization
- Electronic Notebook and OMWebbook for teaching
- Spokentutorial for teaching

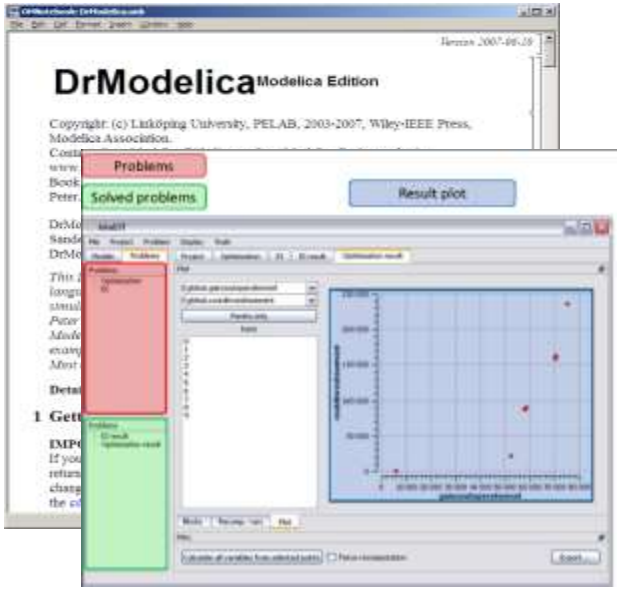


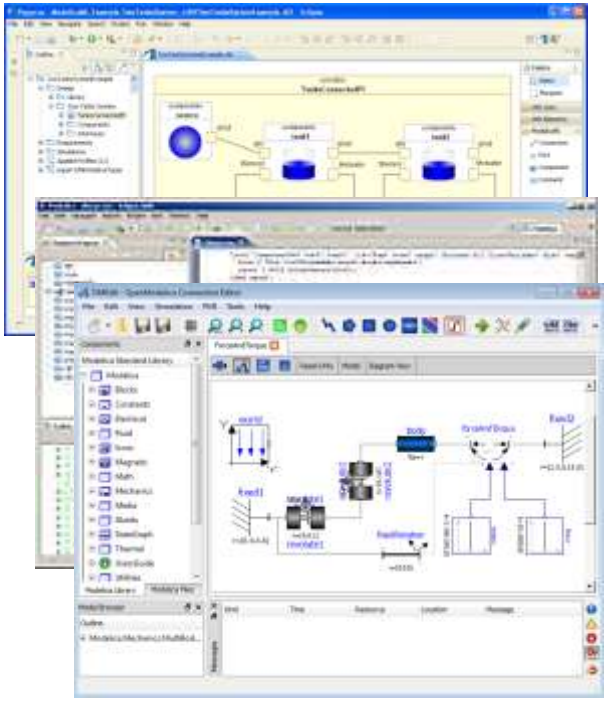
The OpenModelica Open Source Environment
www.openmodelica.org

- Advanced Interactive Modelica compiler (OMC)
  - Supports most of the Modelica Language
  - **Modelica**, **Python, Julia, Matlab scripting**
- OMSimulator – FMI Simulation/Co-simulation
- Basic environment for creating models
  - **OMShell** – an interactive command handler
  - **OMNotebook** – a literate programming notebook
  - **MDT** – an advanced textual environment in Eclipse

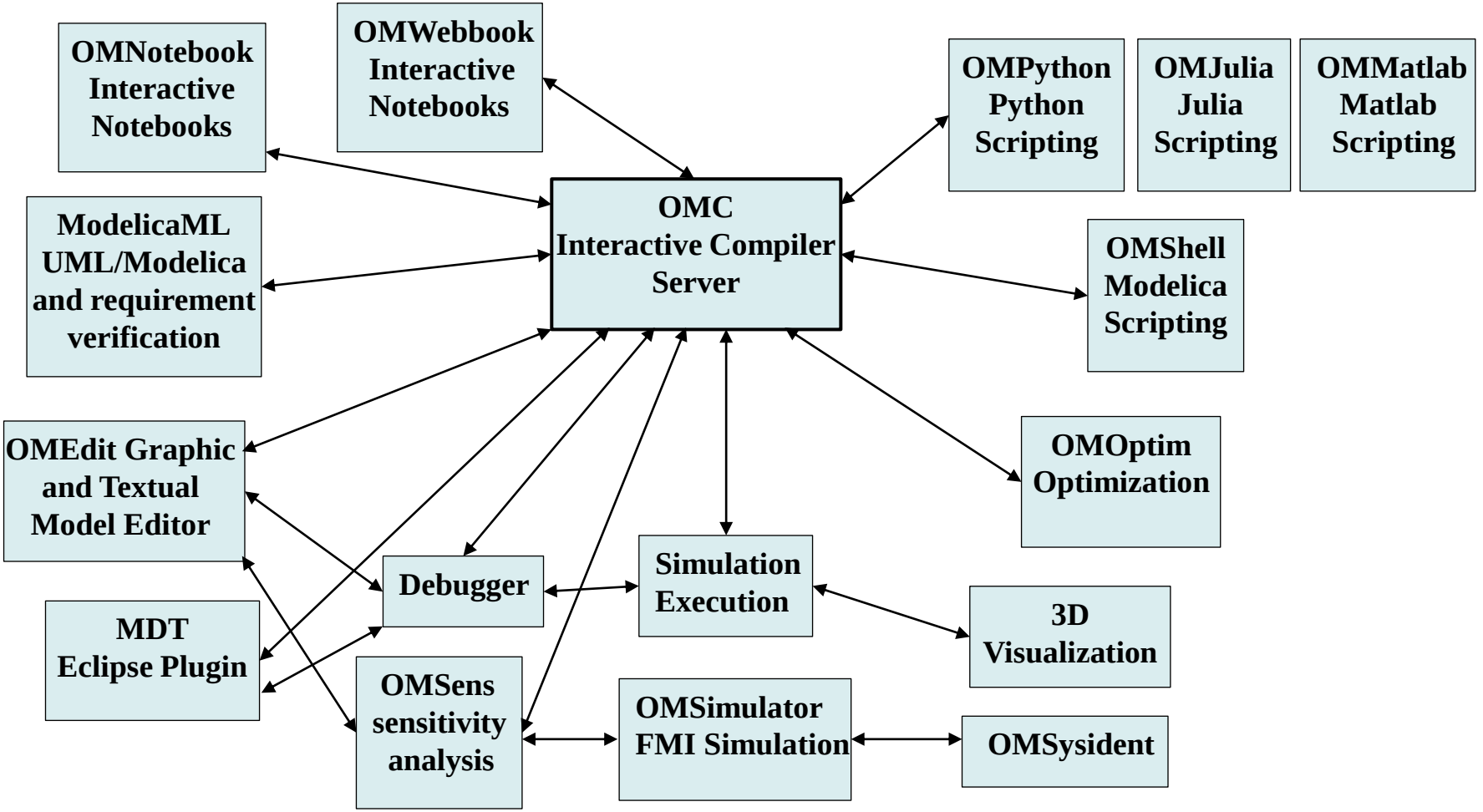
- **OMEdit** graphic Editor
- **OMDebugger** for equations
- **OMOptim** optimization tool
- **OM Dynamic optimizer** collocation
- **ModelicaML** UML Profile
- **MetaModelica** extension
- **ParModelica** extension







The OpenModelica Tool Architecture



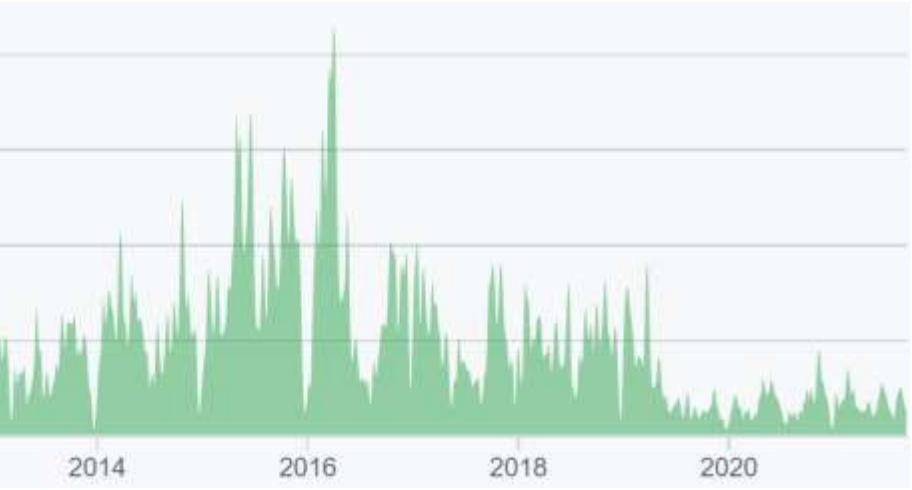
OSMC – International Consortium for Open Source Model-based Development Tools, 53 members Feb 2023

Founded Dec 4, 2007

Open-source community services

- **Website and Support Forum**
- **Version-controlled source base**
- **Bug database**
- **Development courses**
- **www.openmodelica.org**

Commits Statistics



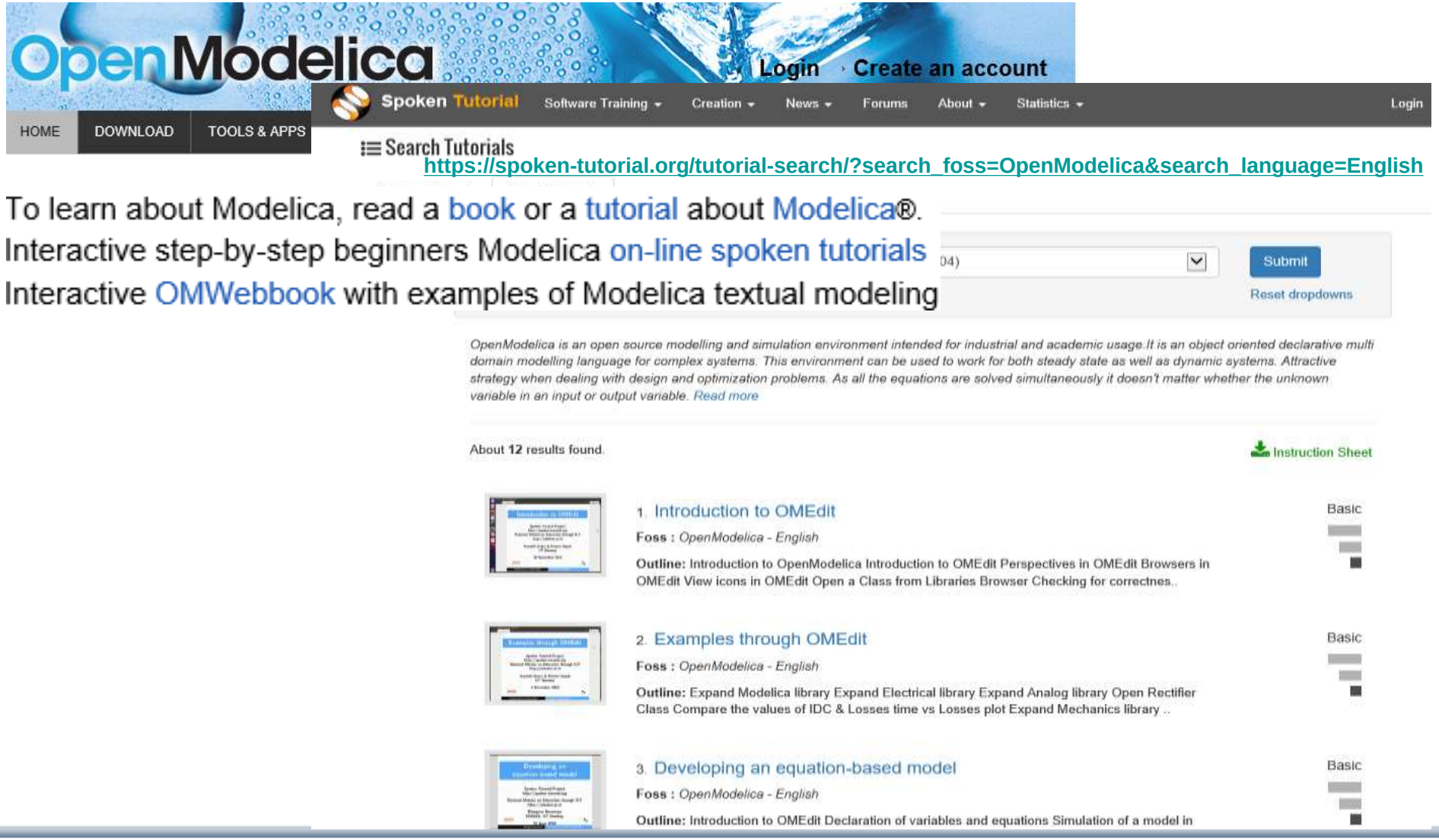
Industrial members

- ABB AB, Sweden
- Bosch Rexroth AG, Germany
- Creative Connections, Prague
- DHI, Aarhus, Denmark
- Dynamica s.r.l., Cremaona, Italy
- EDF, Paris, France
- Equa Simulation AB, Sweden
- Fraunhofer IWES, Bremerhaven
- Fraunhofer FCC, Gthenburg
- INRIA, Rennes, France
- ISID Dentsu, Tokyo, Japan
- Modelicon LLP, Bangalore, India
- JSOL Company, Japan
- Shanghai Duanyan Inf Tech China
- Perpetual Labs, London, UK
- Juelich, FZI, Germany
- Maplesoft, Canada
- Metroscope, France
- REUSE company, Spain
- RTE France, Paris, France
- Saab AB, Linköping, Sweden
- SmartFluidPower, Italy,
- TLK Thermo, Germany
- Sozhou Tongyuan, China
- SRON Space Ins Netherlands
- Talent Swarm, Spain
- Volvo Cars, Sweden
- VTI, Linköping, Sweden
- XRG Simulation, Germany

University members

- Augsburg University, Germany
- Australian Nation Univ., Australia
- FH Bielefeld, Bielefeld, Germany
- University of Bolivar, Colombia
- TU Braunschweig, Germany
- Univ of Buenos Aires, Argentina
- Univ Catalunya, Spain
- Chalmers Univ, Control,Sweden
- Chalmers Univ, Machine, Sweden
- TU Darmstadt, Germany
- TU Delft, The Netherlands
- TU Dresden, Germany
- Université Laval, Canada
- TU Hamburg/Harburg Germany
- KU Leuven, Leuven, Belgium
- Univ Linnaeus, Sweden
- IIT Bombay, Mumbai, India
- Linneaus University, Sweden
- Linköping University, Sweden
- Univ of Maryland, Syst Eng USA
- Univ of Maryland, CEEE, USA
- Politecnico di Milano, Italy
- Politecnica Catalunya Spain
- Mälardalen University, Sweden
- RPI, Troy, USA
- Univ Pisa, Italy
- Univ College SouthEast Norway
- Vanderbilt Univ, USA

Spoken-Tutorial step-by-step OpenModelica and Modelica Tutorial Using OMEdit. Link from www.openmodelica.org

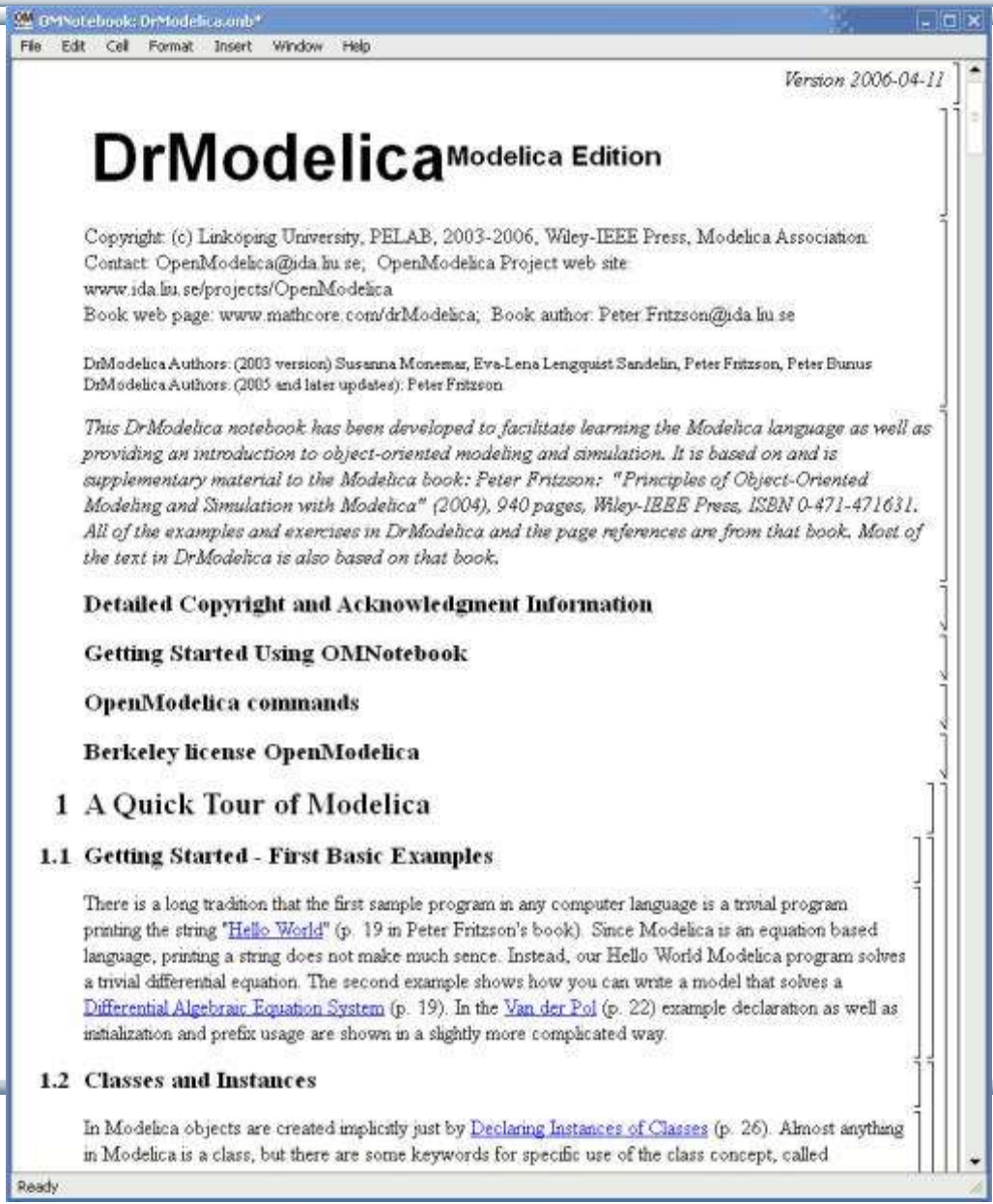


OMNotebook Electronic Notebook with DrModelica

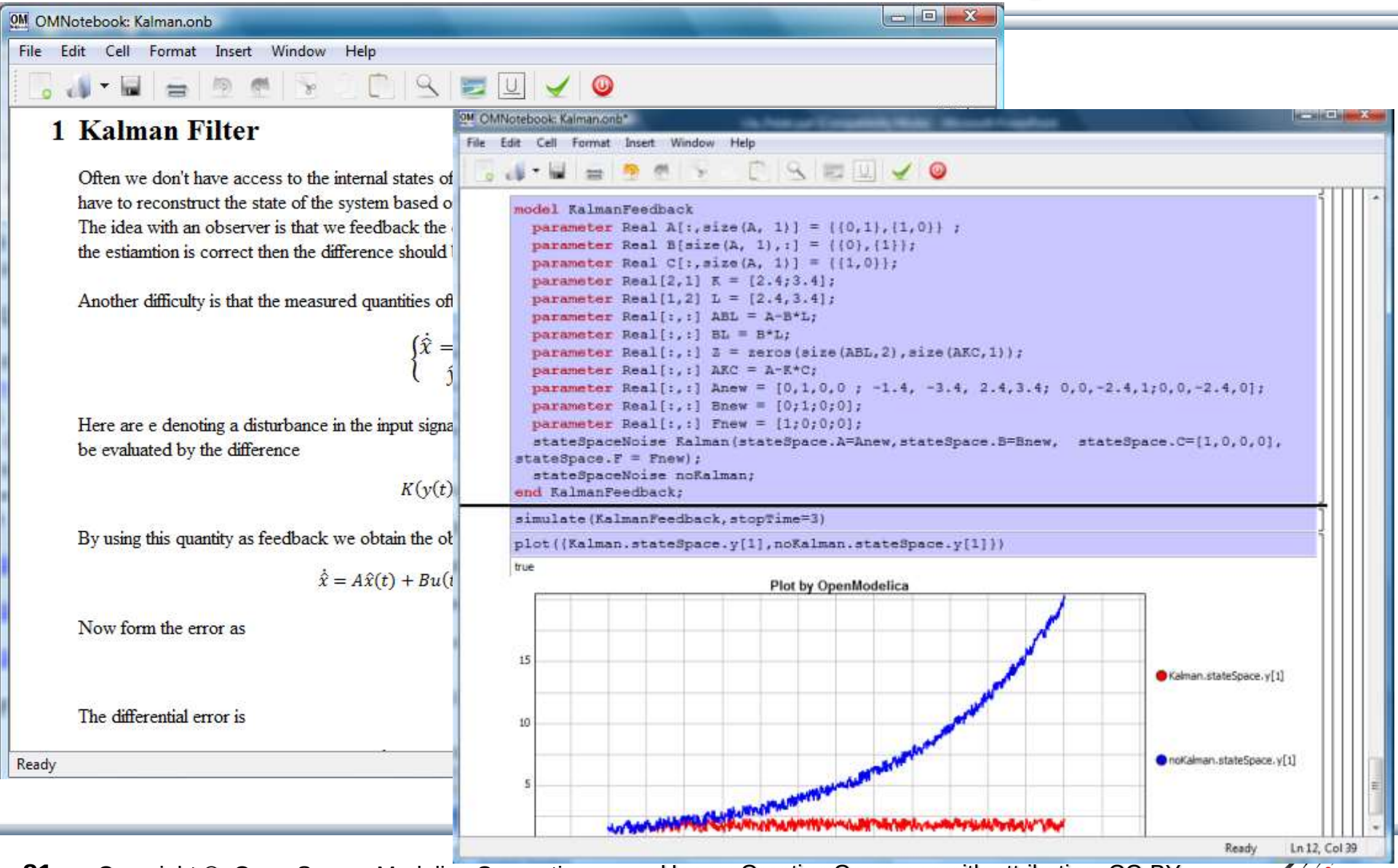
- Primarily for teaching
- Interactive electronic book
- Platform independent

Commands:

- *Shift-return (evaluates a cell)*
- File Menu (open, close, etc.)
- Text Cursor (vertical), Cell cursor (horizontal)
- Cell types: text cells & executable code cells
- Copy, paste, group cells
- Copy, paste, group text
- Command Completion (shift-tab)

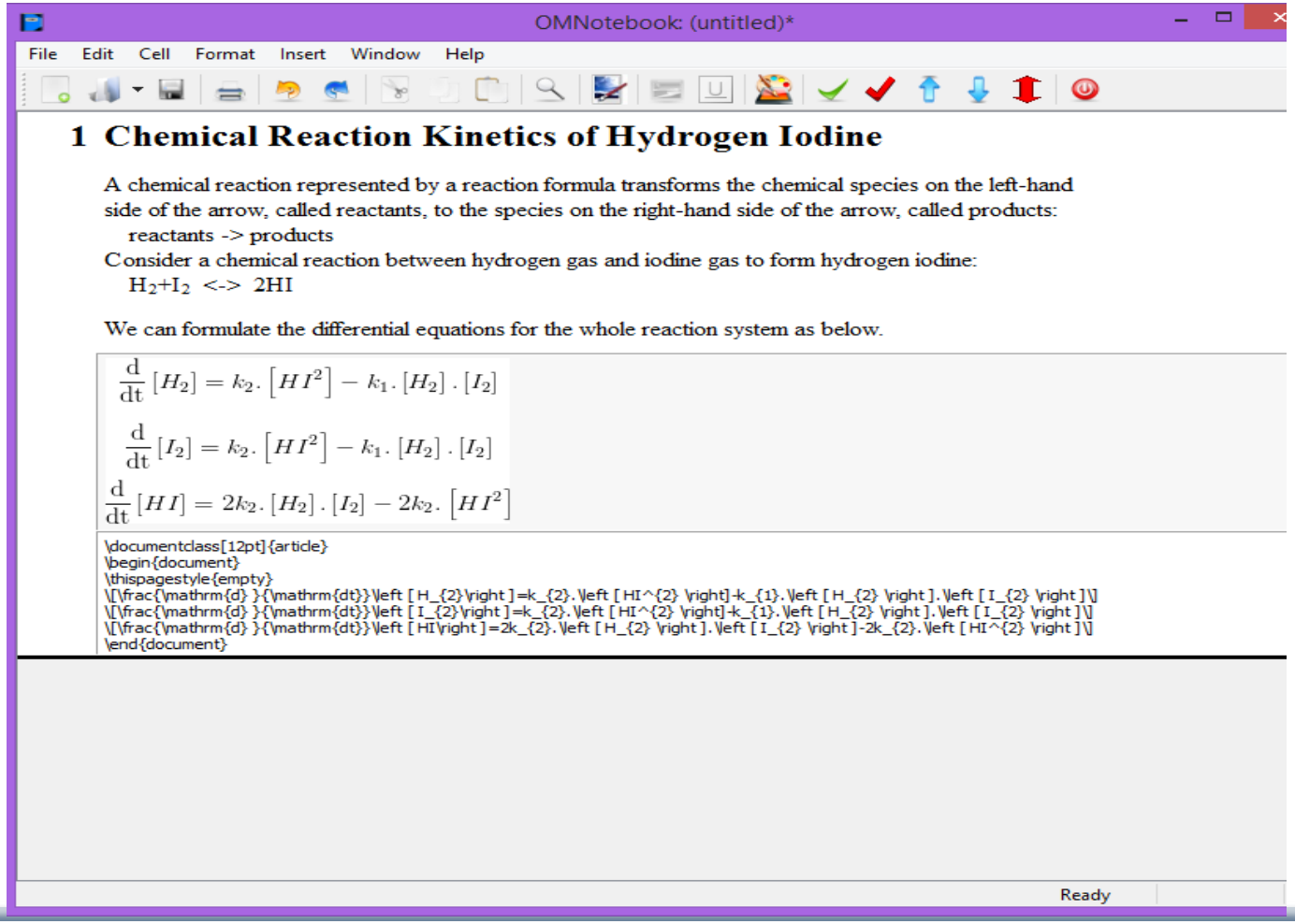


OMnotebook Interactive Electronic Notebook Here Used for Teaching Control Theory



Mathematical Typesetting in OMNotebook and OMWebbook

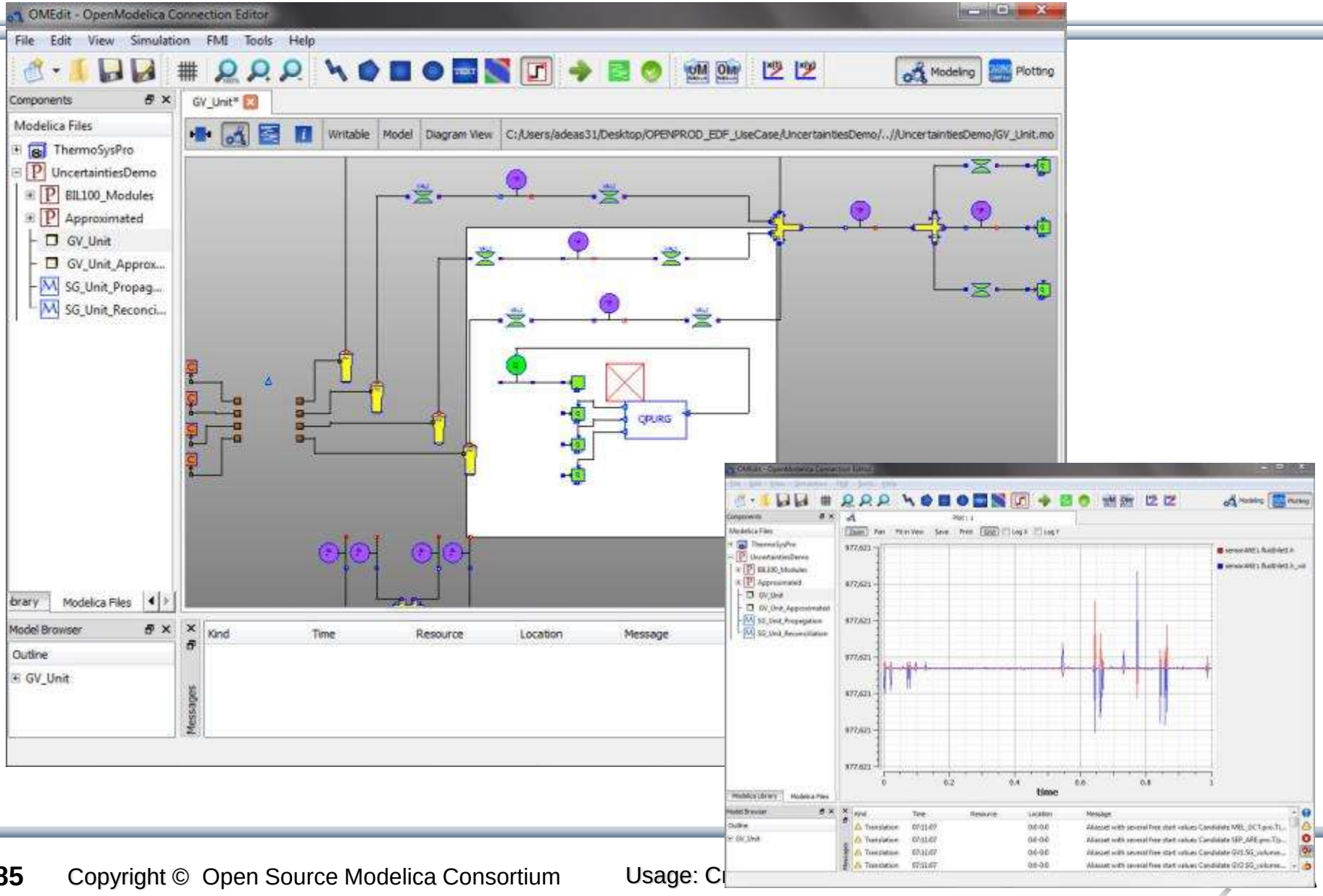
OMNotebook supports Latex formatting for mathematics



Contents in OMWebbook Generated from OMNotebook

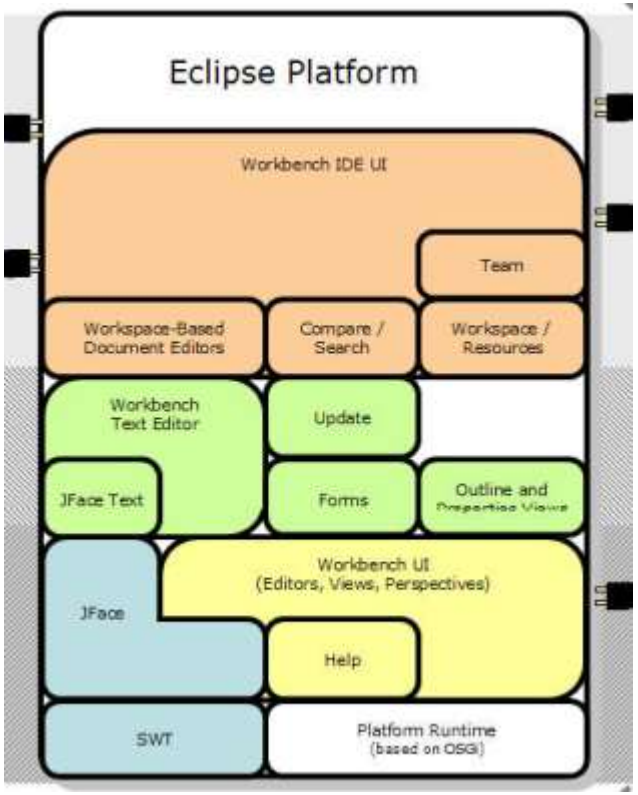
Latex instructions can be hidden by double clicking the Cell in tree view

OpenModelica Environment Demo

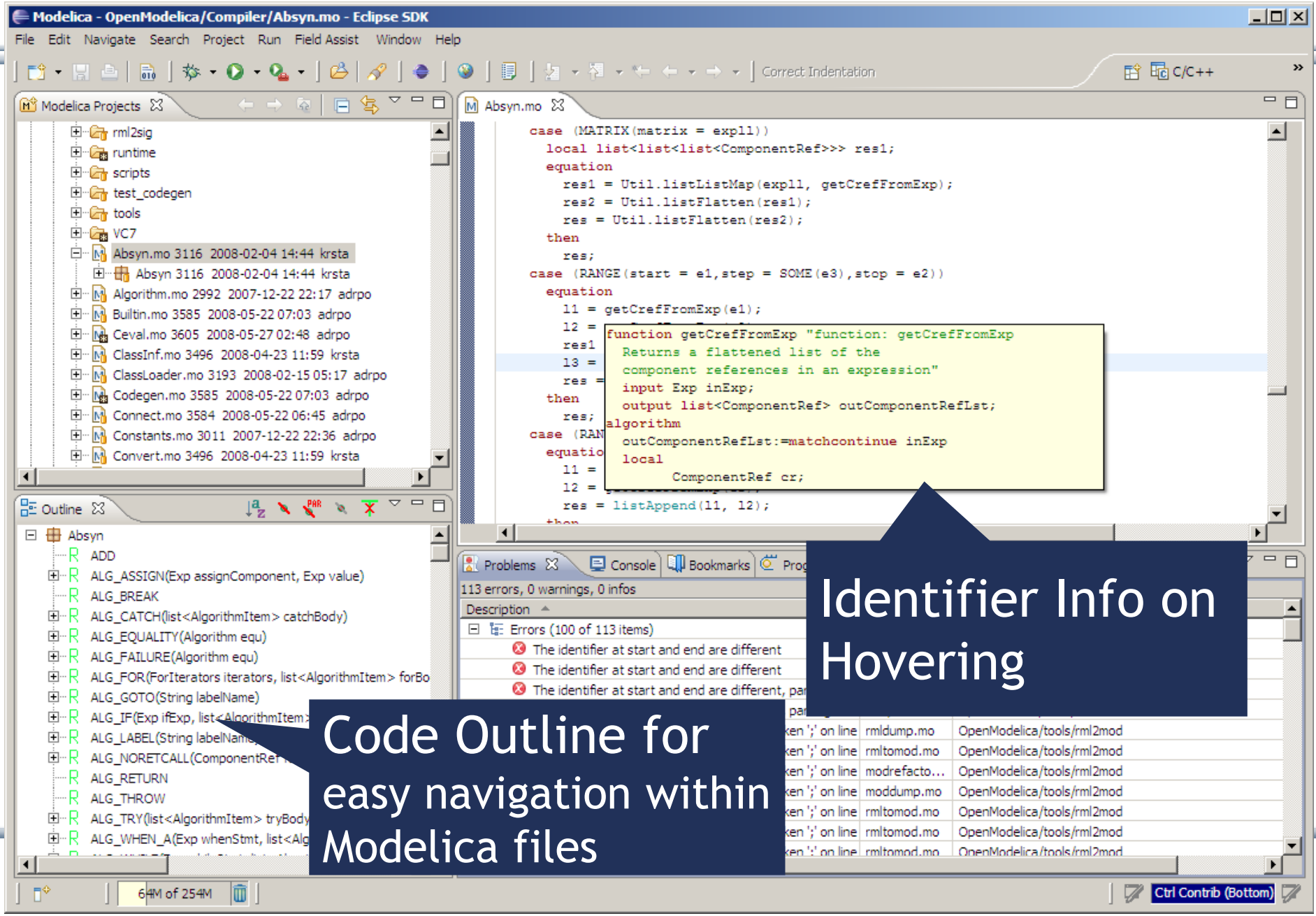


OpenModelica MDT – Eclipse Plugin

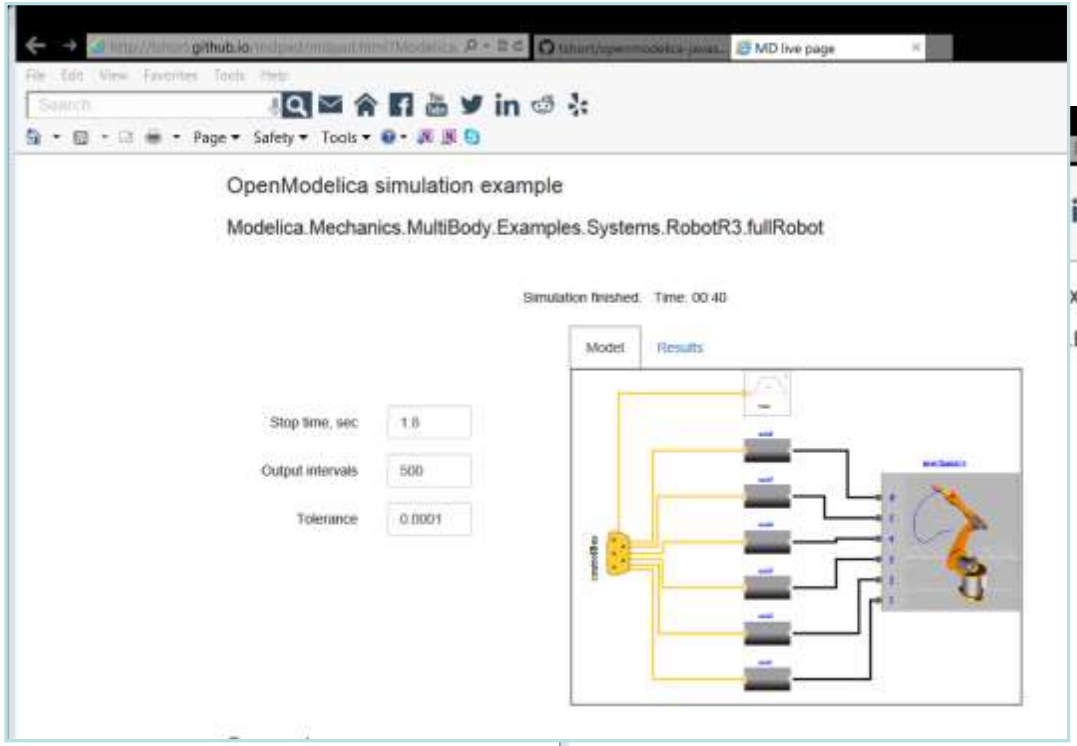
- Browsing of packages, classes, functions
- Automatic building of executables; separate compilation
- Syntax highlighting
- Code completion,
  Code query support for developers
- Automatic Indentation
- Debugger
  (Prel. version for algorithmic subset)



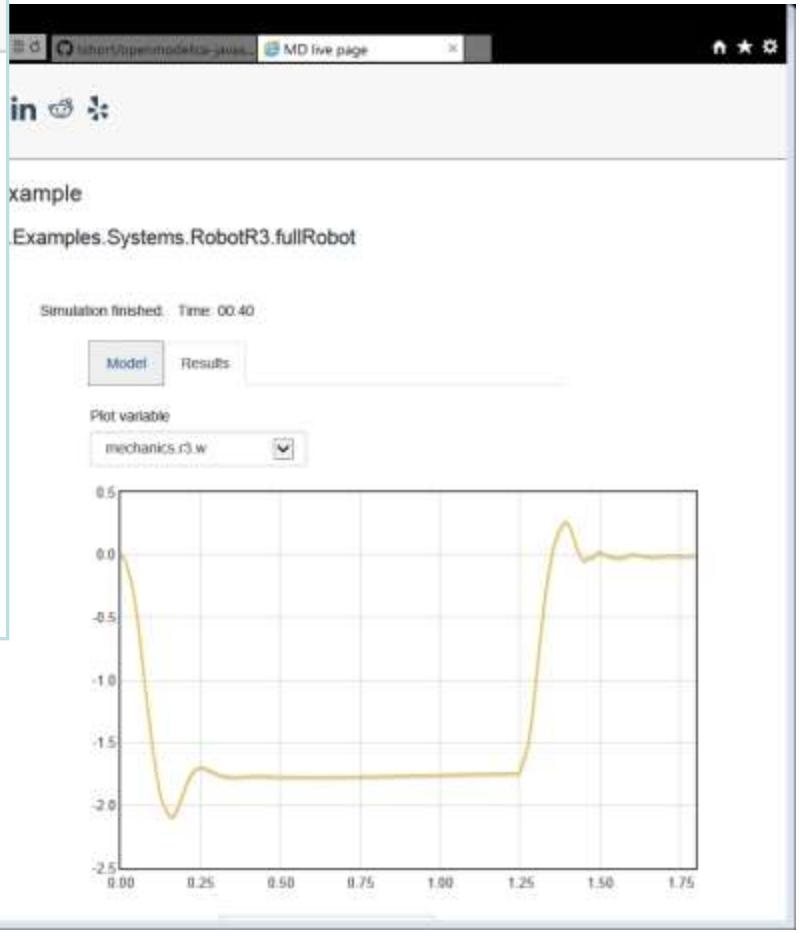
OpenModelica MDT: Code Outline and Hovering Info



OpenModelica Simulation in Web Browser Client



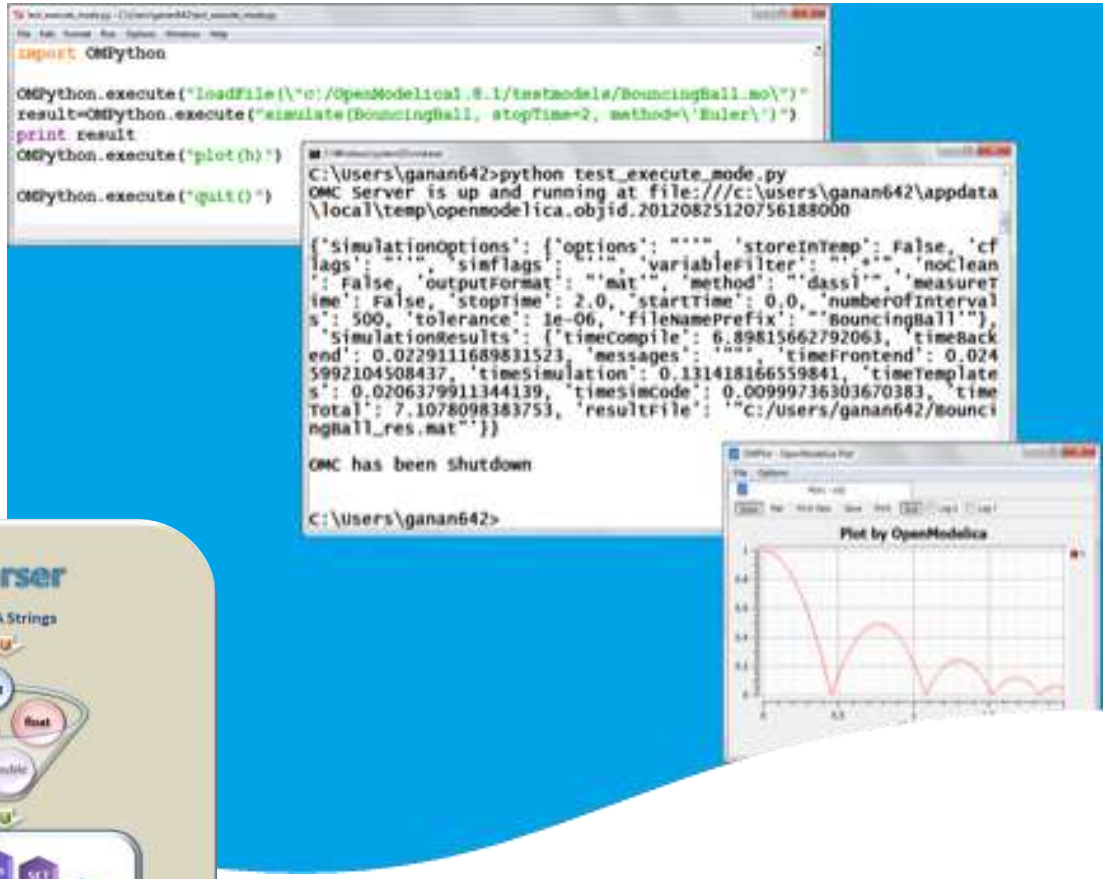
MultiBody RobotR3.FullRobot

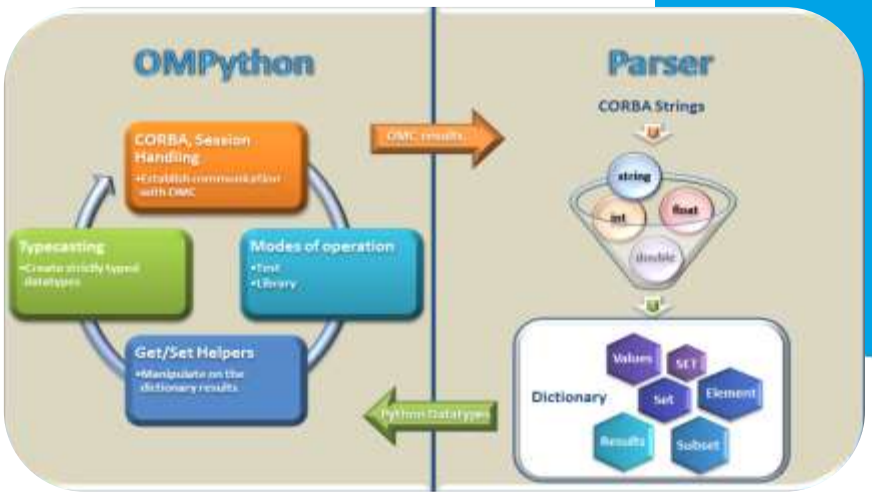


OpenModelica compiles to efficient Java Script code which is executed in web browser

OMPython – Python Scripting with OpenModelica

- Interpretation of Modelica commands and expressions
- Interactive Session handling
- Library / Tool
- Optimized Parser results
- Helper functions
- Deployable, Extensible and Distributable





OMJulia – Julia Scripting with OpenModelica

- Interpretation of Modelica commands and expressions from Julia, transfer of data
- Control design using Julia control package together with OpenModelica
- Interactive Session handling
- Library / Tool
- Separately downloadable. be run with OpenModelica 1.13.2 or later
- Works with Jupyter notebooks

Control example with OMJulia in Jupyter notebooks

Use of Modelica + Julia in Process Systems Engineering Education

Complex models of "Seborg reactor"

Bernt Lie*, Arunkumar Palanisamy, Peter Fritzson****

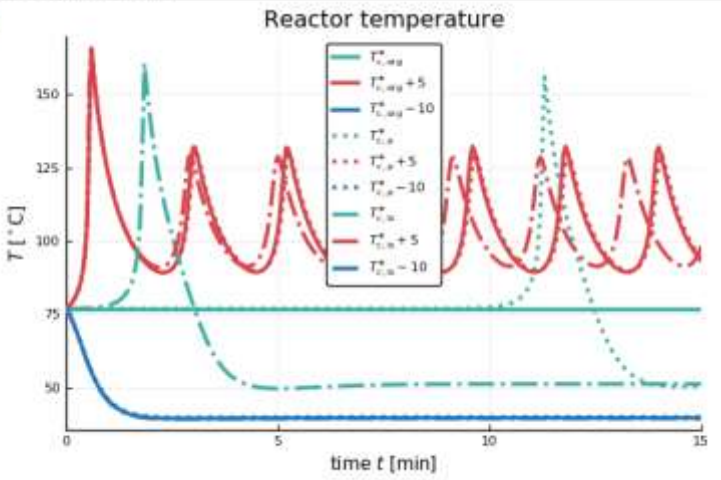
***University of South-Eastern Norway, Norway**

****University of Linköping, Sweden**

Introducing packages

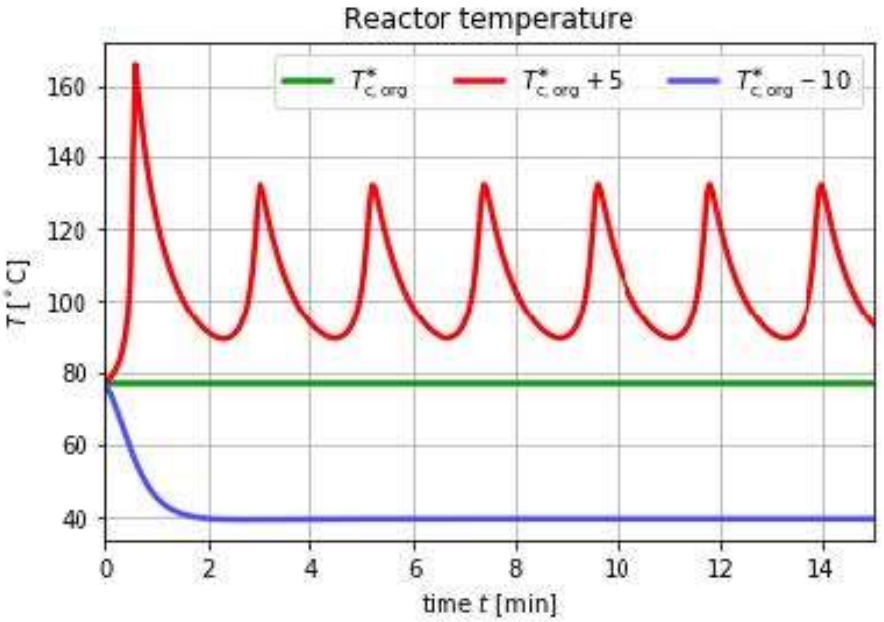
In [1]:
```
# Pkg.add("Plots") -- we assume that this step already has been carried out
using Plots; pyplot()
using LaTeXStrings
using DataFrames
using OMJulia
#using DifferentialEquations
```

Out[9]:



OMMatlab – Matlab Scripting with OpenModelica

- Interpretation of Modelica commands and expressions from Matlab, transfer of data
- Interactive Session handling
- Library / Tool
- Separately downloadable. be run with OpenModelica 1.13.0 or later
- Similar API functions as in OMJulia and OMPython
- Complete API e.g. useful for control system design



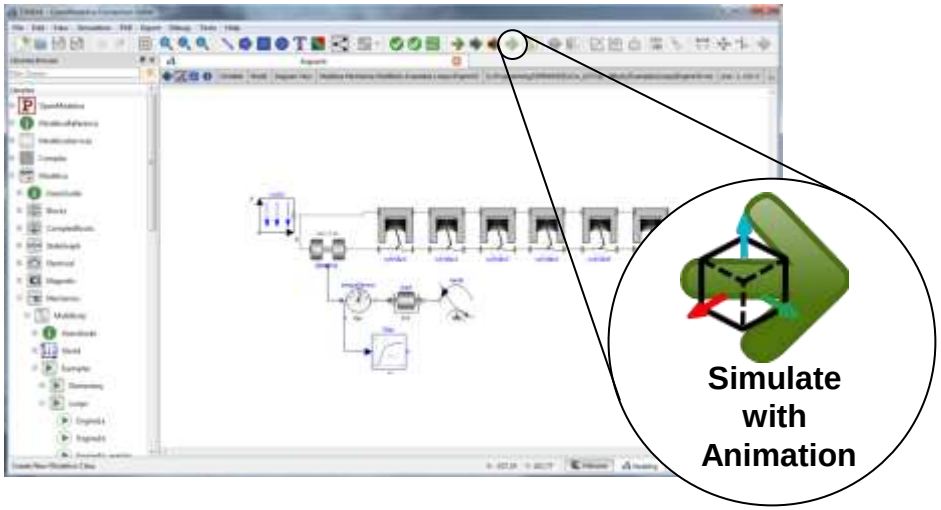
Experimental OpenModelica Compiler in Julia
John Tinnerholm and Adrian Pop)

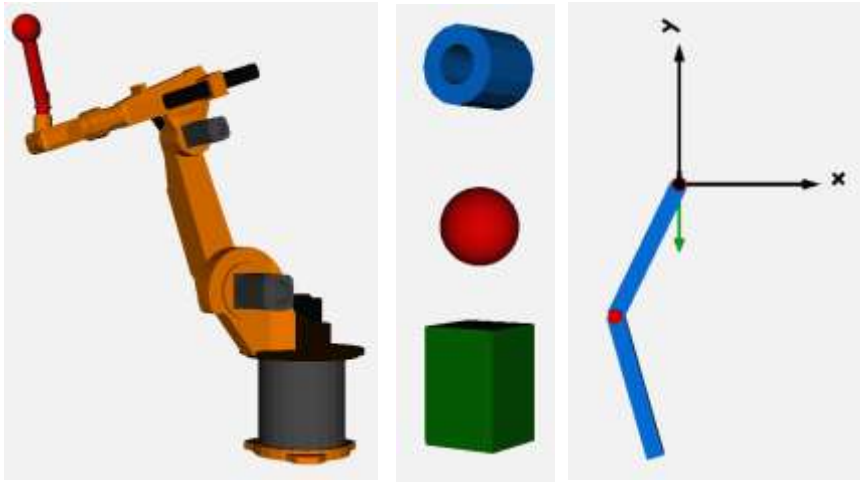
- OpenModelica.jl: modular and extensible Modelica compiler framework in Julia

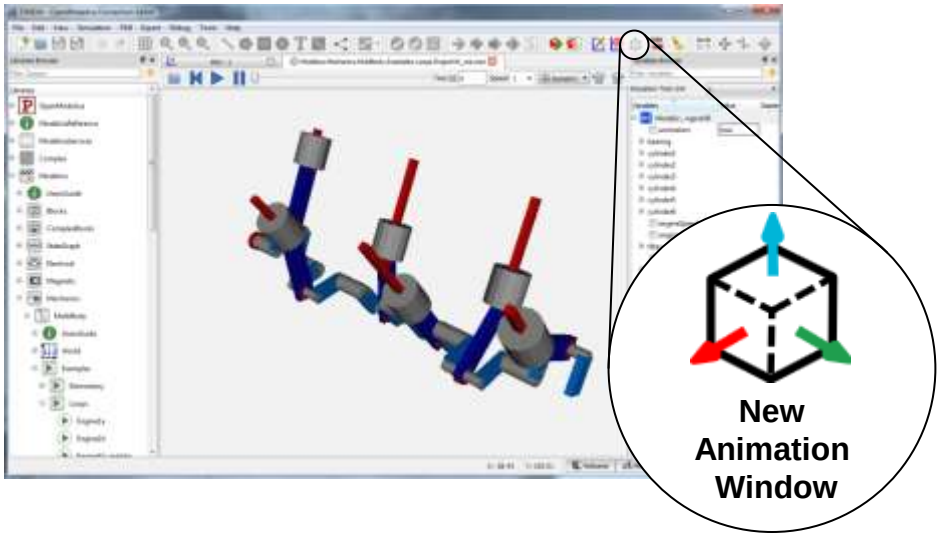
- Developed a preliminary MetaModelica to Julia translator
- **Translated the high-performance frontend.**
- **Able to execute and translate MetaModelica functions**
- **Able to simulate discrete-hybrid systems + regular continuous systems**
- **Experimental backends developed**
  - Targeting DifferentialEquations.jl and ModelingToolkit.jl (MTK)
  - Completed causalization sorting, matching.
  - Integrated LightGraphs.jl package, DAG representation of the hybrid DAE
  - Integrated Plots.jl for interactive plotting and animation
  - Integrated the Reduce Computer Algebra system for automatic symbolic manipulation and symbolic derivation.
  - Integration with Sundials. IDAS used for numerical integration
- Further performance **tuning needed**
- Currently experimenting with **variable-structure systems**

OMEdit 3D Visualization of Multi-Body Systems

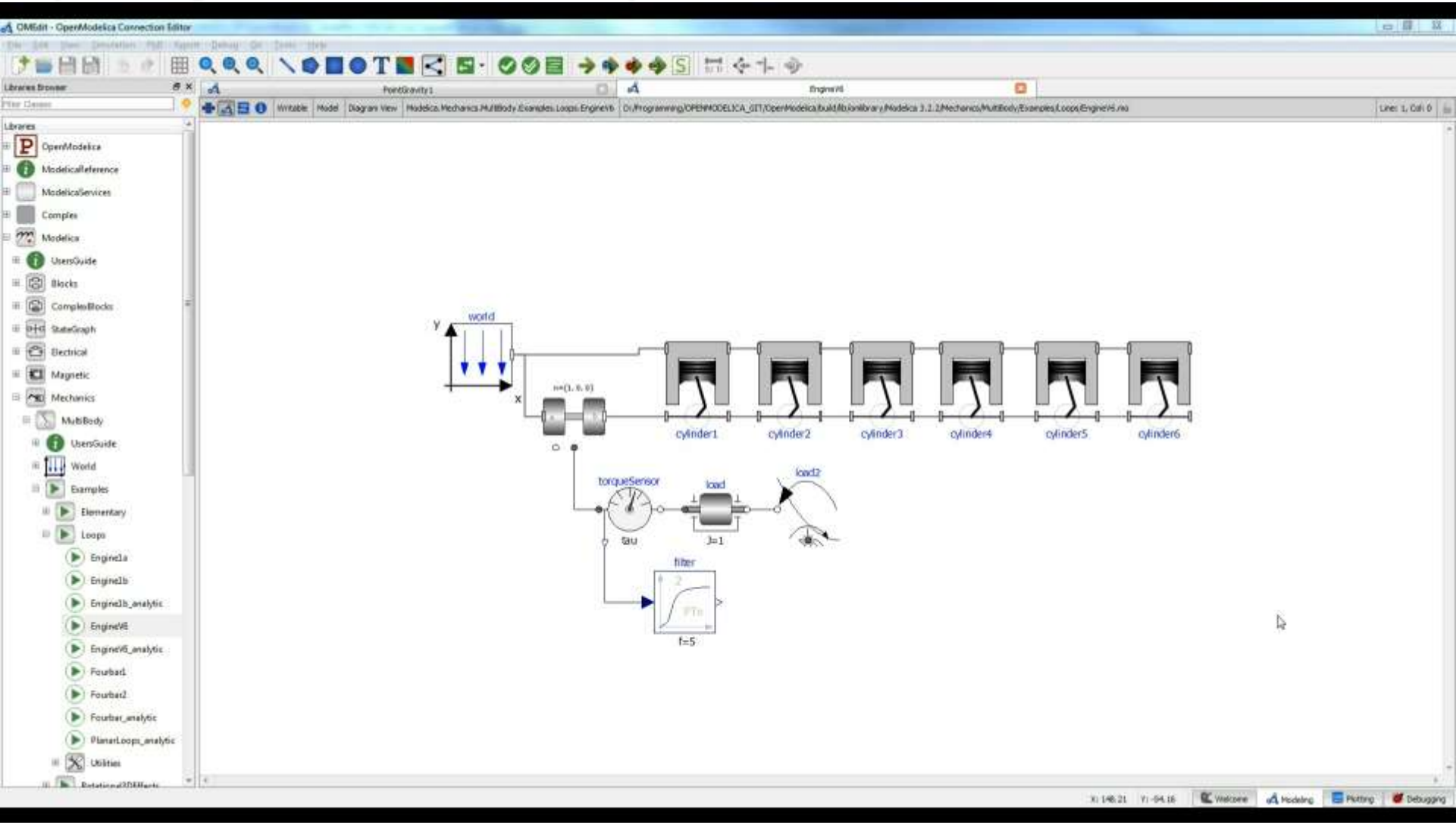
- Built-in feature of OMEdit to animate MSL-Multi-Body shapes
- Visualization of simulation results
- Animation of geometric primitives and CAD-Files



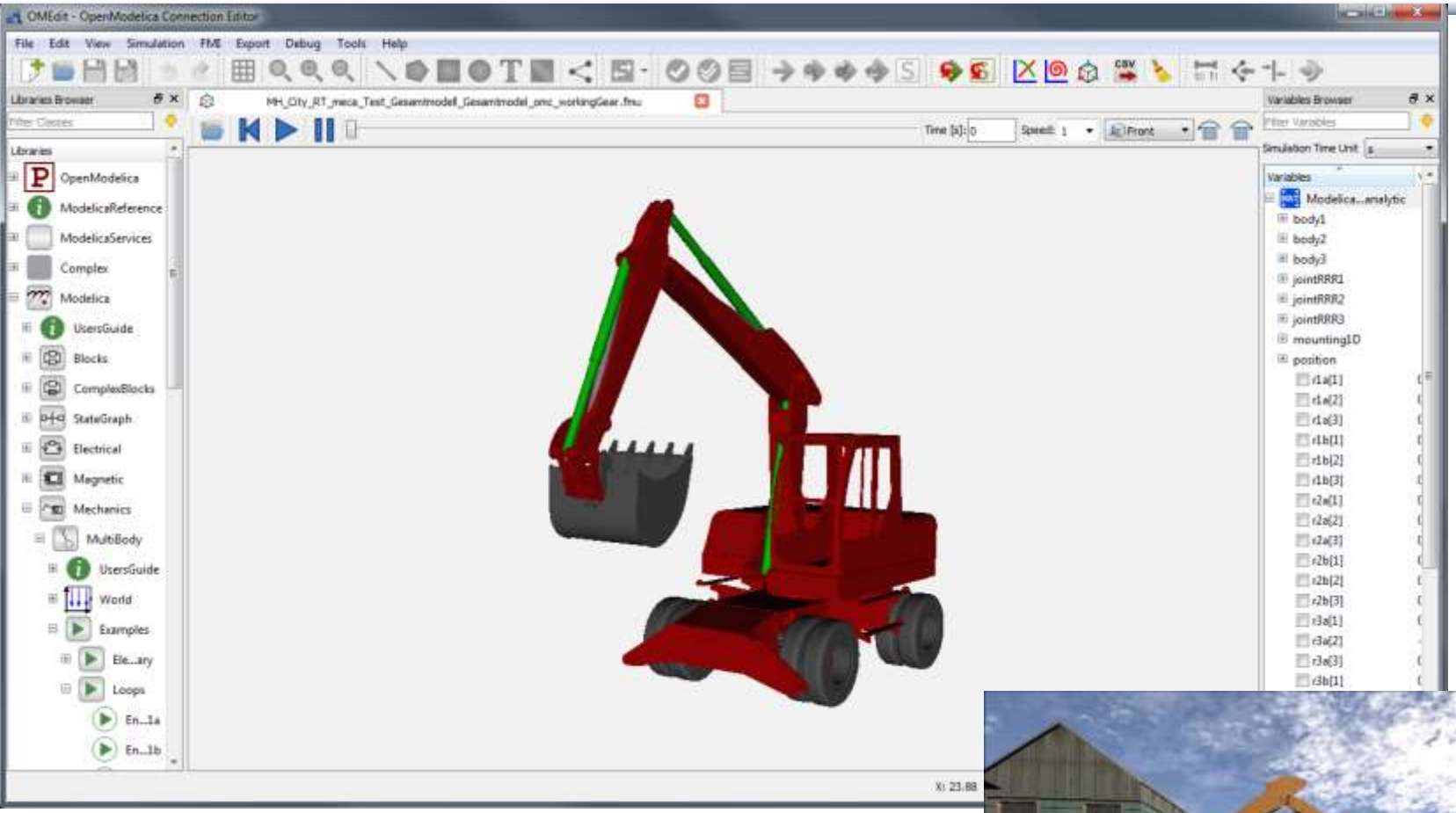




OpenModelica 3D Animation Demo
(V6Engine and Excavator)



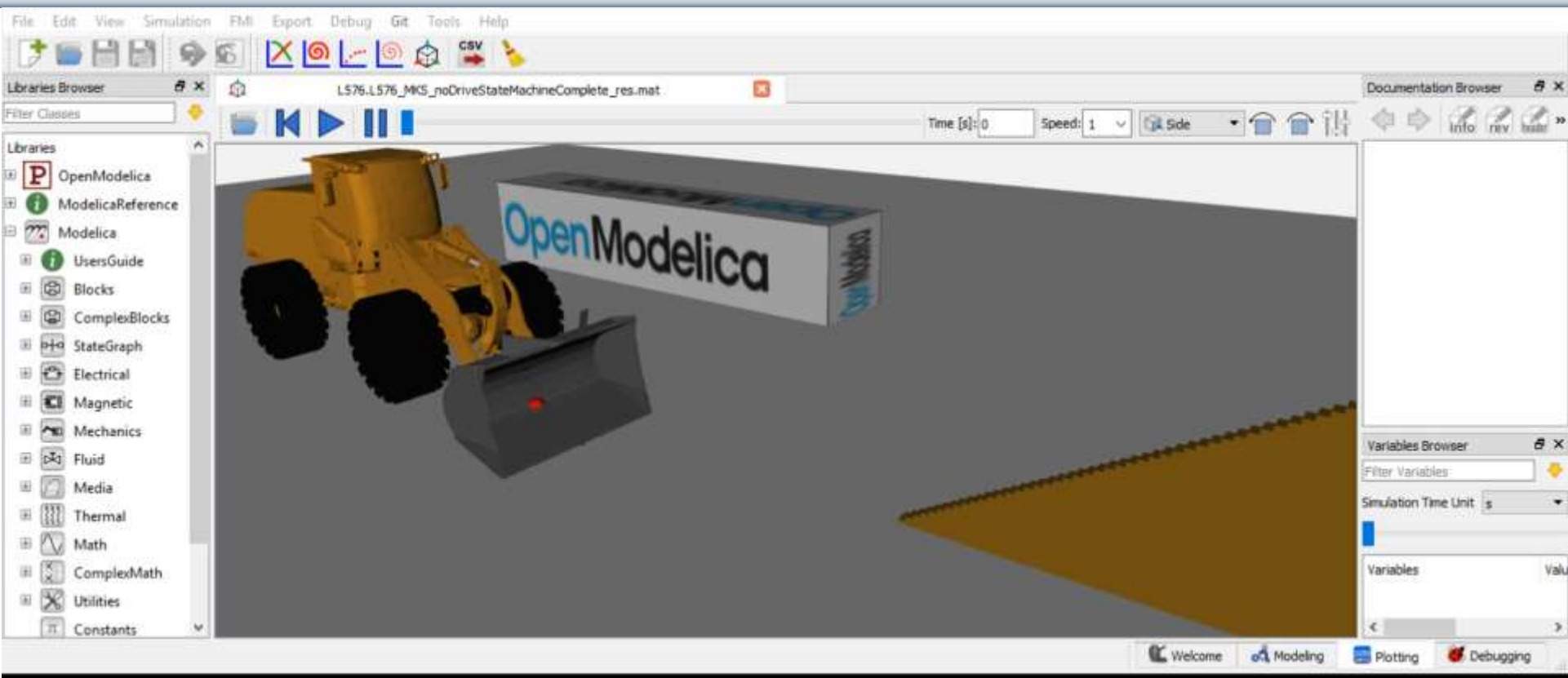
OpenModelica 3D Animation – Excavator



Connection with Unity

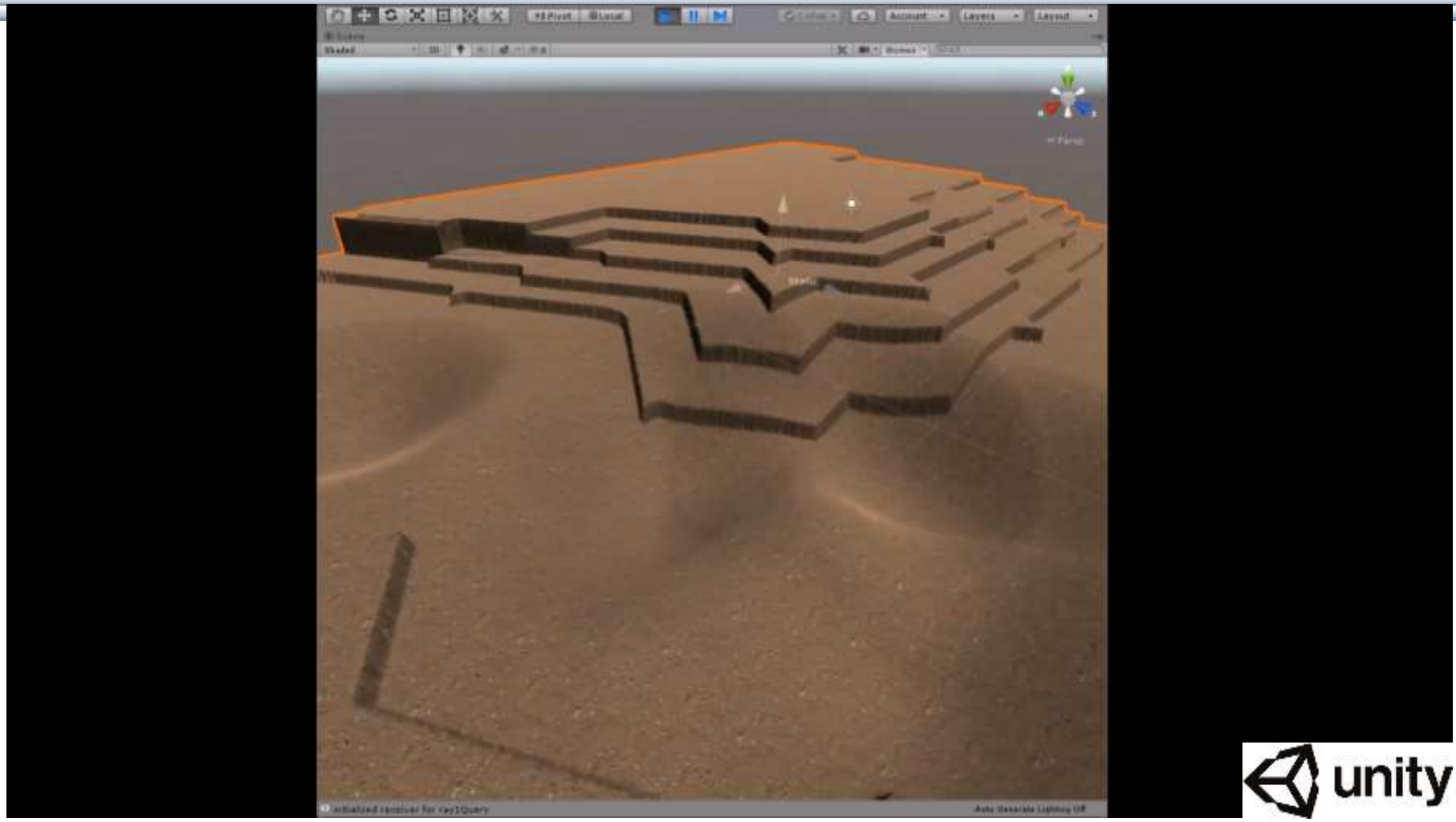
Courtesy of Volker Waurich - TU Dresden

OpenModelica 3D Animation – WheelLoader



Courtesy of Volker Waurich - TU Dresden

OpenModelica 3D Animation – BouncingBall

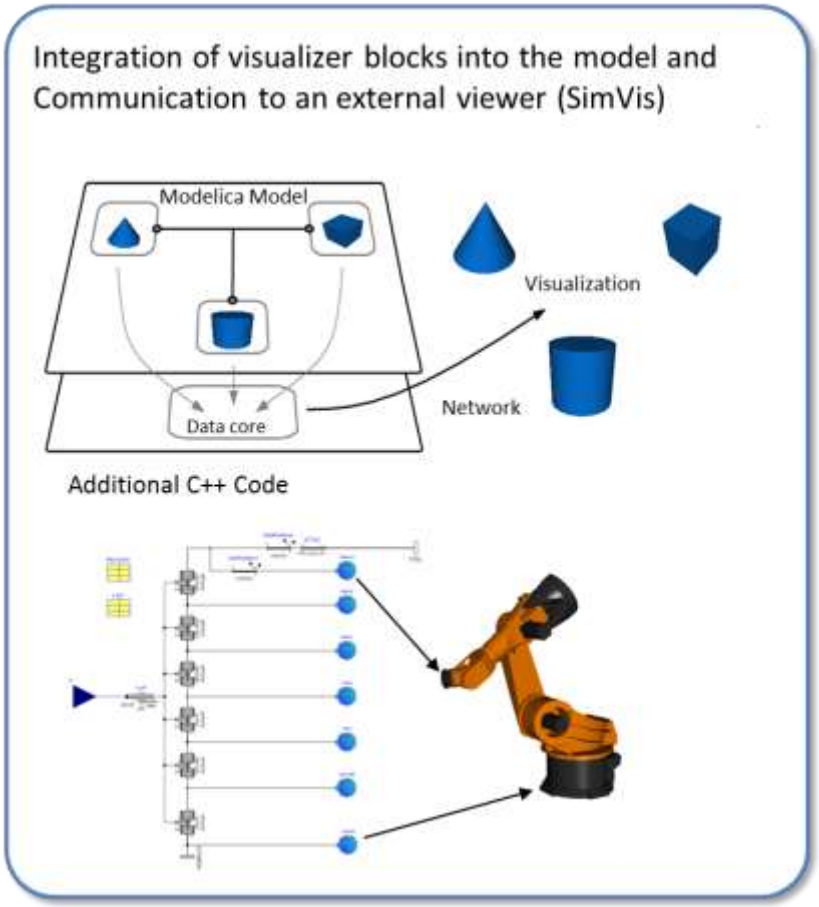


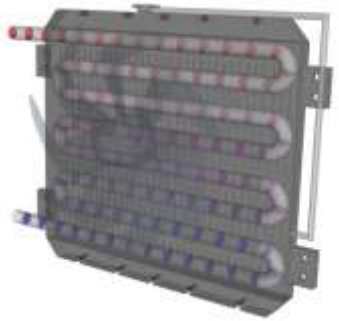
Collision detection in Unity

Courtesy of Volker Waurich - TU Dresden

Visualization using Third-Party Libraries: DLR Visualization Library

- Advanced, model-integrated and vendor-unspecific visualization tool for Modelica models
- Offline, online and real-time animation
- Video-export function
- Commercial library, feature reduced free Community Edition exists

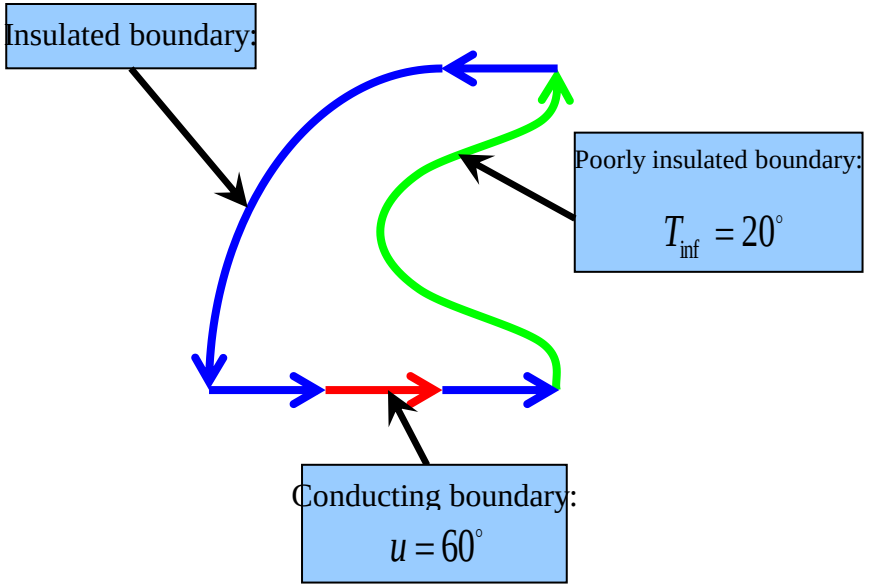


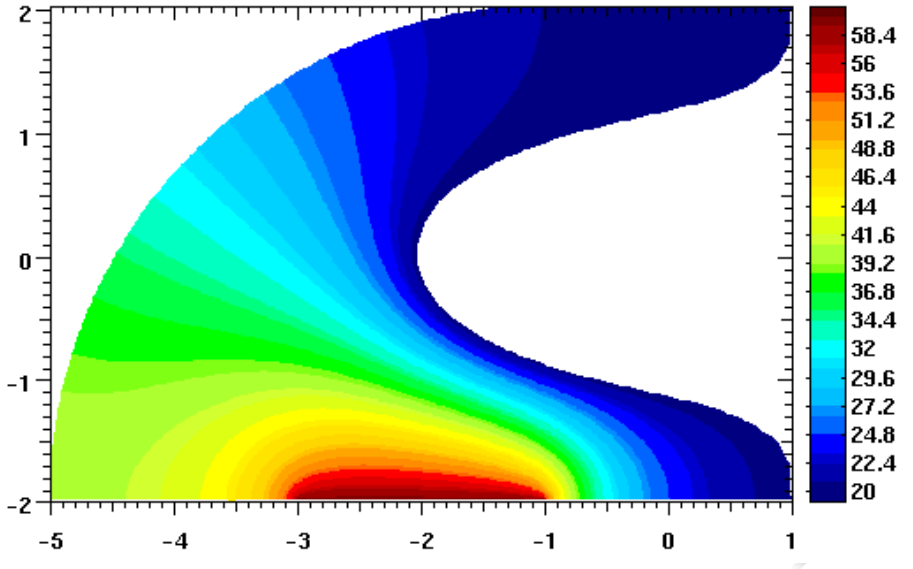


Courtesy of Dr. Tobias Bellmann (DLR)

Extending Modelica with PDEs for 2D, 3D flow problems – Research

```
class PDEModel
   HeatNeumann h_iso;
   Dirichlet h_heated(g=50);
   HeatRobin h_glass(h_heat=30000);
   HeatTransfer ht;
   Rectangle2D dom;
equation
   dom.eq=ht;
   dom.left.bc=h_glass;
   dom.top.bc=h_iso;
   dom.right.bc=h_iso;
   dom.bottom.bc=h_heated;
end PDEModel;
```

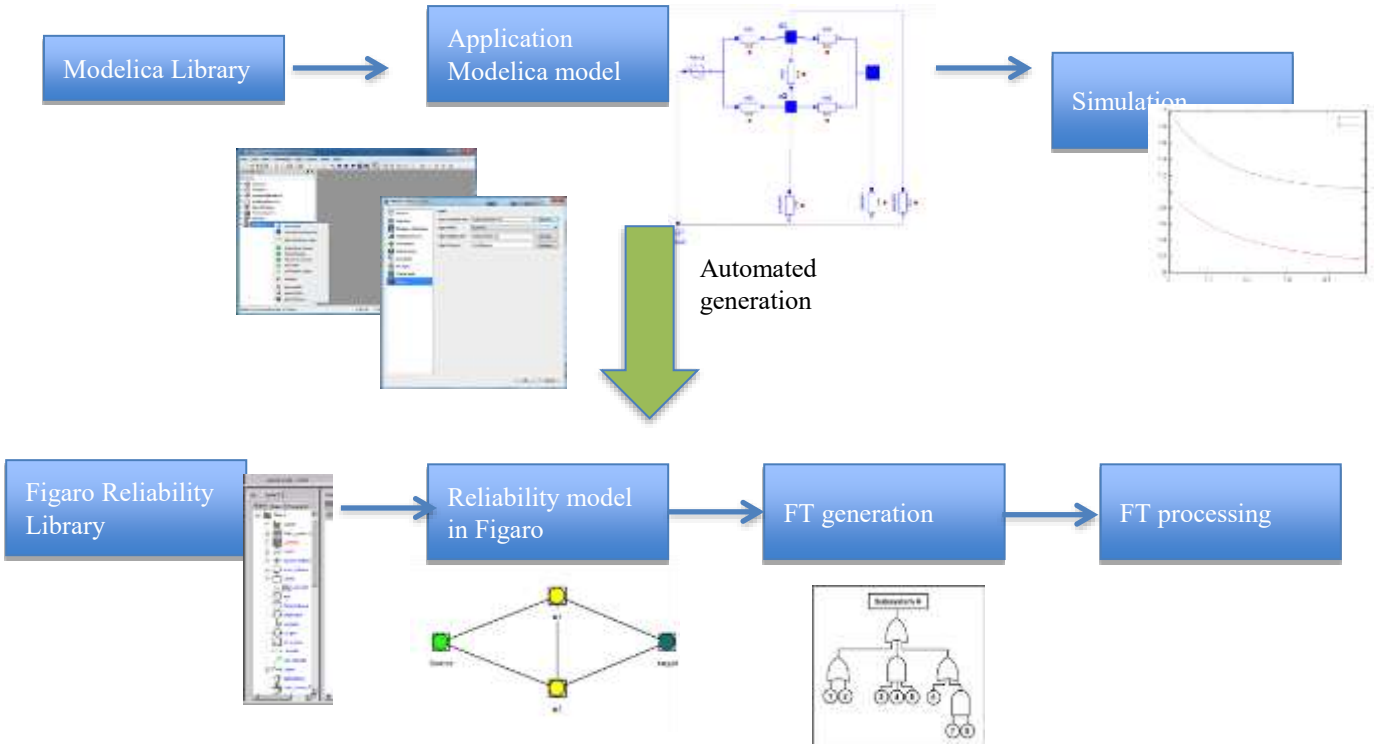




Prototype in OpenModelica 2005
PhD Thesis by Levon Saldamli
www.openmodelica.org
Currently not operational

Failure Mode and Effects Analysis (FMEA) in OM

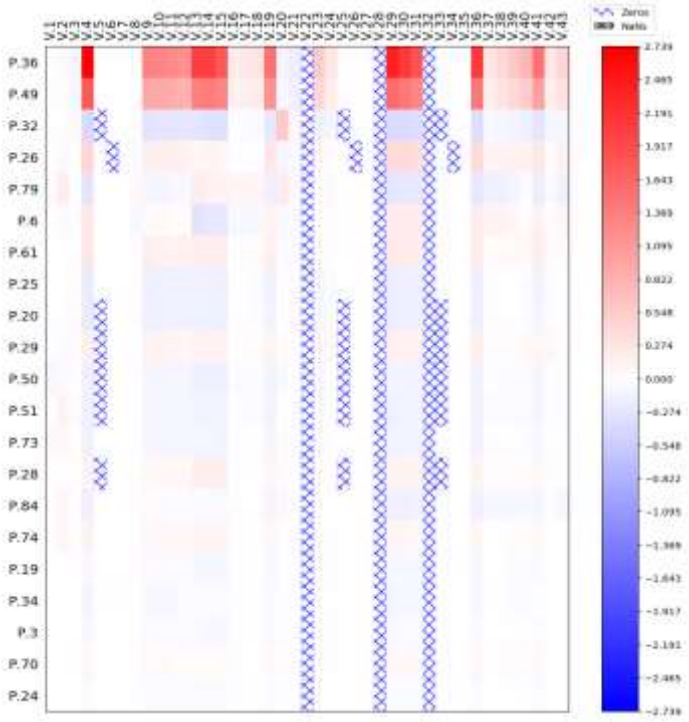
- Modelica models augmented with reliability properties can be used to generate reliability models in Figaro, which in turn can be used for static reliability analysis
- Prototype in OpenModelica integrated with the Figaro tool.



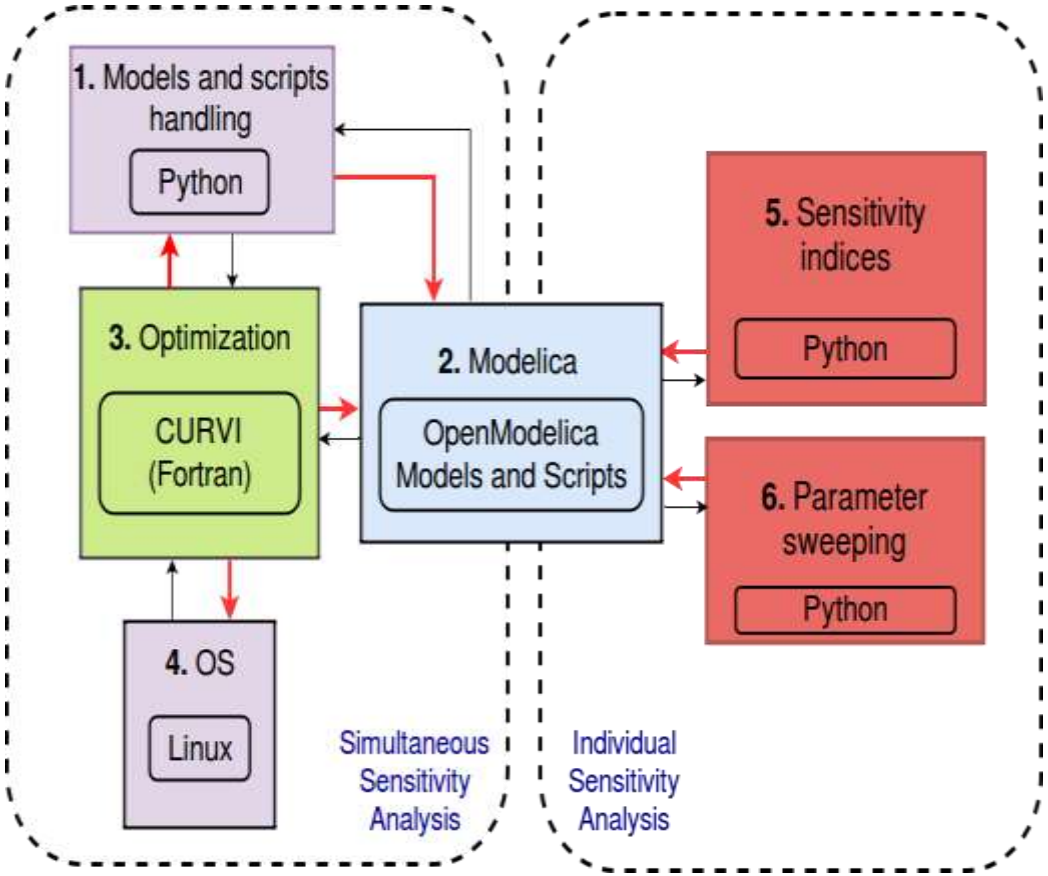
OMSens – Multi-Parameter Sensitivity Analysis and Robust Optimization

- Individual and simultaneous multi-parameter analysis
- Optimization-based simultaneous analysis
- Robust derivative free optimizer

Heatmap visualization



Tool architecture



OMSysIdent – System Parameter Identification

- OMSysIdent is a module for parameter estimation of behavioral models (wrapped as FMUs) on top of the OMSimulator API.
- Identification of the parameter values is typically based on measurement data
- It uses the Ceres solver (http://ceres-solver.org/) for the optimization task.

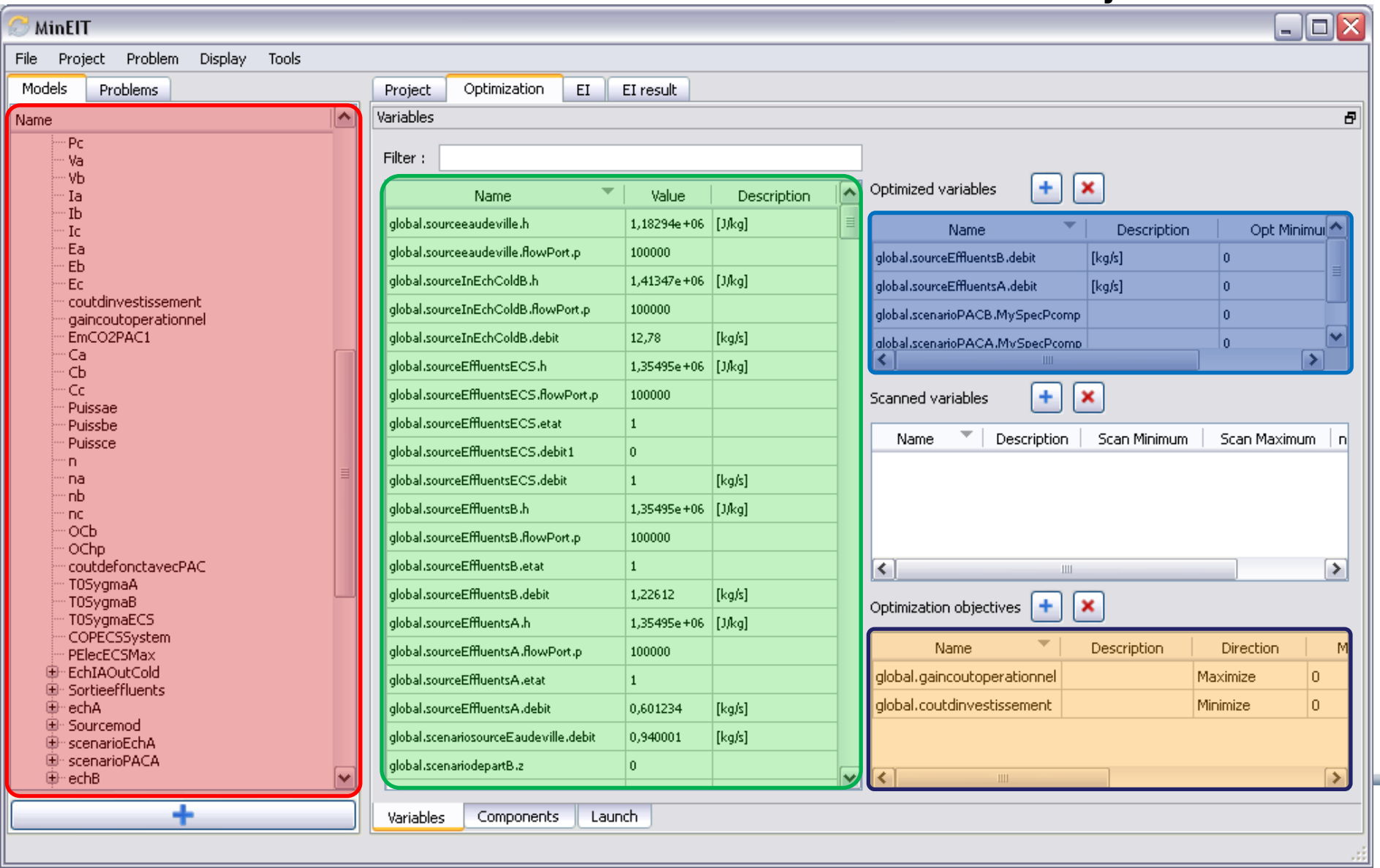
OMOptim – Optimization (1)

Model structure

Model Variables

Optimized parameters

Optimized Objectives



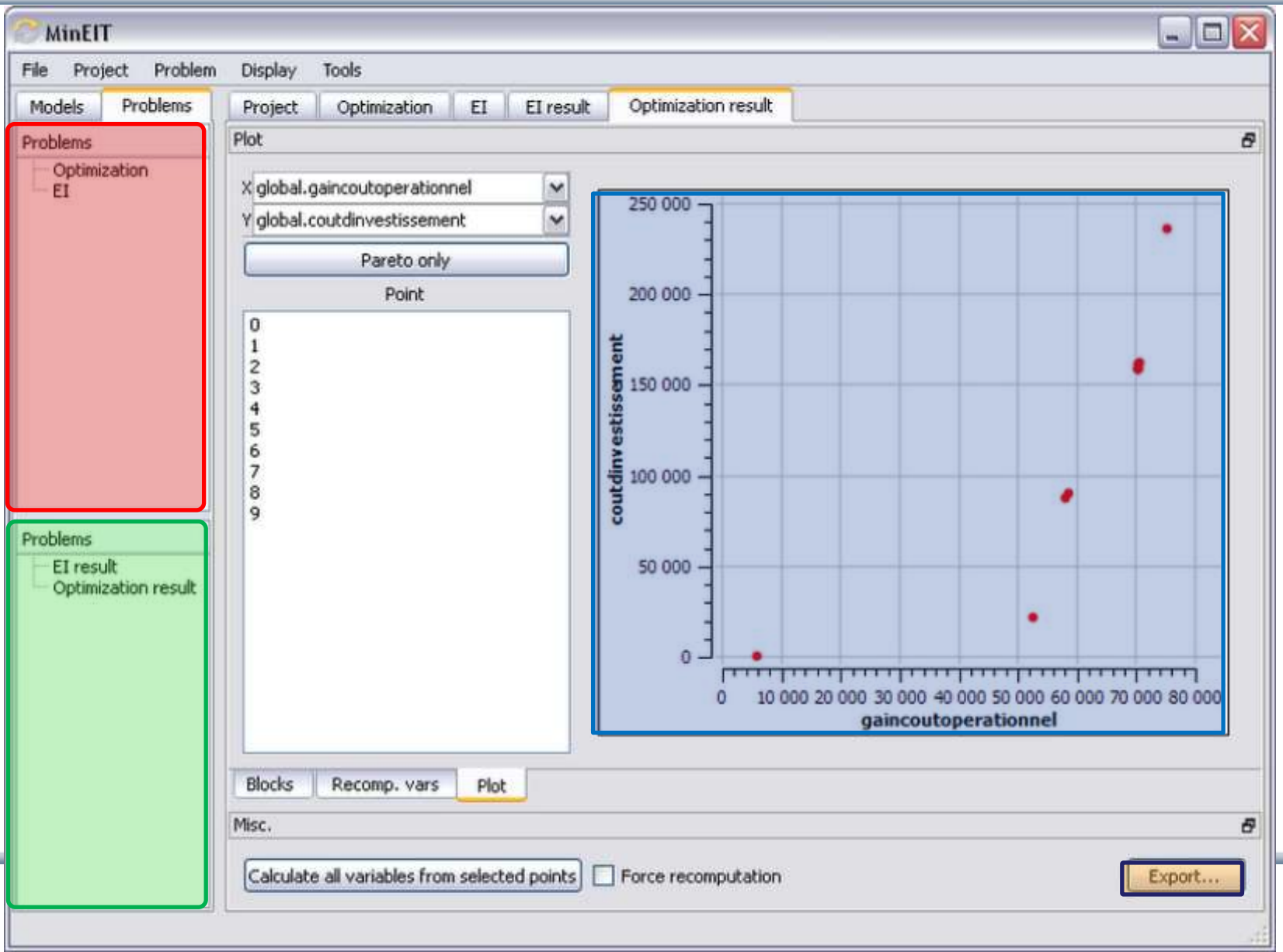
OMOptim – Optimization (2)

Problems

Solved problems

Result plot

Export result data .csv

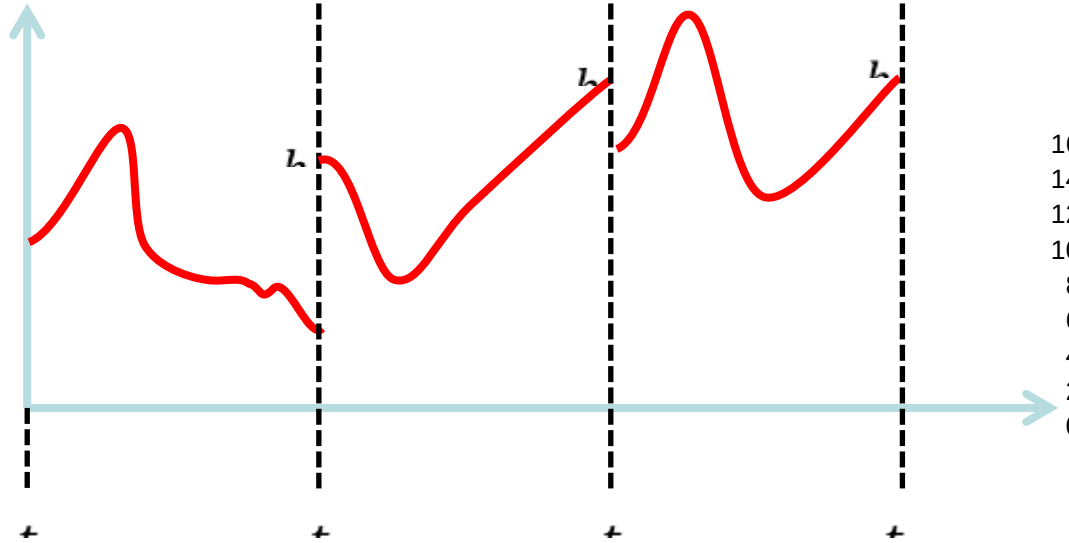


MODELICA

Multiple-Shooting and Collocation Dynamic Trajectory Optimization

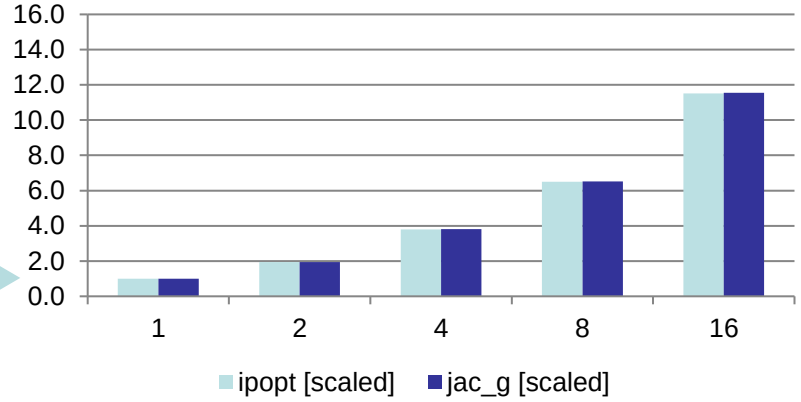
- Minimize a goal function subject to model equation constraints, useful e.g. for NMPC
- Multiple Shooting/Collocation
  - Solve sub-problem in each sub-interval

$$x_i(t_{i+1}) = h_i + \int_{t_i}^{t_{i+1}} f(x_i(t), u(t), t)\, dt \approx F(t_i, t_{i+1}, h_i, u_i), \qquad x_i(t_i) = h_i$$

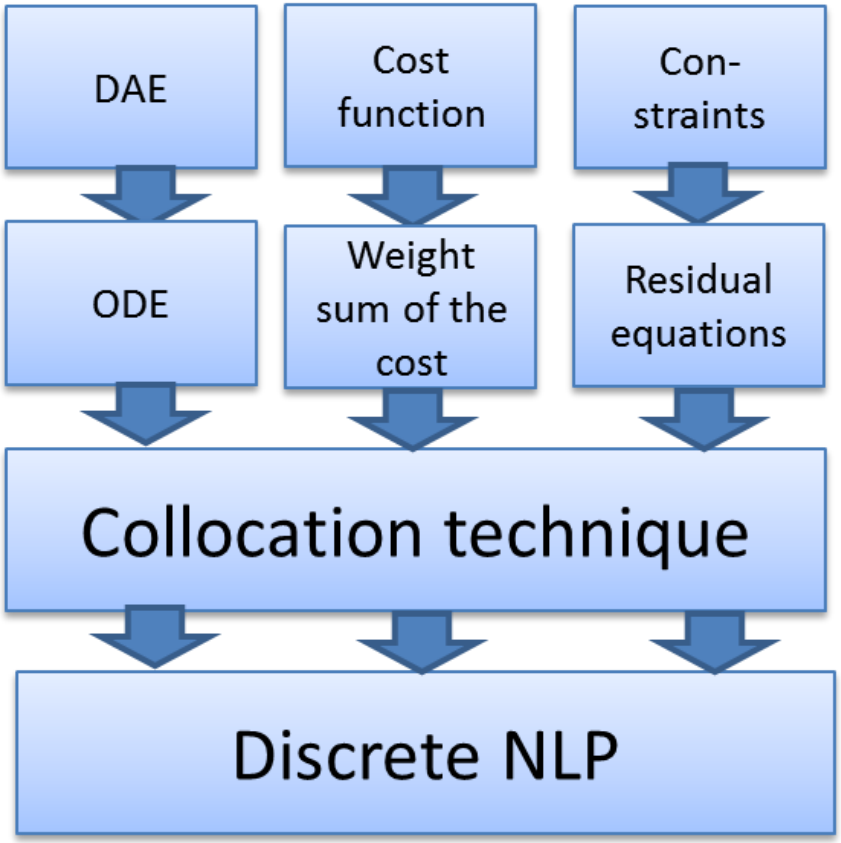


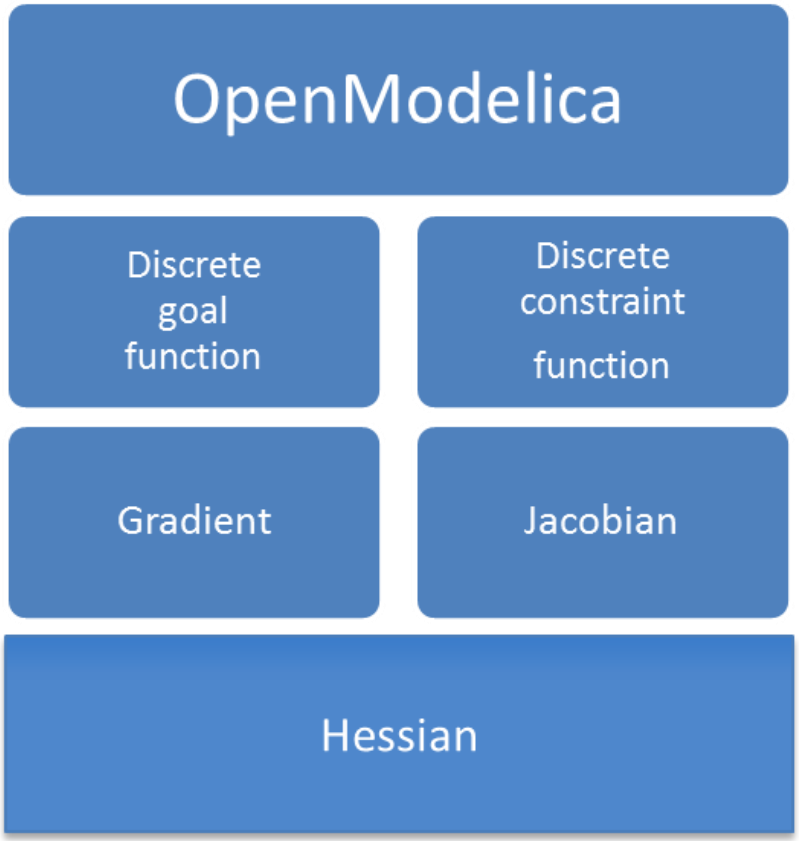
Example speedup, 16 cores:

MULTIPLE_COLLOCATION



OpenModelica Dynamic Optimization Collocation





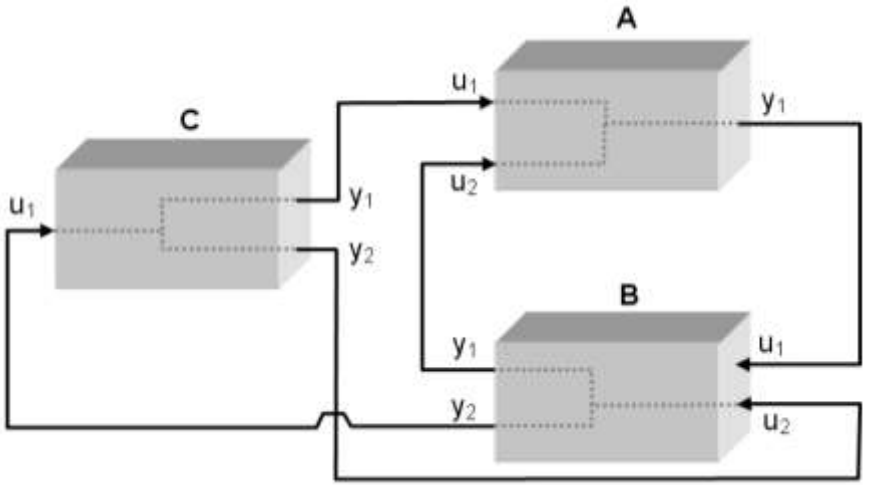
General Tool Interoperability & Model Exchange Functional Mock-up Interface (FMI)

courtesy Daimler

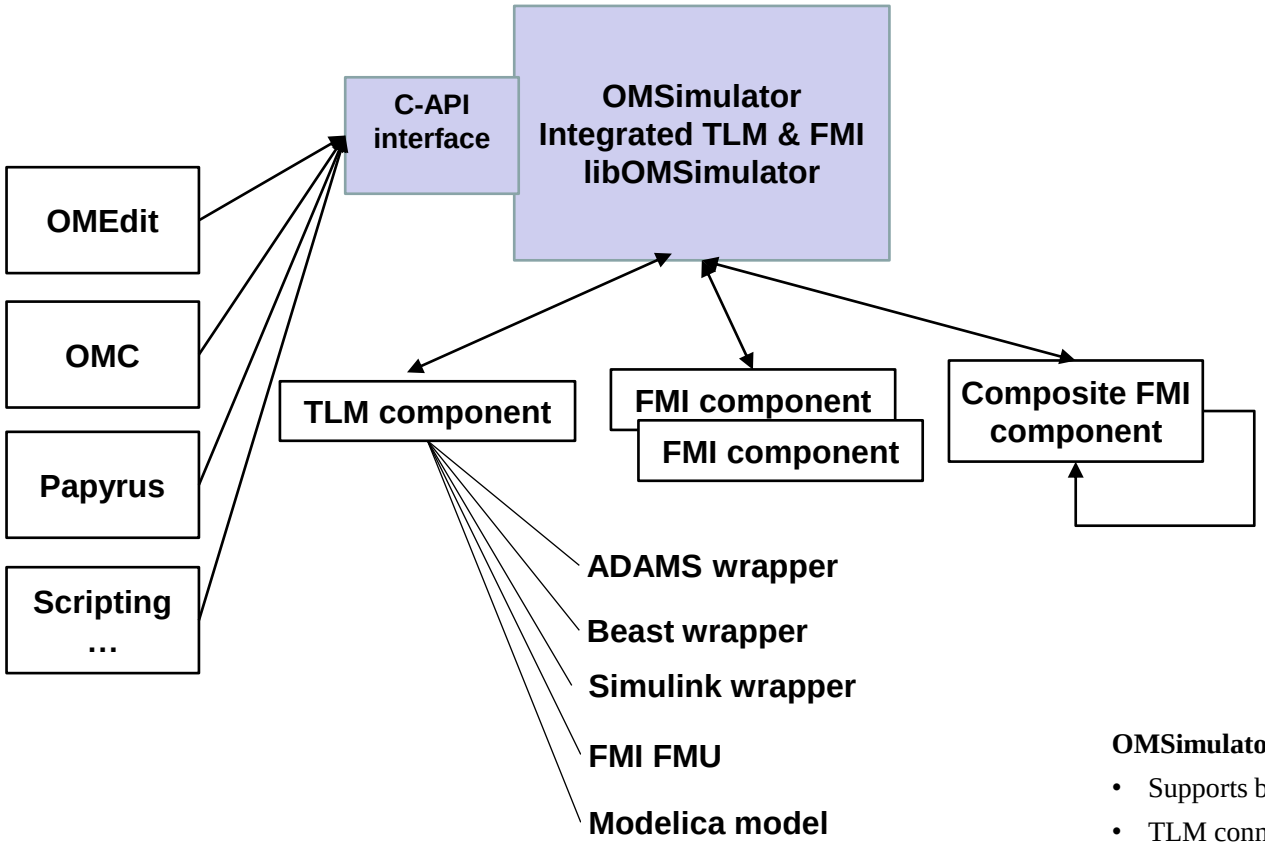
- FMI development was started by ITEA2 MODELISAR project. FMI is now a Modelica Association Project
- **Version 1.0**
- FMI for Model Exchange (released Jan 26,2010)
- FMI for Co-Simulation (released Oct 12,2010)
- **Version 2.0** (released July 25 2014) **2.0.4** (released Dec 1, 2022)
- **Version 3.0** (release May 10 2022)
- FMI for Model Exchange and Co-Simulation
- **~ 180 tools** supporting it (https://www.fmi-standard.org/tools)

Functional Mockup Units

- Import and export of input/output blocks –
  Functional Mock-Up Units – FMUs, described by
  - differential-, algebraic-, discrete equations,
  - with time-, state, and step-events
- An FMU can be large (e.g. 100 000 variables)
- An FMU can be used in an embedded system (small overhead)
- FMUs can be connected together



OMSimulator – Integrated FMI and TLM-based Cosimulator/Simulator



Main Framework Aspects

Unified co-simulation/simulation tool

- FMI 2.0 (model exchange and co-simulation)
- TLM (transition line modelling)
- Real-time and offline simulation

Standalone open source simulation tool with rich interfaces

- C/Java
- Scripting languages

Co-simulation framework as a solid base for engineering tools

- Integration into OpenModelica/Papyrus
- Open for integration into third-party tools and specialized applications (e.g. flight simulators, optimization)

OMSimulator 2.0 in OpenModelica 1.13.0

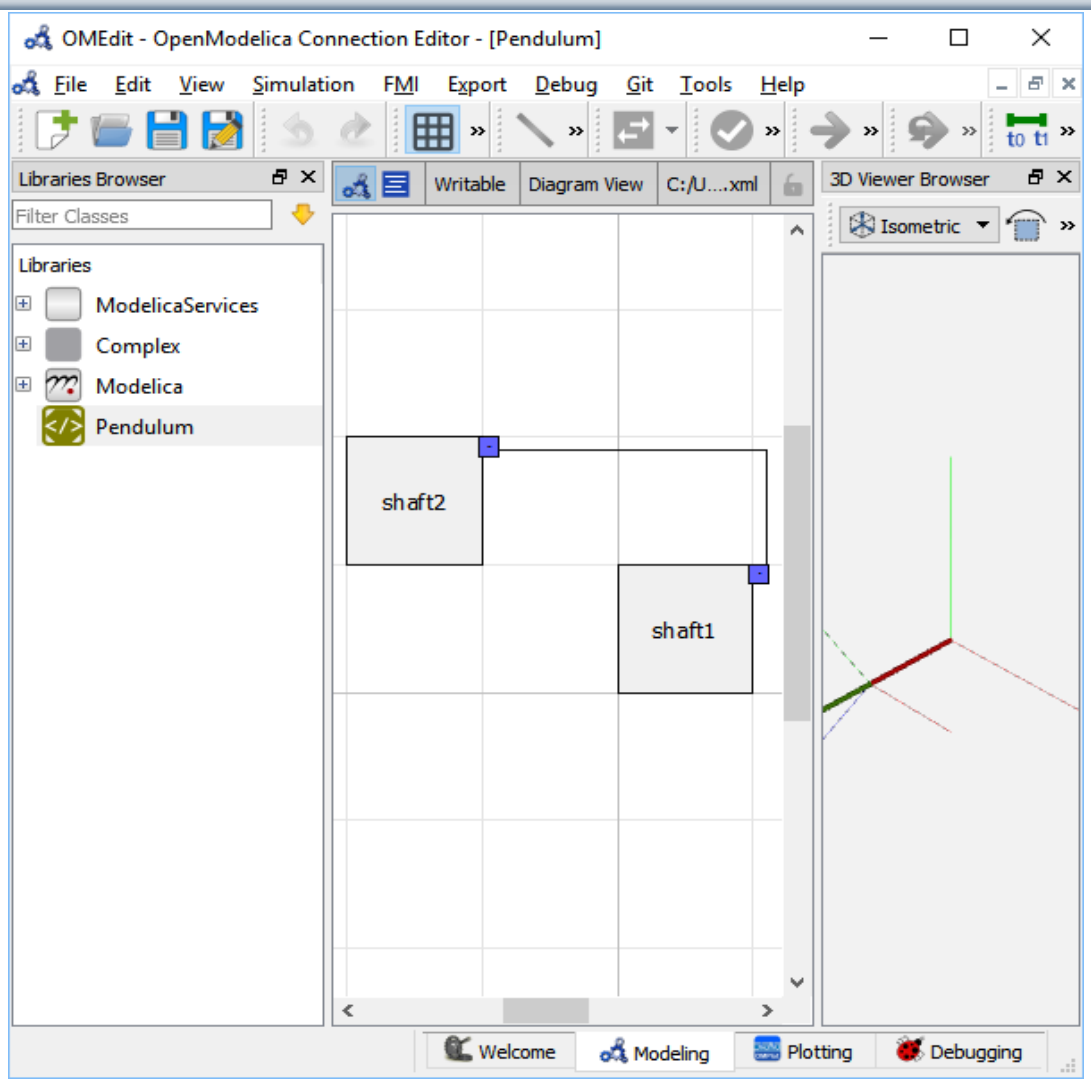
- Supports both FMI and TLM
- TLM connections are optional
- Co-simulation to multiple tools
- Composite model editor operational
- External API interface and scripting not yet finalized

Received ITEA Award of Excellence, Sept, 2019

- The **OPENCPS** project for which **OMSimulator** was the major result, received the ITEA award of excellence, September 2019

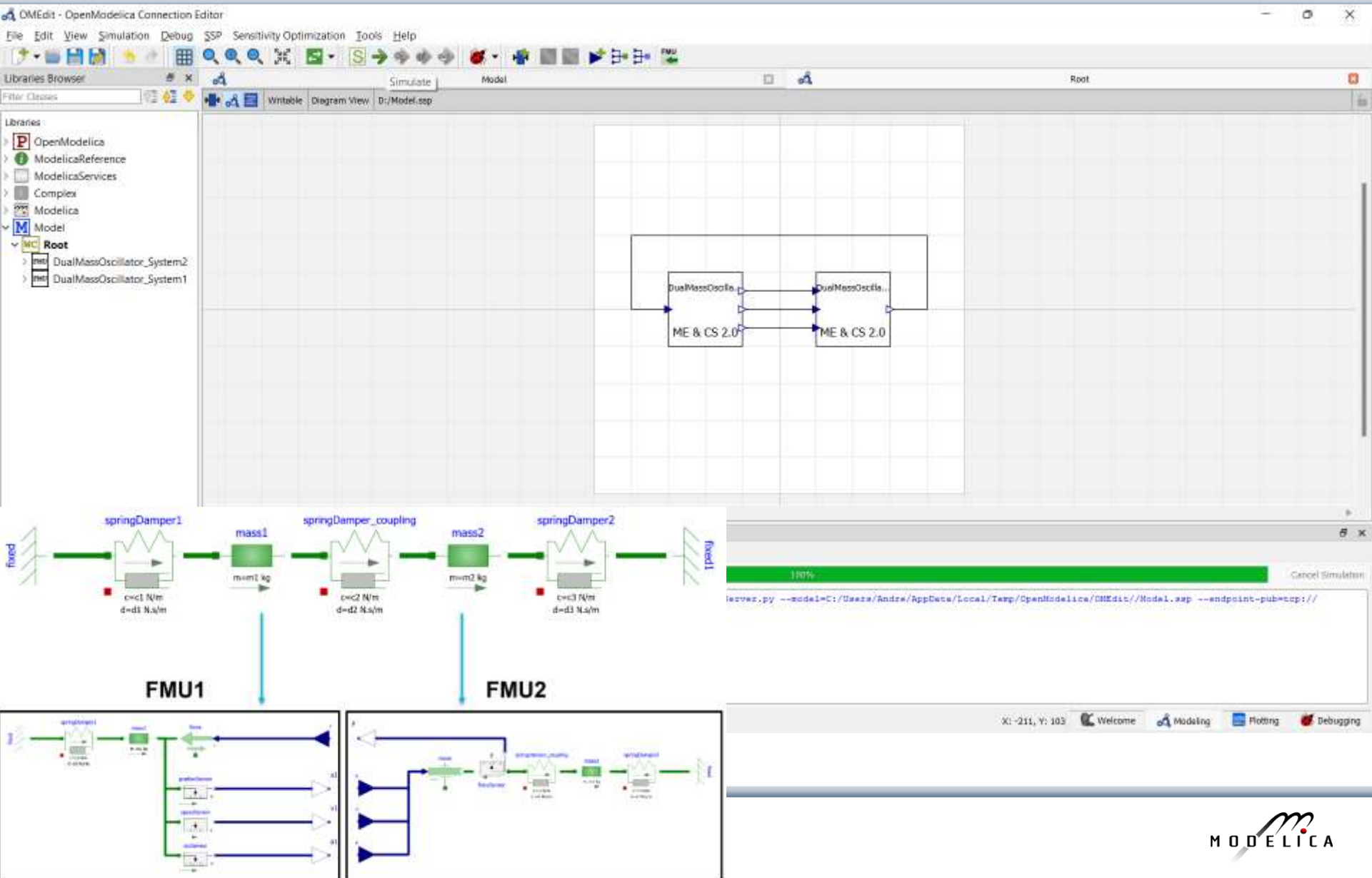
- ITEA Vice-chairman, Philippe Letellier referred to the major results delivered by the project, calling it "**a milestone on the path of open and standardised co-design and simulation of complex systems, that delivers major results**".

OMSimulator Composite Model Editor with 3D Viewer



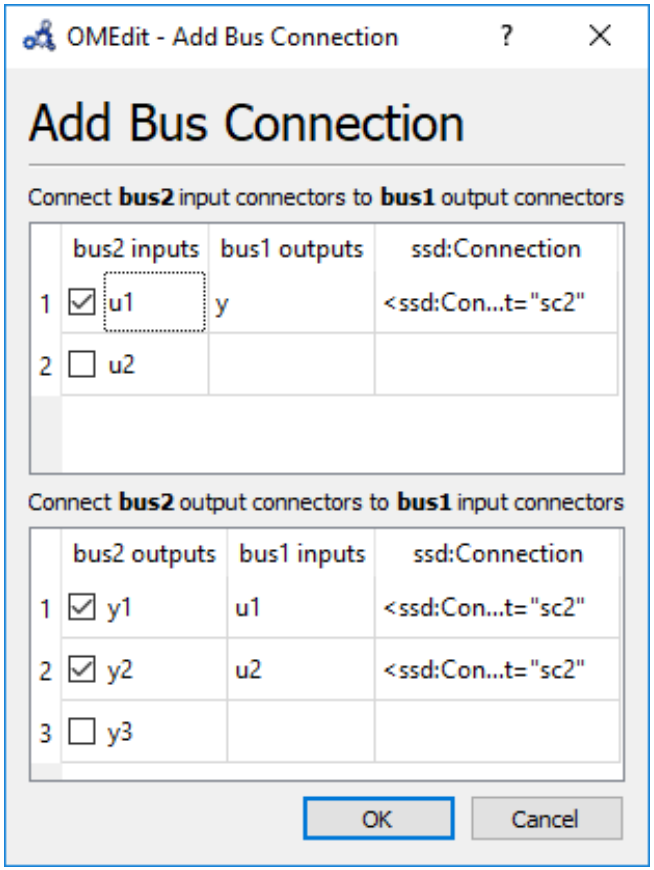
- **Composite model editor** with 3D visualization of connected mechanical model components which can be FMUs, Modelica models, etc., or co-simulated components
- **3D animation** possible
- Composite model saved as SSP XML-file
- **Support for SSP** – System Structure and Parameterization standard
- **Numerically stable** co-simulation with **TLM**

OMSimulator – GUI and SSP support

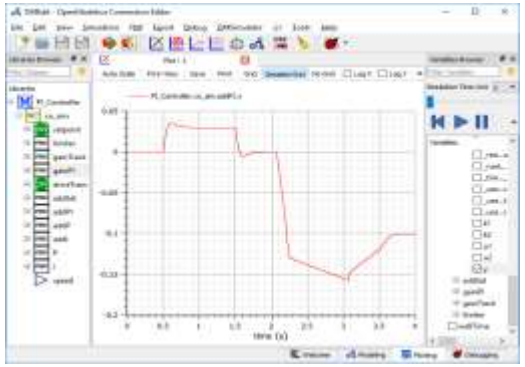


OMSimulator Simulation, SSP, and Tool Comparison

Adding SSP bus connections



FMI Simulation results in OMEdit

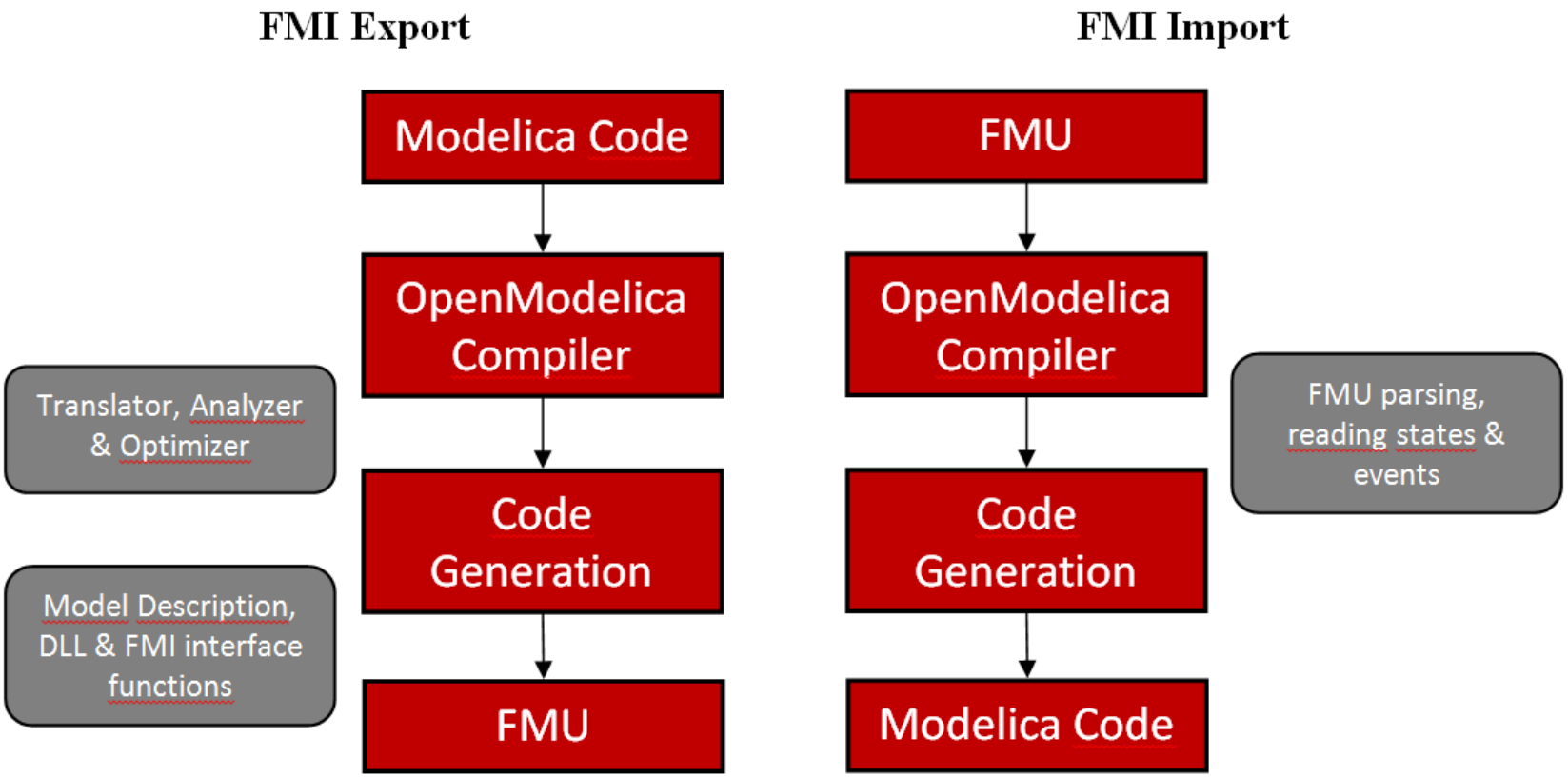


FMI Simulation Tool Comparison

	OMSimulator	DACCOSIM	Simulink	PyFMI
Commercial	No	No	Yes	No
Open-source	OSMC-PL, GPL	AGPL2	No	LGPL
Lookup Table	Yes	Yes	Yes	No
Alg. Loops	Yes	Yes	No	Yes
Scripting	Python, Lua	proprietary	proprietary	Python
GUI	Yes	Yes	Yes	No
SSP	Yes	No	No	No
platform	Linux/Win/macOS	Linux/Win	Linux/Win/macOS	Linux/Win/macOS

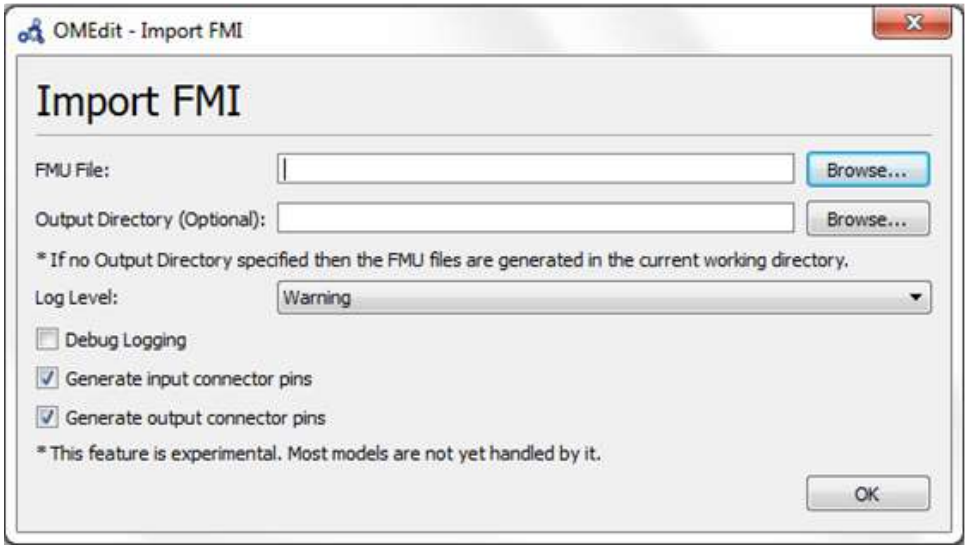
	Dymola	PySimulator	FMI Go!	FMI Composer
Commercial	Yes	No	No	Yes
Open-source	No	BSD	MIT	No
Lookup Table	Yes	Yes	Yes	Yes
Alg. Loops	Yes	Yes	Yes	Yes
Scripting	proprietary	Python	Go	No
GUI	Yes	Yes	No	Yes
SSP	No	No	Yes	Yes
platform	Linux/Win	Linux/Win	Linux/Win/macOS	Linux/Win/macOS

OpenModelica Functional Mockup Interface (FMI)



FMI in OpenModelica

- Model Exchange implemented (FMI 2.0)
- FMI 2.0 Co-simulation implemented
- The FMI interface is accessible via the **OpenModelica scripting environment,** the **OpenModelica Connection Editor** and the **OMSimulator** tool in OpenModelica



OpenModelica Code Generators for Embedded Real-time Code

- A **full-fledged** OpenModelica-generated source-code FMU (Functional Mockup Unit) code generator
  - Can be used to **cross-compile FMUs** for platforms with more available memory.
  - These platforms can **map** FMI inputs/outputs to analog/digital I/O in the importing FMI master.
- A very **simple code generator** generating a **small footprint** statically linked executable.
  - Not an FMU because there is no OS, filesystem, or shared objects in microcontrollers.

Code Generator Comparison, Full vs Simple

	Full Source-code FMU targeting 8-bit AVR proc	**Simple code generator targeting 8-bit AVR proc**
Hello World (0 equations)	43 kB flash memory 23 kB variables (RAM)	130 B flash memory 0 B variables (RAM)
SBHS Board (real-time PID controller, LCD, etc)	**68 kB** flash memory **25 kB** variables (RAM)	**4090 B** flash memory **151 B** variables (RAM)

The largest 8-bit AVR processor MCUs (Micro Controller Units) have 16 kB SRAM.

One of the more (ATmega328p; Arduino Uno) has 2 kB SRAM.

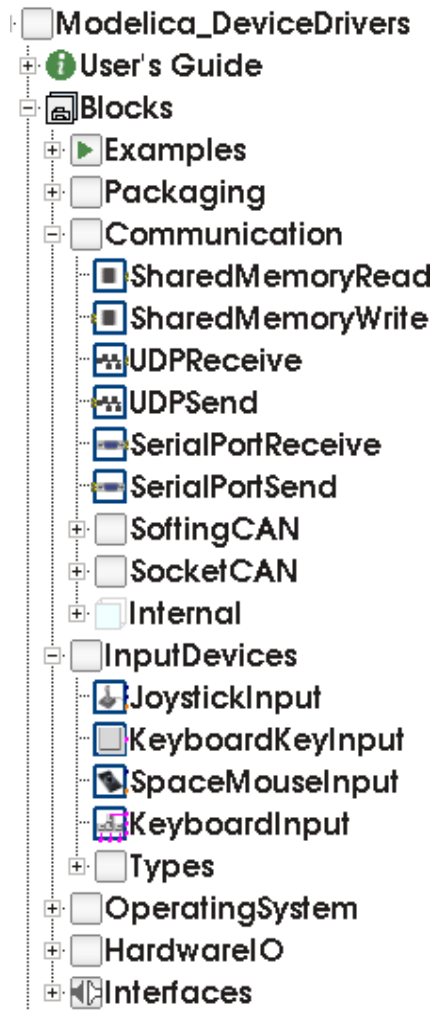
The ATmega16 we target has **1 kB SRAM available** (stack, heap, and global variable

The Simple Code Generator

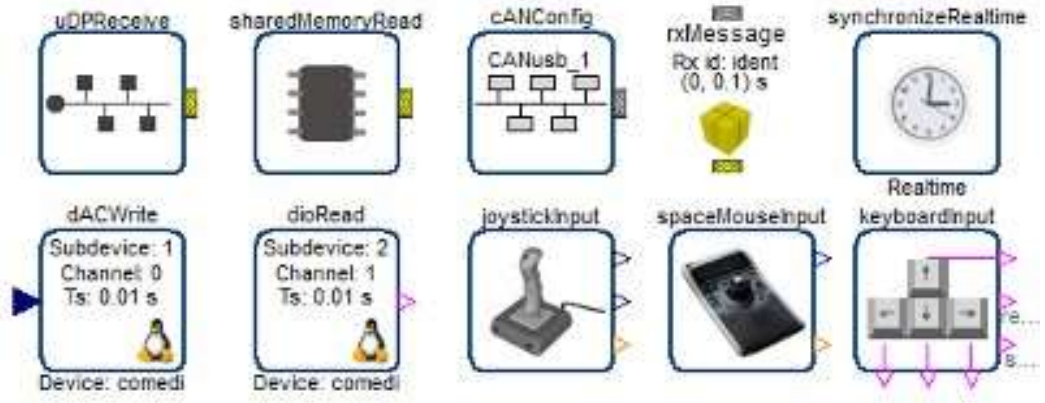
Supports only a limited Modelica subset

- No initialization (yet)
- No strongly connected components
- No events
- No functions (except external C and built-in)
- Only parts that OpenModelica can generate good and efficient code for right now (extensions might need changes in the intermediate code)
  - Unused variables are not accepted (OM usually duplicates all variables for pre() operators, non-linear system guesses, etc… but only a few of them are actually used)
- FMU-like interface (but statically linked)

Communication & I/O Devices:
Modelica_DeviceDrivers Library



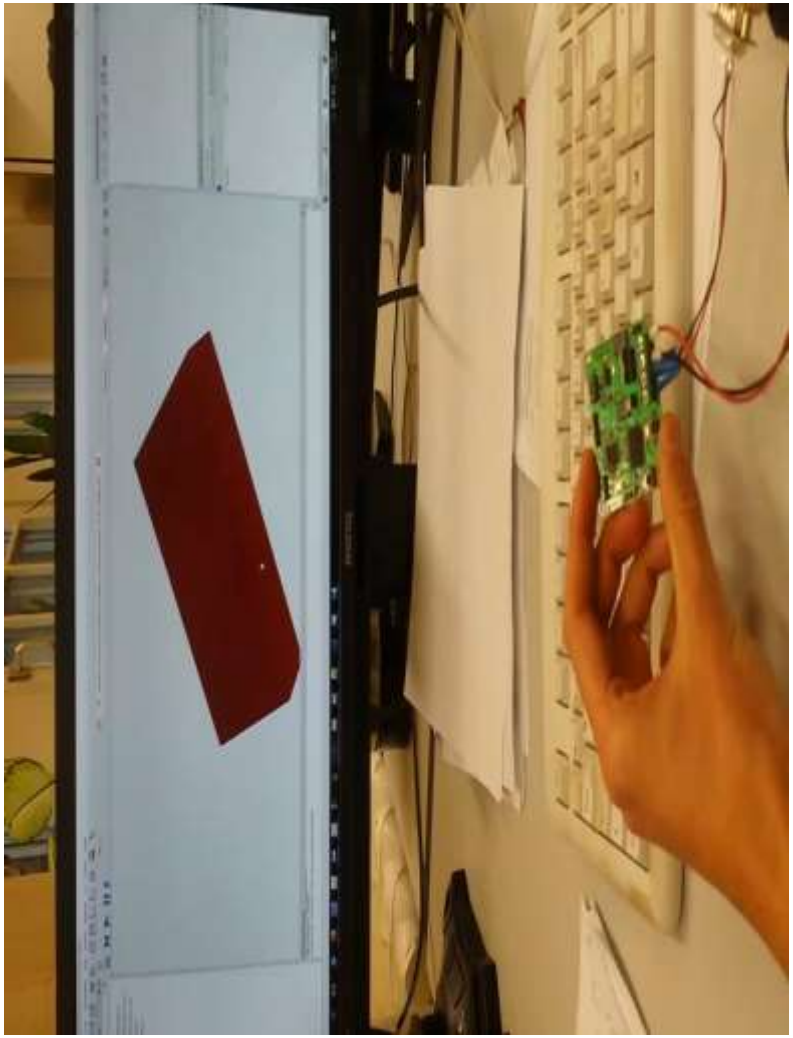
- **Free library** for interfacing hardware drivers
- **Cross-platform** (Windows and Linux)
- UDP, SharedMemory, CAN, Keyboard, Joystick/Gamepad
- DAQ cards for digital and analog IO (only Linux)
- Developed for **interactive real-time** simulations



https://github.com/modelica/Modelica_DeviceDrivers/

Modelica connected to external hardware

- IMU (Inertial Measurement Unit)
- Interfaced with a CAN-bus (Controller Area Network bus) - uses Modelica_DeviceDrivers Library
- Visualized in OMEdit



Courtesy of Volker Waurich - TU Dresden

OpenModelica and Device Drivers Library
AVR Processor Support

- No direct Atmel AVR or Arduino support in the OpenModelica compiler
- **Everything is done by the Modelica DeviceDrivers library**
- All **I/O** is **modeled explicitly in Modelica**, which makes code generation very simple

Modelica Device Drivers Library - AVR processor sub-packages:

- IO.AVR.Analog (ADC – Analog Input)
- IO.AVR.PWM (PWM output)
- IO.AVR.Digital.LCD (HD44780 LCD driver on a single 8-pin digital port)
- OS.AVR.Timers (Hardware timer setup, used by real-time and PWM packages)
- OS.AVR.RealTime (very simple real-time synchronization; one interrupt per clock cycle; works for single-step solvers)

Use Case: SBHS (Single Board Heating System)

Single board heating system (IIT Bombay)

- Use for teaching basic control theory
- Usually controlled by serial port (set fan value, read temperature, etc)
- OpenModelica can generate code targeting the ATmega16 on the board (AVR-ISP programmer in the lower left). Program size is 4090 bytes including LCD driver and PID-controller (out of 16 kB flash memory available).

Movie Demo, see next page!

Example – Code Generation to SHBS

OpenModelica – ModelicaML UML Profile

SysML/UML to Modelica OMG Standardization

- ModelicaML is a UML Profile for SW/HW modeling
  - Applicable to "pure" UML or to other UML profiles, e.g. SysML
- Standardized Mapping UML/SysML to Modelica
  - Defines transformation/mapping for **executable** models
  - Being **standardized** by OMG
- ModelicaML
  - Defines graphical concrete syntax (graphical notation for diagram) for representing Modelica constructs integrated with UML
  - Includes graphical formalisms (e.g. State Machines, Activities, Requirements)
    - Which do not exist in Modelica language
    - Which are translated into executable Modelica code
  - Is defined towards generation of executable Modelica code
  - Current implementation based on the Papyrus UML tool + OpenModelica

Example: Simulation and Requirements Evaluation

«model»
(TwoTanksSystemExample::SystemSimulations)
TankSystemSimulation

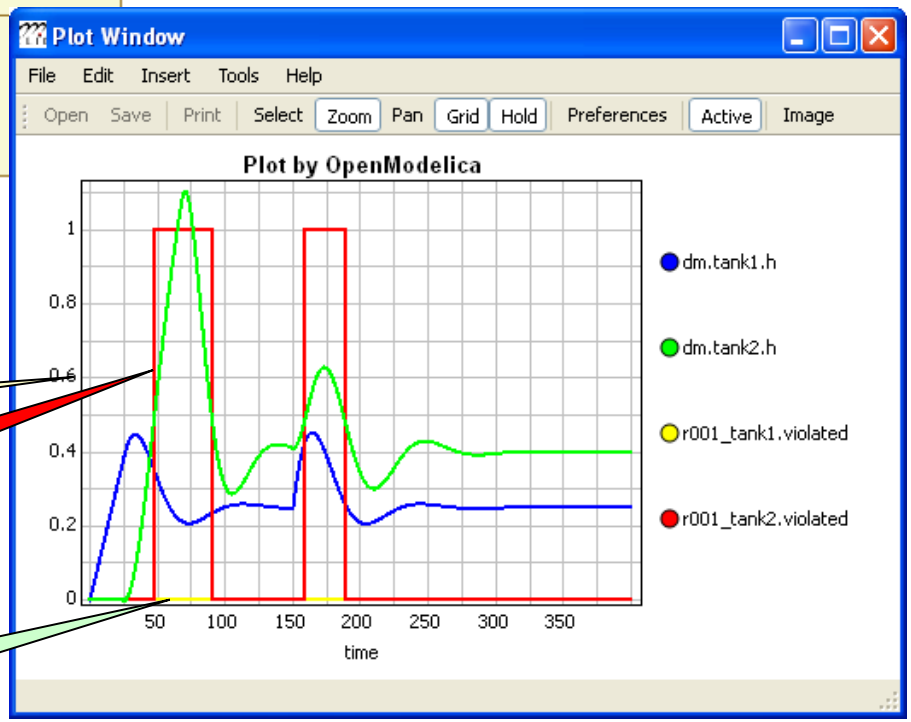
«component» dm: TanksConnectedPI
«requirementInstance» r001_tank1: Max level of liquid in a tank
«requirementInstance» r001_tank2: Max level of liquid in a tank
«requirementInstance» r002_tank1: Volume of the tank1

Req. 001 is instantiated 2 times (there are 2 tanks in the system)

tank-height is 0.6m

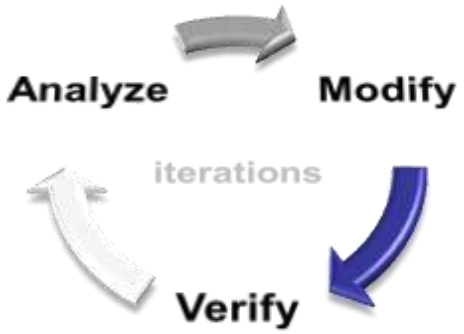
Req. 001 for the tank2 is violated

Req. 001 for the tank1 is not violated



vVDR Method – virtual Verification of Designs vs Requirements

Actor	Task	Created Artifact
	Formalize Requirements	RMM — Requirement Monitor Models
	Formalize Designs	DAM — Designs Alternative Models
	Formalize Scenarios	SM — Scenario Models
AUTOMATED	Create Verification Models *	VM — Verification Models
AUTOMATED	Execute and Create Report	Reports
	Analyze Results	



Goal: Enable on-demand verification of designs against requirements using automated model composition at any time during development.

Need for Debugging Tools
Map Low vs High Abstraction Level

- A **major part** of the total **cost** of software projects is due to testing and debugging
- US-Study 2002:
  Software errors cost the US economy **annually~ 60 Billion $**

- **Problem: Large Gap in Abstraction Level**
  from **Equations** to **Executable Code**
- Example error message (hard to understand)

  Error solving nonlinear system 132

  time = 0.002

  residual[0] = 0.288956

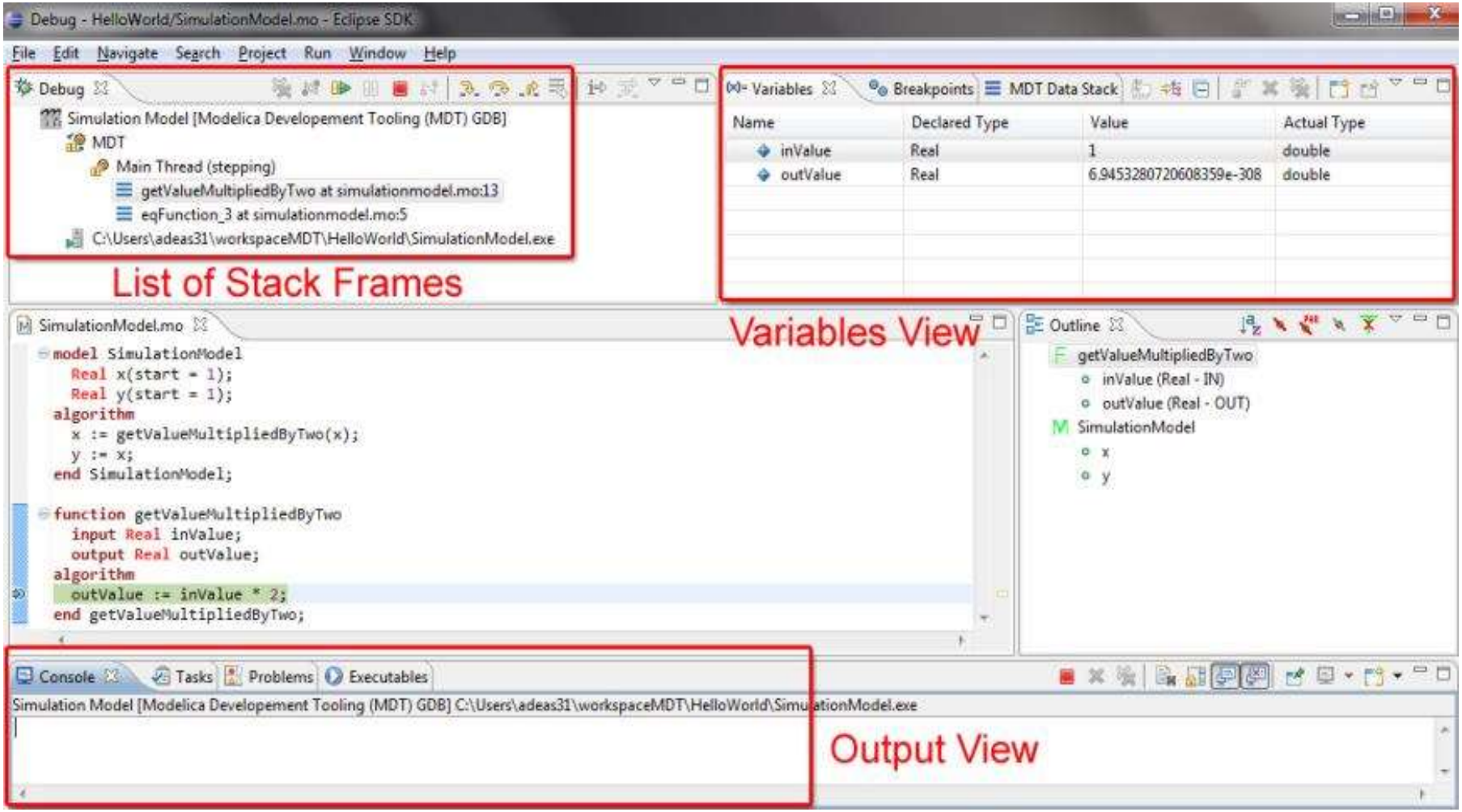
  x[0] = 1.105149

  residual[1] = 17.000400

  x[1] = 1.248448

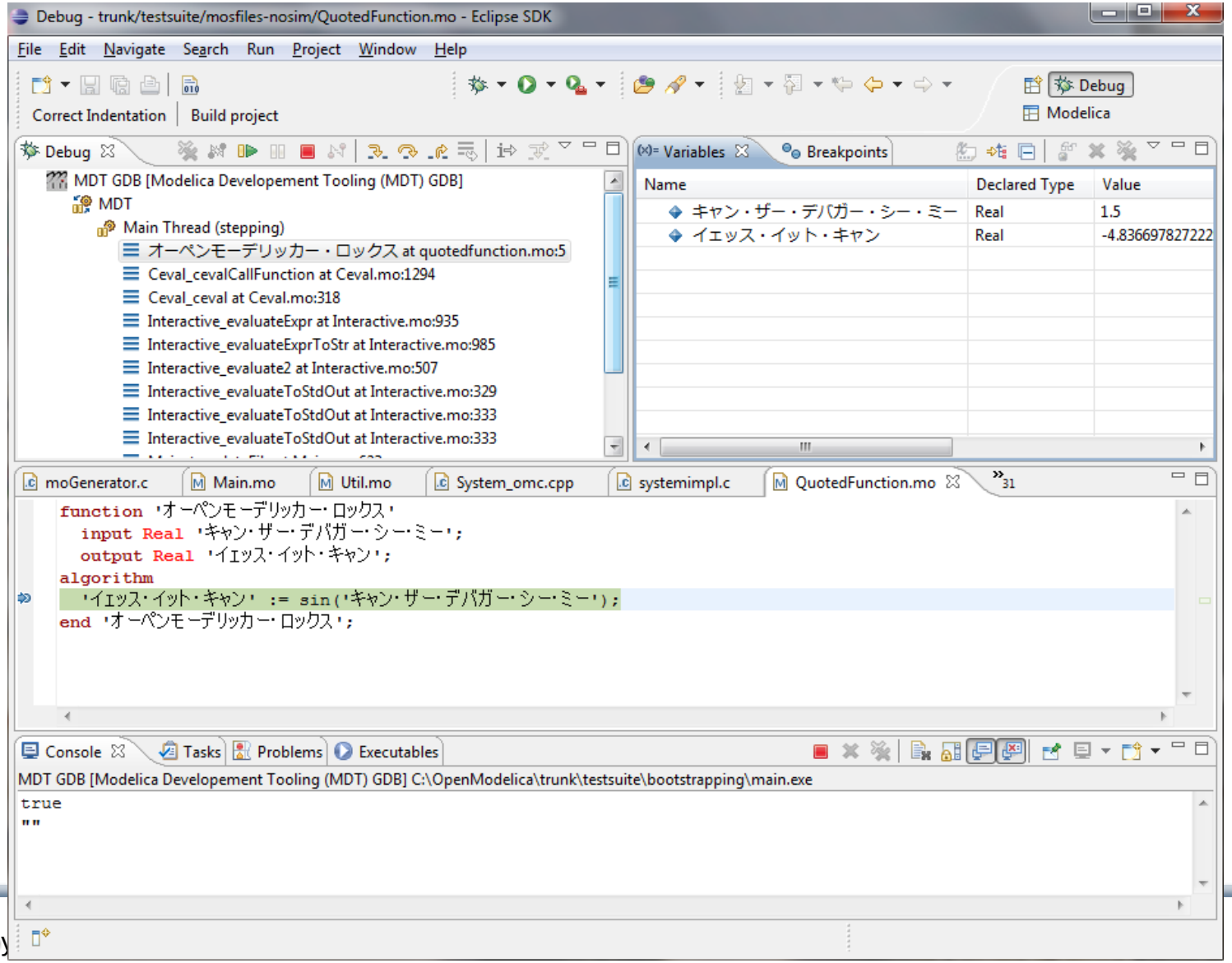
  ...

OpenModelica MDT Algorithmic Code Debugger

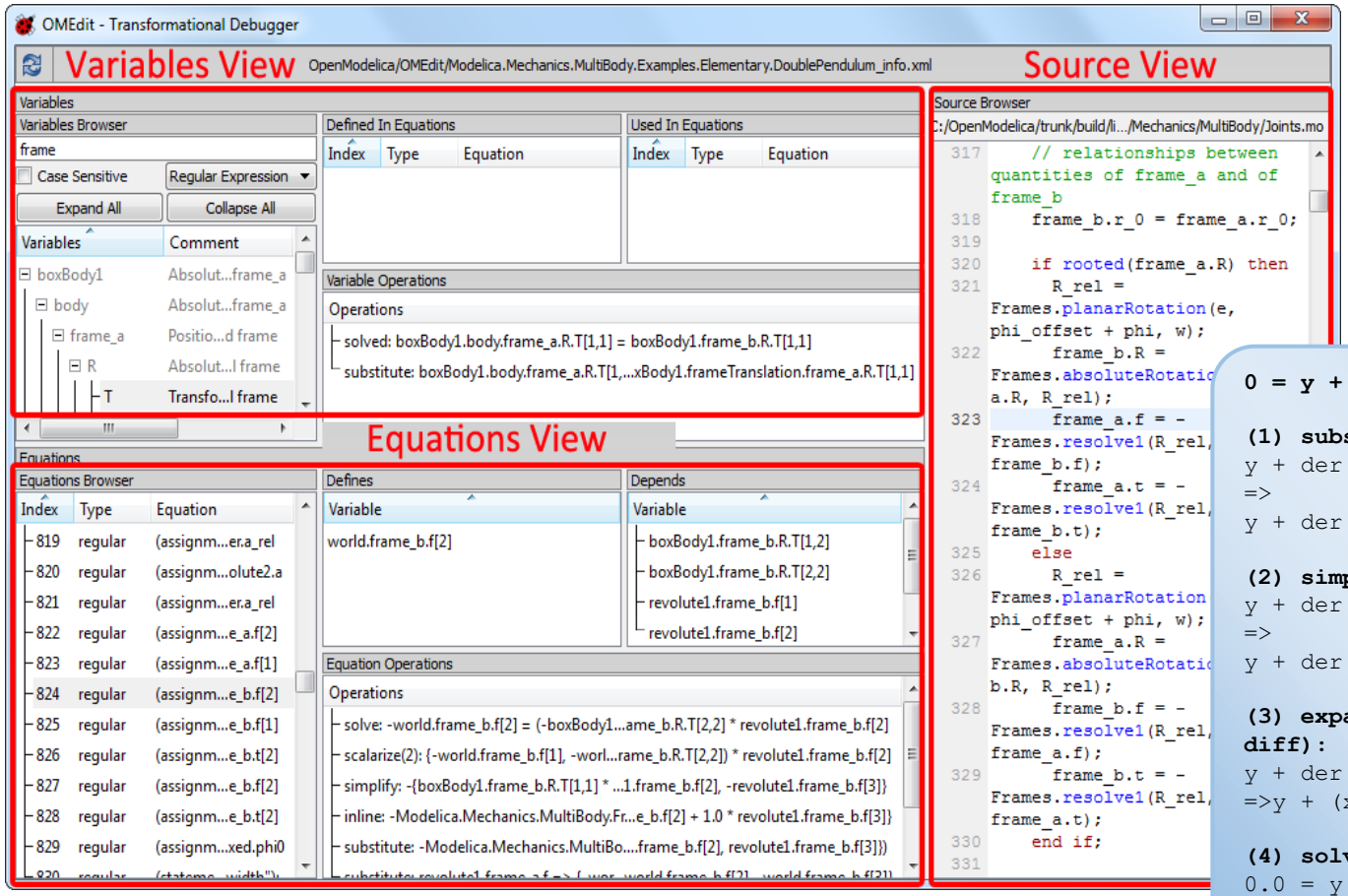


The OpenModelica MDT Debugger (Eclipse-based)

Using Japanese Characters



OpenModelica Equation Model Debugger



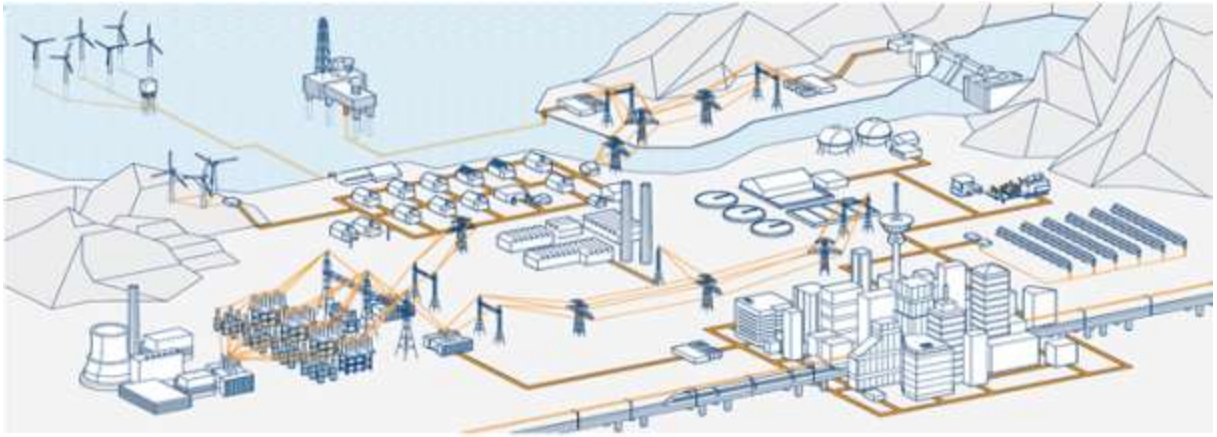
Showing equation transformations of a model:

```
0 = y + der(x * time * z); z = 1.0;

(1) substitution:
y + der(x * (time * z))
=>
y + der(x * (time * 1.0))

(2) simplify:
y + der(x * (time * 1.0))
=>
y + der(x * time)

(3) expand derivative (symbolic diff):
y + der(x * time)
=>y + (x + der(x) * time)

(4) solve:
0.0 = y + (x + der(x) * time)
=>
der(x) = ((-y) - x) / time
time <> 0
```

Mapping run-time error to source model position

ABB Industry Use of OpenModelica FMI 2.0 and Debugger

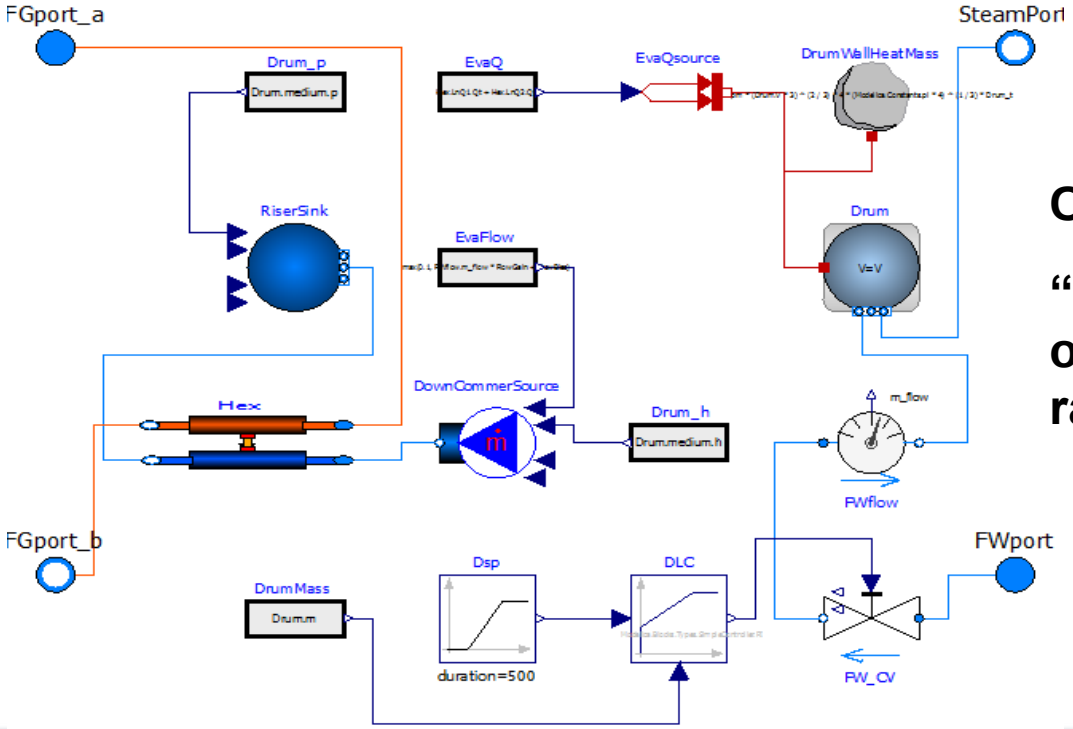
- ABB OPTIMAX® provides advanced model based control products for power generation and water utilities



- ABB: "*ABB uses several compatible Modelica tools, including OpenModelica, depending on specific application needs.*"
- ABB: "*OpenModelica provides outstanding debugging features that help to save a lot of time during model development.*"

Performance Profiling for faster Simulation
(Here: Profiling equations of Siemens Drum boiler model with evaporator

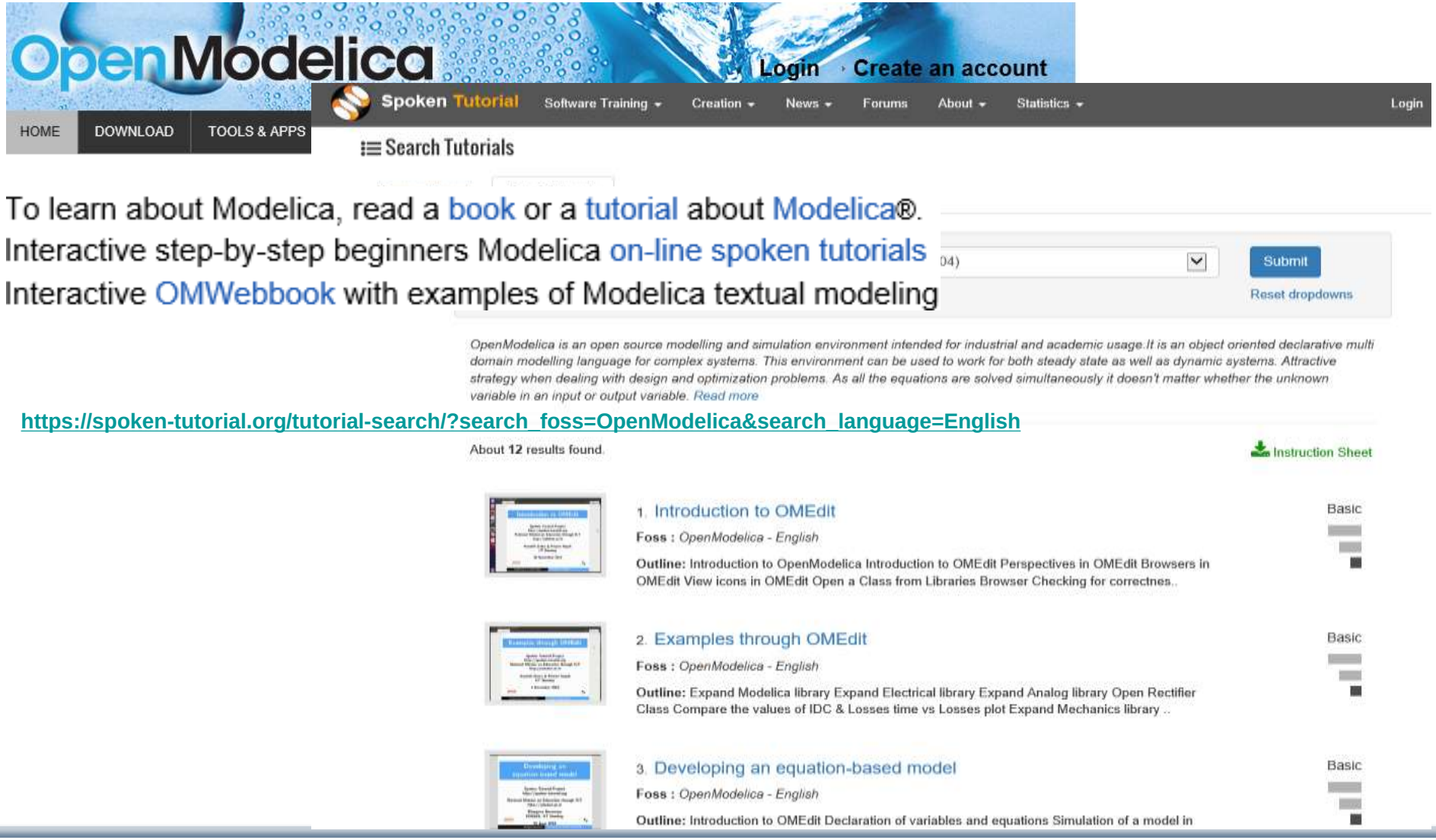
- Measuring **performance** of equation blocks to find bottlenecks
  - Useful as input before model simplification for real-time applications
- Integrated with the debugger to **point out the slow equations**
- Suitable **for real-time profiling** (collect less information), or a complete view of all equation blocks and function calls



Conclusion from the evaluation:

"…the profiler makes the process of performance optimization radically shorter."

Exercise: Try Some Spoken-Tutorial Exercise on OpenModelica. Link from www.openmodelica.org

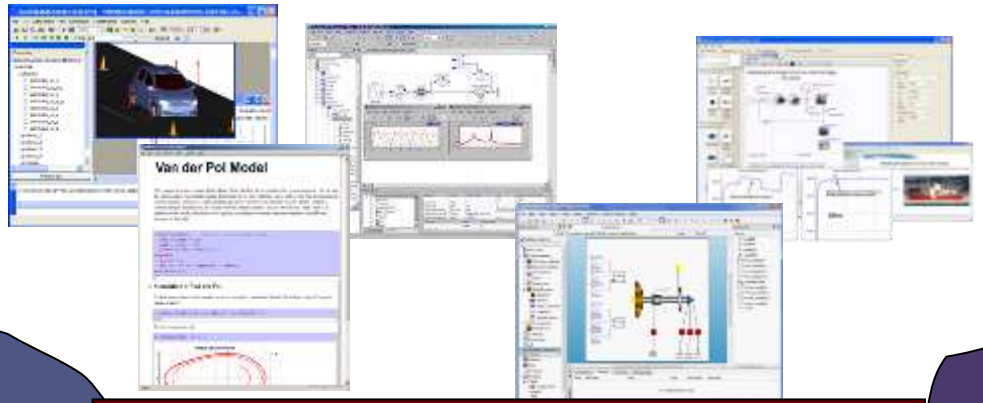


Summary

Multi-Domain Modeling

Visual Acausal Component Modeling

MODELICA



Typed Declarative Textual Language

Thanks for listening!

Hybrid Modeling