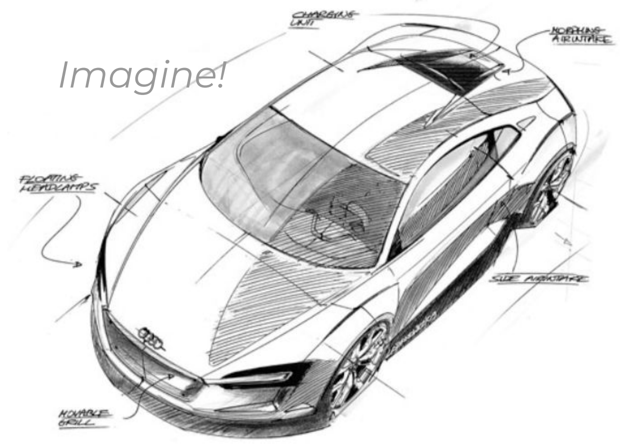
ECSE 4961/6961

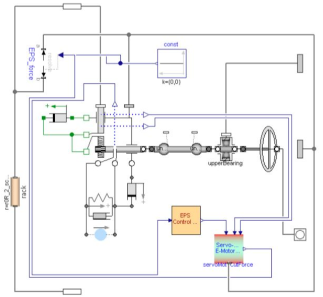
Modeling and Simulation for Cyber-Physical Systems

Fall 2018
Prof. Luigi Vanfretti,
http://ALSETLab.com

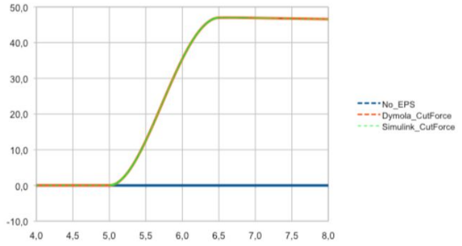
Imagine!



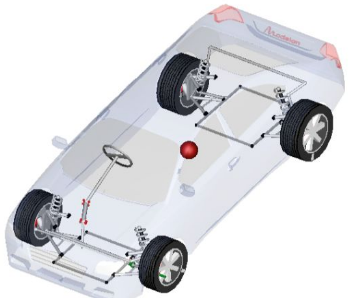
Source: http://dx.doi.org/10.3384/ecp1106313



Model!



Simulate!



Visualize!

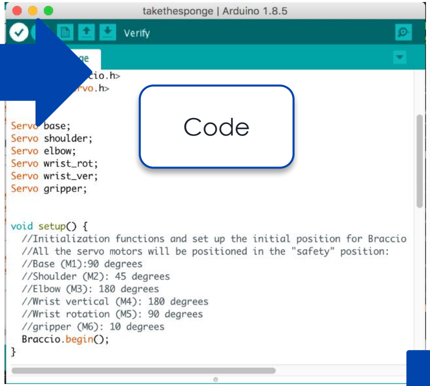
Agenda

- Administrative Matters
  - Go over the Syllabus
  - Go over the Schedule
- Introduction to Modeling and Simulation
- Introduction to CPS
- Introduction to Dymola

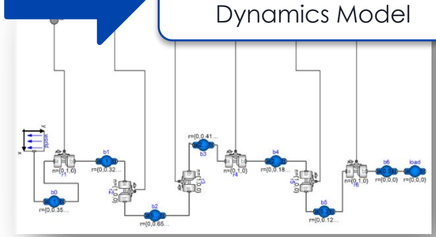
Example project proposal: *6 DOF Robot Arm*

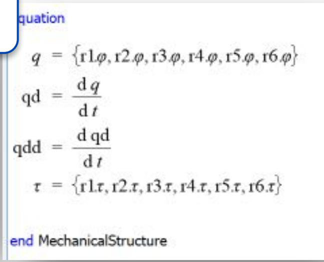
- Virtual Prototyping:
  - Model, code and simulate!
- Build the Prototype!
- Deploy control code.
- Compare real control system with the design!

Code

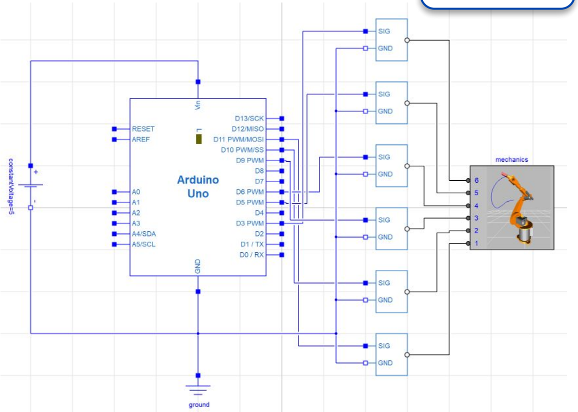


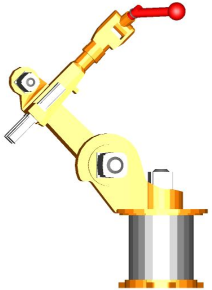
Mechanical Multi-body Dynamics Model



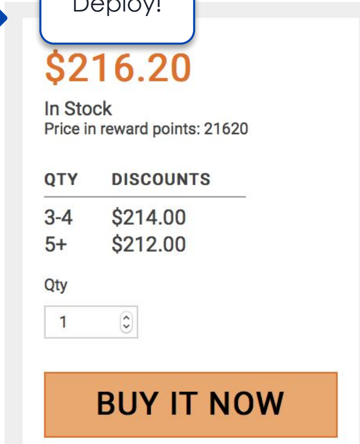


Simulate





Deploy!



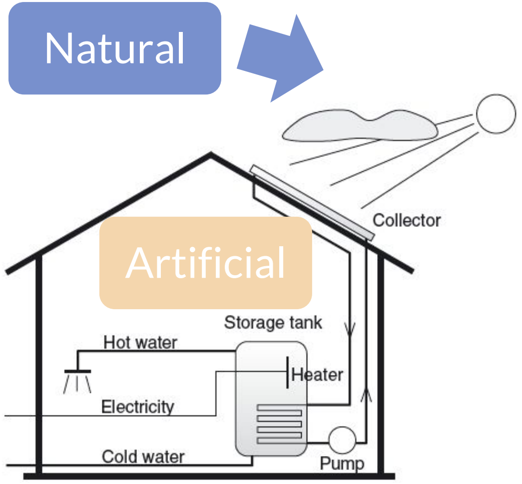
Introduction to Modeling and Simulation

General Concepts about Systems

- **What is a system?**
  - Space shuttle, tank, power system, etc.
  - A system can contain sub-systems that are themselves systems. (eg. Power sys. contains generators, generators are subsystems with different controls, protections, etc)
  - **A system is an object or collection of objects whose properties are of interest.**
- **We want to study selected properties of these objects.**
- *Why study a system?*
  - Understand it in order to build it: engineer's point of view
  - Satisfy human curiosity (understand more): researcher's point of view

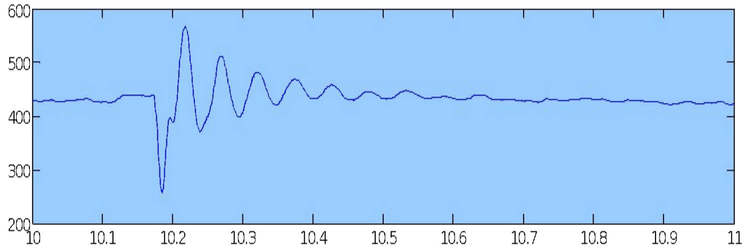
https://www.nasa.gov/feature/goddard/2017/new-night-lights-maps-open-up-possible-real-time-applications

System Types and Properties



- Natural and Artificial Systems:
  - A system can occur naturally (e.g. the universe) or artificially (e.g. space shuttle)
  - It can also be a mix of both: the solar-heated water system is artificial while the sun and clouds: natural
- Properties:
  - **Observability:** being able to take measurements of the system during the process.
  - **Controllability:** influence on the behavior of the system through inputs.
  - **Inputs:** variables of the environment that can influence the behavior of the system. These inputs may or not be ***intentionally*** controlled.
  - **Outputs:** variables that are determined by the system and may influence the surrounding environment.

Experiments (1/2)



- Observability is essential to study a system:
  - We need to observe outputs
  - Learn if its possible to excite the system by controlling its inputs
  - The experimentation process consists of extracting information from a system by varying the input signals.
- Requirement: the system is controllable and observable
  - We apply a set of external conditions to the accessible inputs and observe the reaction of the system by measuring the outputs.
- Experiments at the **system** scale are very rare in certain kinds of systems (e.g. critical infrastructure)

Chief Joseph Dynamic Breaker – "The Toaster"

[BPA] "It can consume 1,440 MW - more than the output of Bonneville Dam. It's only capable of staying on for 3 seconds - beyond that, it would destroy itself."

History of the DC Pacific intertie: [link]

Experiments (2/2)

- Difficulties:
  - Often systems have many inputs are not accessible (e.g. inside a control system) and controllable (disturbance inputs)
  - Many useful outputs are not accessible for measurements (internal states)
  - **Cost:** it is possible damage of the system.
  - **Danger:** training nuclear plant operators

  - **The system may not even exist (we are going to build it).**
- **The difficulties of experimentation lead us to the development of models!**
- A model of a system allows investigation and may answer many questions regarding the real system **if the model is realistic/good enough!**

Models

Lex. II.

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

- A model of a system is anything an “experiment” can be applied to in order to answer questions about the system being mimicked.
  - …without doing experiments on the real system.
  - Instead **simplified** experiments are performed on the **model!**
  - We have then ***a simplified system that reflects properties of the real system.***

- Types:
  - ***Mental*** model: a statement “person A is reliable” (models the behavior of the person)
  - ***Verbal*** model: expressed in words *(see model above)!*

Mathematical model: *A description of the system where the relationships between variables of the system are expressed in mathematical form.*

Mathematical Models

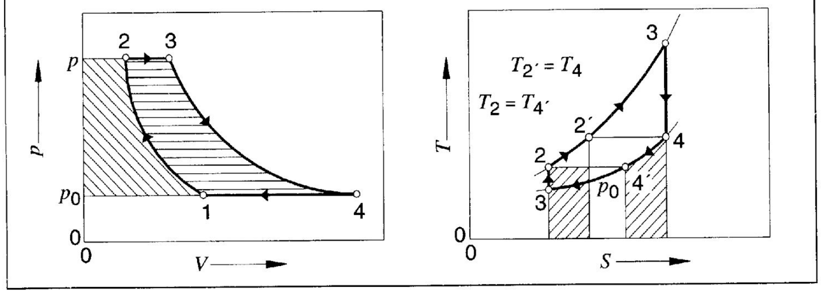
Mathematical models have been developed from physical principles (laws of nature!), experiments and/or observations, **an understood by humans → knowledge.**

Model knowledge is stored in:

- Books (equations and text in “natural” language and
- human minds

which computers cannot access or (uniquely) interpret.

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

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

and the quantity of heat to be removed is

$$q_{out} = c_p \cdot (T_{4'} - T_1) = c_p \cdot (T_2 - T_1).$$

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

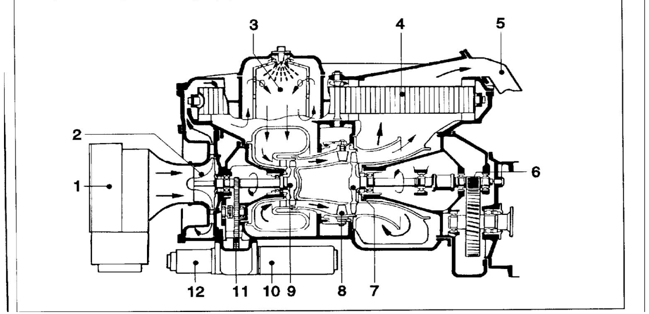
$$\eta_{th} = 1 - Q_{out}/Q_{ir}$$

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

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

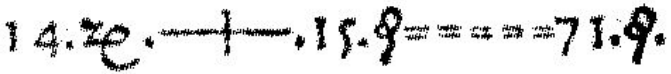
Current gas-turbine powerplants achieve thermal efficiencies of up to 35 %.
Advantages of the gas turbine: clean exhaust without supplementary emissions-control devices; extremely smooth running; multifuel capability; good static torque curve; extended maintenance intervals.
Disadvantages: manufacturing costs still

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.*

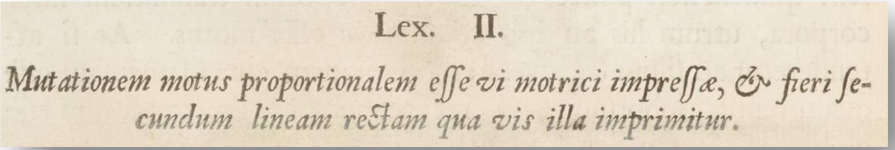


The Form of Mathematical Models – *Equations*

- Although forms of mathematics were used before 1000 BC, he first attempt on solving a form of first order linear equations in 1650 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 "

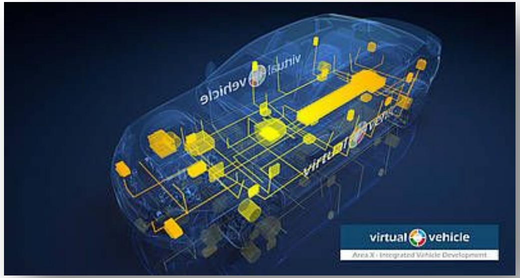


Lex. II.

*Mutationem motus proportionalem esse vi motrici impressæ, & fieri se-
cundum lineam rectam qua vis illa imprimitur.*

- CSSL (1967) introduced a special form of "equation":
  - variable = expression
  - v = INTEG(F)/m
- Programming languages usually do not allow equations!
  - Explicit assignment statements are used.
- In this course we will learn the Modelica modeling language, which allows for
  - Acasual and
  - Object-oriented equation based modeling using a **standardized computer language**

Models and Simulation



- *We represent CPSs in two different ways:*

- Equations and functions | `- Computer programs`

- *The artifacts represented by mathematical models in a computer are called [virtual prototypes]()*

- ***Simulation: from latin "Simulare"* means to pretend.**
    - **A simulation is an experiment performed on a model.**
    - This definition does not require a model to be present in mathematical or computer form.
    - We will however focus on models that can be written in computer-representable forms.
    - Hence, we will perform numerical experiments by performing computations (by hand) or in a computer.
- The **value of the simulation** is completely dependent on how well the model represents the real system regarding the questions to be answered.

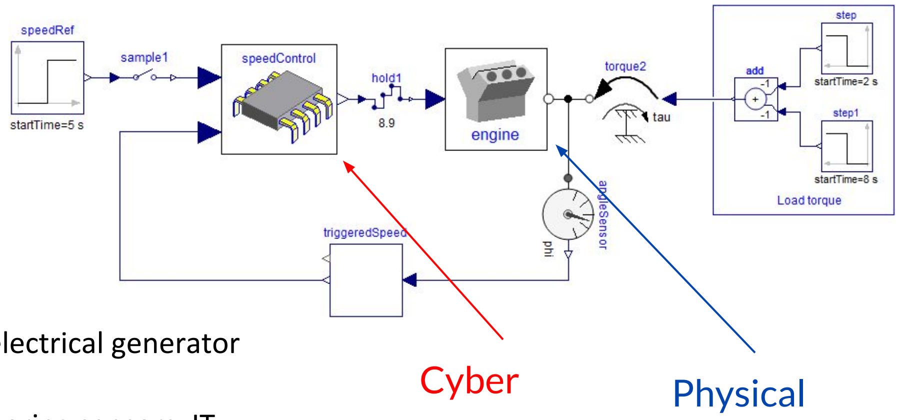
A model can NEVER be accepted as a final and true/definite description of an actual cyber-physical system.

Introduction to CPS

Cyber-Physical Systems (CPS)

CPS are “engineered” systems **integrate** cyber and physical components into a “hybrid” system:

- **Cyber components:** “follow the **rules** of algorithms”, examples
  - Computation (e.g. computers, IT systems), communication protocols
- **Physical components / systems:** “follow the **laws** of nature”, examples
  - Thermal Domain:
    - Component: a water heater
    - System: a building’s Air Conditioning (HVAC) system
  - Electrical Domain:
    - Component: a transistor
    - System: a data acquisition board for a sensor.
  - Multi-domain Domain:
    - Component: gas turbine.
    - System: power plant with a gas turbine and an electrical generator
- **Cyber-physical multi-domain:**
  - **Cyber components:** digital control system, digital monitoring sensors, IT …
  - **Cyber-physical System:** power plant as above, but with digital monitoring and control!



Why are CPS important?

CPS technologies are transforming the way people interact with engineered systems:

- Just as the Internet has transformed the way people interact with information
- From the Internet of Information to the “Internet of Things”

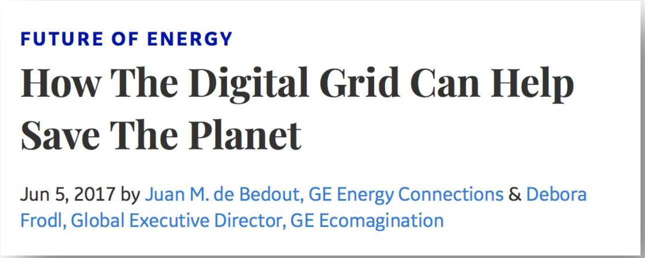
The “CPS” view and CPS in general help drive innovation and competition in:

- aeronautics, building design, energy,
- electrical power grids (‘smart grid’)
- healthcare, manufacturing, and transportation...

Advances in CPS will enable:

- capability, adaptability, scalability, resiliency,
- safety, security, and usability

to expand the horizons of these critical systems.


FUTURE OF ENERGY
How The Digital Grid Can Help Save The Planet
Jun 5, 2017 by Juan M. de Bedout, GE Energy Connections & Debora Frodl, Global Executive Director, GE Ecomagination

A Fundamental Question:
Why do we need to develop models and perform simulations for Cyber-Physical Systems?

- To reduce the lifetime cost of a system:
  - ***In requirements:*** trade-off studies
  - ***In test and design:*** fewer proto-types
  - ***In training:*** avoid accidents
  - ***In operation:*** anticipate problems!

- (1910) The prospective pilot sat in the top section of this device and was required to line up a reference bar with the horizon.
- 42% of the British pilots who died in WW1 were killed in training [Jones, Dr.]

Example:

Boeing's Model-Based Systems Engineering (MBSE) approach to build a ***Complex Cyber-Physical "System-of-Systems"***

Simulating Success

How do modeling and simulation activities, capabilities benefit Boeing? Let us count the ways—9 of them

By Debby Arkell

Hands-on experience often can be the best way to tackle complex problems or master challenging skills. But when it comes to navigating intricate, variable-laden scenarios, or combat situations involving complex military maneuvers using expensive equipment, "on-the-job training" often is not a prudent approach.

That's why Boeing Integrated Defense Systems, Commercial Airplanes and Phantom Works engage in a wide variety of modeling and simulation activities, designed to provide ever more realistic simulations to internal customers across the enterprise—and to external customers as well.

"There is a tremendous amount of diversity in modeling and simulation being worked on at Boeing, encompassing very complex issues within a very broad spectrum," said Ron Fuchs, director of Modeling and Simulation for IDS. "Right now there are more than

U.S. Navy legacy platform and deliver a comprehensive and credible concept of operations.

Boeing analysts have a variety of tools available—or under development—that can demonstrate concepts and provide significant cost savings by exploring ideas, developing systems, testing and manufacturing within a virtual environment before committing to specific approaches.

4 Product or system testing

Models and simulations are used to test

M&S used to test prototypes in variety of environments.

networked computer systems in the FCS system of systems will be tested in a large-scale distributed simulation facility called the FCS System of Systems Integration Lab. The SoSIL provides a

Training systems and maintenance

M&S are used to *train users in the operational environment* – enhancing learning.
Simulation *costs 1/10* of running actual scenarios.

Network communications

Tactical military communications networks—such as Joint

Scale of networks: cost-prohibitive or technically impossible for field tests.

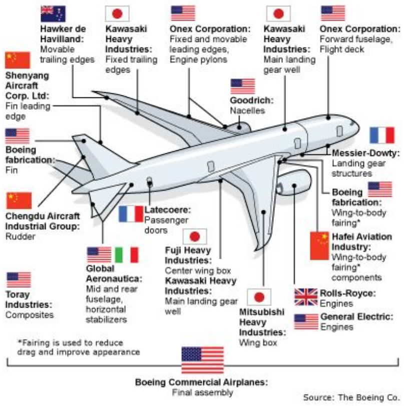
M&S used to test and validate networking protocols in laboratory - environment acting as a test bed.

8

Calif., is an environment that acts as a distributed virtual test bed, and the Boeing Transformational Communications Laboratory in El Segundo, Calif., performs a similar function for satellite communications.

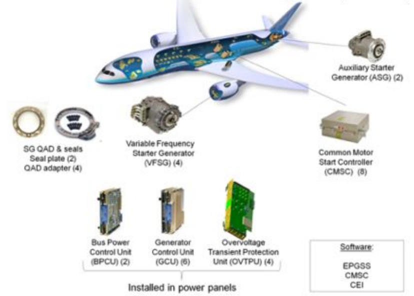
Large Number of Vendors for the Final System

787 structure suppliers



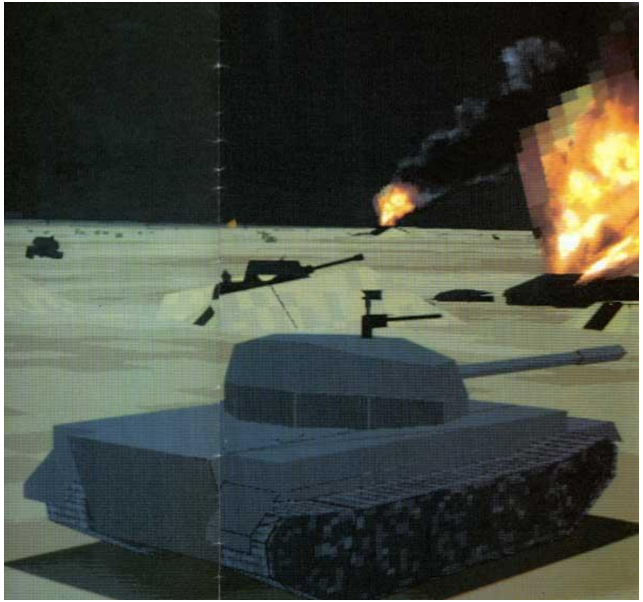
A Flying Micro-Grid!

Electric Power Generation & Start System (EPGSS)



Another Example:
The power of models in SIMNET

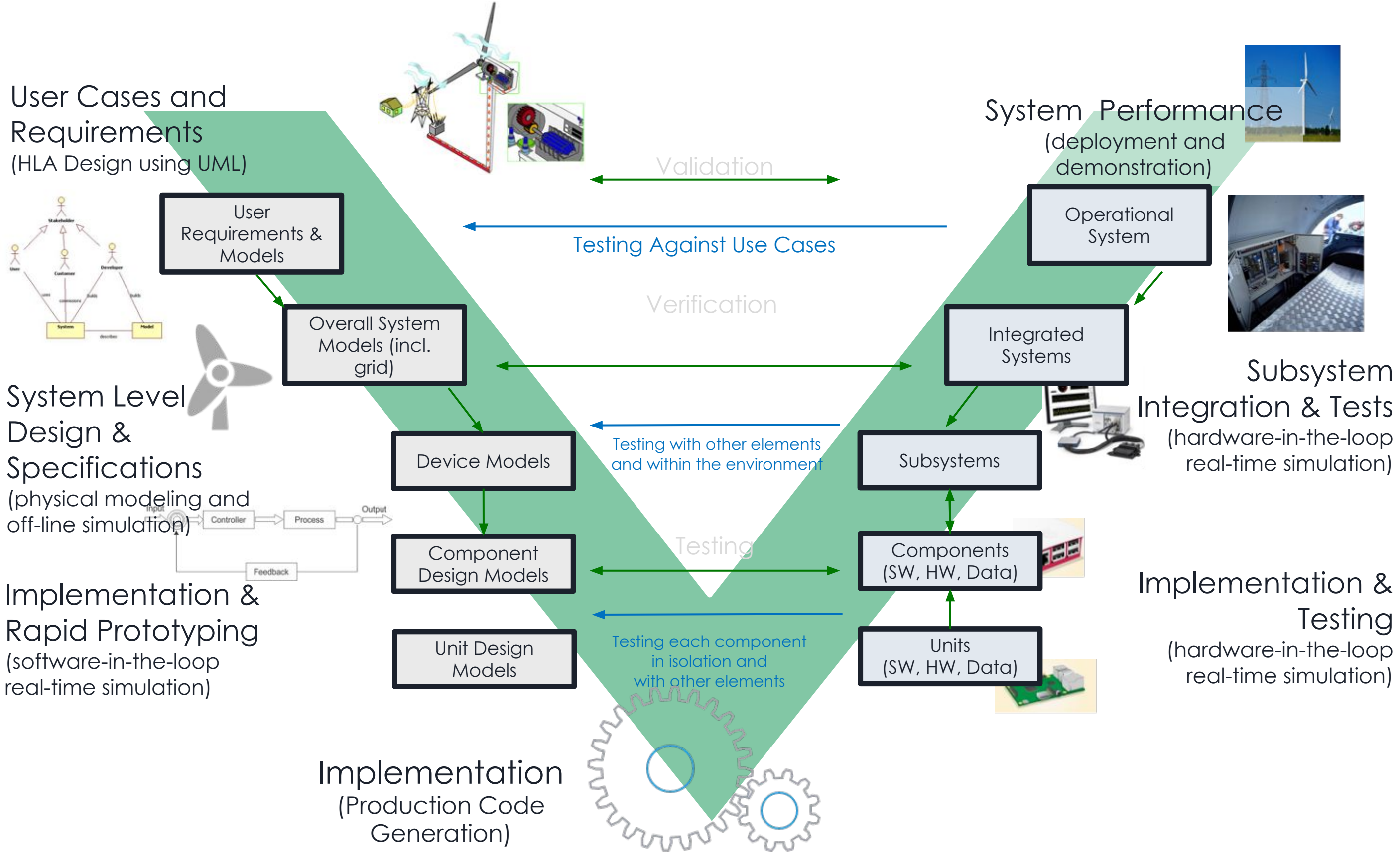
- Developed in 1980 to early 1990’s
- Distributed, interactive simulation for training combat units
- 10 year development cycle, $300 million
- Started the huge (multi-billion dollar) industry of networked simulations that are relied upon by DoD for training and engineering
- Where do you think the technology to play “Call of Duty” comes from?



Simnet screenshot From Bruce Sterling's "War is Virtual Hell," Wired 1.01 (March-Apr. 1993)

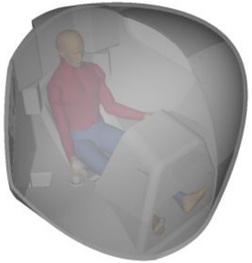
Roles of M&S in Cyber-Physical System Development

And the Model-V Development Approach for Model-Based Systems Engineering (MBSE)



Example of MBSE CPS Development using Modelica

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

Source: Tobias Bellmann, DLR, Oberphaffenhofen, Germany

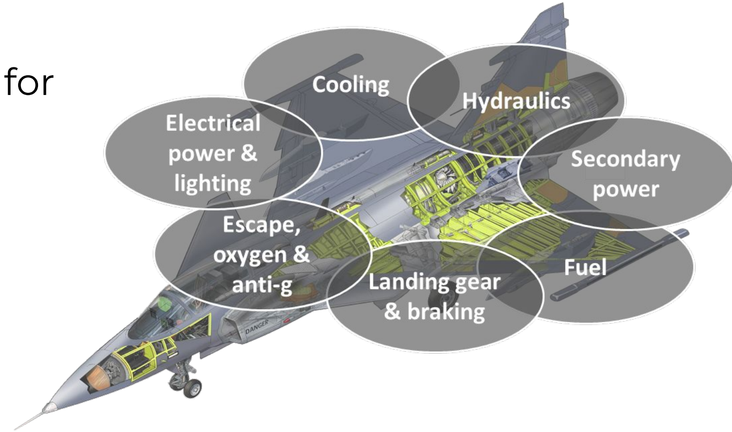
Why Modelica and FMI standards are important for

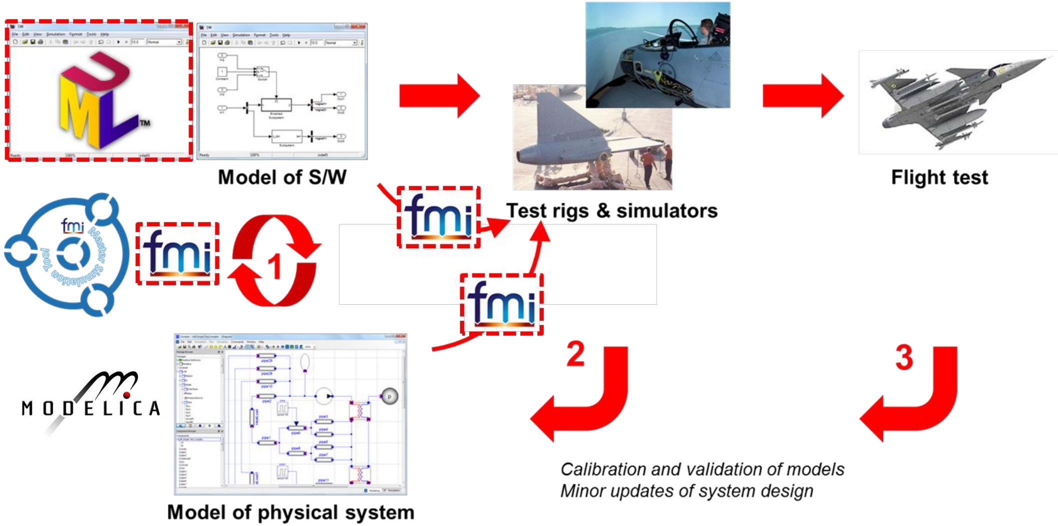
CPS Development?

- SAAB's Grippen Fighter Use Case resulted in enhanced development process with OpenCPS.eu project results implemented:
  - 1st loop covers a larger part of total system functionality
    - Possible to include FMUs of S/W developed in xtUML
    - Efficient distributed simulation of a connected set of large models (FMUs)
  - Early discovery of design errors & improved decision support in early model-based design decisions
  - Reduced pressure on test rigs
  - Increased use of models, possibility of standardized deployment of models to new users
  - Further increased knowledge in MBSE, human capital, contact network

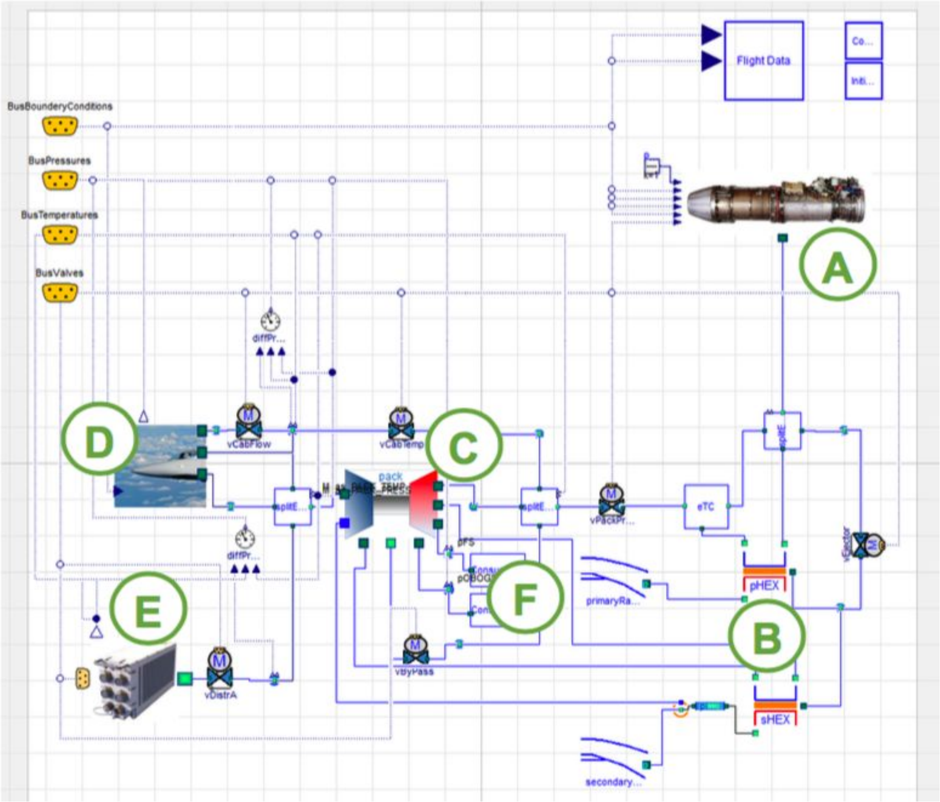
Quantitative estimation of business impact, regarding cost for development and V&V of a new aircraft vehicle subsystem

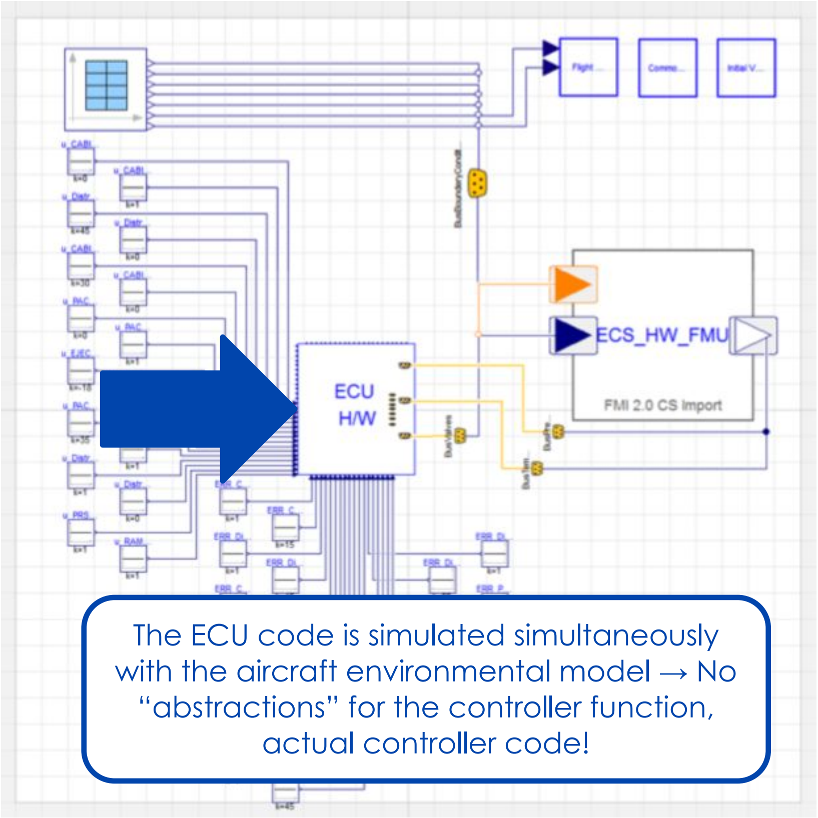
15% cost increase in 1st loop
15% cost reduction in 2nd loop
20% cost reduction in 3rd loop





Modelica Model of Grippen's Electronic Control Unit (ECU)





The ECU code is simulated simultaneously with the aircraft environmental model → No "abstractions" for the controller function, actual controller code!

Why CPS and this course should matter to you?!

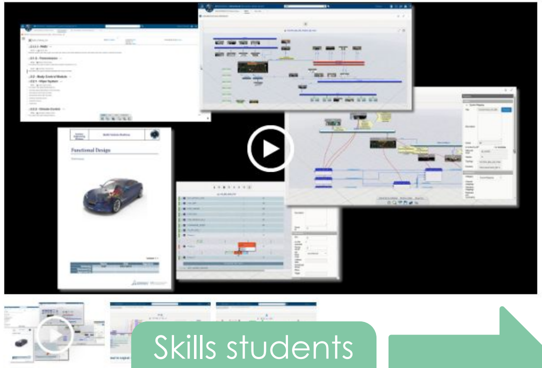
- Boeing's relationship with Dassault's 3DS Platform:

Boeing and Dassault Systèmes Announce Extended Partnership

Boeing Extends Use of Dassault Systèmes to Include 3DEXPERIENCE Platform for Manufacturing Operations Management and Product Lifecycle Management

"Boeing will deploy the 3DEXPERIENCE platform in phases and rely on Winning Program, Co-Design to Target, Ready for Rate, Build to Operate and License to Fly industry solution **experiences for aerospace and defense** to deepen its **end to end digital collaboration, design, engineering, analysis, manufacturing planning** and shop floor execution capabilities throughout the enterprise."

- Boeing and similar companies will benefit from research and teaching that involves the development of these skills.
- You will develop some of these skills in this course.



Skills students need

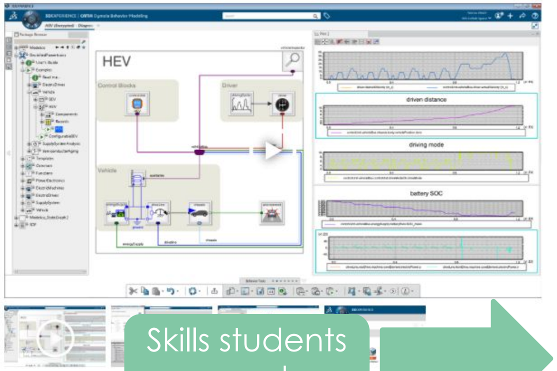
SYSTEMS ENGINEERING

Electrical and Electronics Architect

on premise

Integrates the required functionalities for the development and integration of all Electrical and Electronics systems and components.

- Provides a single source of truth for all vehicle Electrical, Electronics and Software Engineering data.
- Enables collaborative design between different disciplines specific data and the management of all design commonality and reuse across vehicle platforms.
- Define and optimize system Electrical & Electronics (E/E) Architecture by distributing functions onto Hardware and Software components, including network definition.



Skills students need

SYSTEMS ENGINEERING

Dynamic Systems Engineer

on cloud | on premise

Accelerate the development and understanding of complex dynamic systems through modeling and simulation.

- Rapidly model and simulate the performance of complex products and systems.
- Accelerate understanding and validation of complex systems through early virtual simulation.
- Quickly find solutions to complex multi-physic system design problems.
- Uses Modelica compliant component models to ensure Intellectual Property capture and re-use.
- Size, tune and optimize system components and parameters quickly, accurately and early in the system design process.

Why this course matters for your future?!

Work with the most exciting companies!

Vehicle Dynamics Controls Engineer
Tesla
Palo Alto, CA, US
Experience with numerous software packages and programming languages (Dymola, C/C++, Python, Matlab/... www.tesla.com
16 connections work here
1 year ago

powertrain traction control, electric power steering, or other chassis control systems.

- Basic experience, understanding, and intuition for the physics of electric drive-trains.
- Experience with numerous software packages and programming languages (Dymola, C/C++, Python, Matlab/Simulink).

Firmware Validation Engineer - Chassis firmware team
Tesla
Palo Alto, CA, US
Modeling experience using Simulink or Dymola is a plus. We are looking for a Sr. FW Validation devel... www.tesla.com
16 connections work here
3 months ago

- Experience with test automation and verification.
- Experience with version control (Git, SVN).
- Modeling experience using Simulink or Dymola is a plus.
- Experience working in an automotive environment is a plus.

Software Engineer - Simulation Community Lead Promoted
Boeing
St. Louis, MO, US
To succeed in this role you should have experience in modeling & simulation concepts, an understanding of discrete-event and frame-based simulation and an ability to work in a ... jobs.boeing.com
3 connections work here
1 week ago

Why this course matters for your future?!

Do cool things!

Simulation Engineer
Hendrick Motorsports
Charlotte, North Carolina Area
The ideal candidate will have substantial knowledge of vehicles and vehicle subsystems, vehicle dynamics, tire performance and mod...
3 weeks ago

About the Job:

- Utilize Dymola and Modelica software to develop vehicle models and validate models against lab and track test data.
- Develop and validate track based dynamic simulation using Dymola software.

Wolfram Technology Engineer
Wolfram Research, Inc.
Champaign, IL, US
Modelica experience or system modeling skills are a plus. Wolfram, creator of Mathematica, Wolfram|A... my.jobs
Be an early applicant
1 month ago

- Self-motivated and self-disciplined
- Excellent written and oral communication skills
- Able to articulate ideas and instructions
- Desire to work with clients on a daily basis
- Interest in growing into a technology consultant
- Wolfram Language programming skills are a plus
- Modelica experience or system modeling skills a a plus

Research Scientist in Applied Mathematics for Design Optimizatio
PARC, a Xerox Company
Palo Alto, CA, US
We are searching for a research scientist in applied mathematics, specifically with expertise in alg... www.jsco.re
Be an early applicant
3 weeks ago

The Following Experience Is a Plus

- Experience with Category Theory.
- Experience with Functional Programming e.g. Haskell, Scheme.
- Experience with Computational Physics and Computational Geometry.
- Familiarity with Modelica/Matlab Simulink.

Research Scientist AI & Human-Computer Interacton
PARC, a Xerox Company
Palo Alto, CA, US
We are searching for a research scientist with expertise in design of human-computer search methodol... www.jsco.re
Be an early applicant
3 weeks ago

The Following Are Pluses

- Familiarity with Knowledge Representation in AI
- Familiarity with Modelica/ Matlab Simulink.
- Experience with Solid Modeling and CAD

Software R&D Engineer II - Circuit/System Simulation
ANSYS, Inc.
Pittsburgh, PA, US
Experience in scientific programming in C/C++ and excellent software development skills. 2 years... chp.tbe.taleo.net
2 connections work here
3 weeks ago

Preferred Qualifications

- Familiarity with other numerical solvers used in system and circuit simulation preferred
- Familiarity with standardized modeling languages like VHDL-AMS, Verilog-AMS, Modelica, etc is a plus
- A minimum of 2 years of technical experience in software product development methodologies, design and implementation

Dangers of Models and Simulation

- **Falling in love with a model**
  The Pygmalion effect (forgetting that model is not the real world)
  - From the Greek myth of Pygmalion, a sculptor who fell in love with a statue he had carved.
- **Forcing reality into the constraints of a model**
  The Procrustes effect (e.g. economic theories)
  - Procrustes: "the stretcher [who hammers out the metal]", a rogue smith from Attica that physically attacked people by cutting/stretching their legs, so as to force them to fit the size of an iron bed.
  - A **Procrustean bed** is an arbitrary standard to which exact conformity is forced.
- **Forgetting the model's level of accuracy**
  Simplifying assumptions forgotten more than yesterday's pudding…