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Simulating Cyber-Physical Systems using SysML and Numerical Simulation Tools

Acknowledgements

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- Main contributors:
  - Takashi Sakairi, IBM Research - Tokyo
  - Chaim Cohen, IBM Rational
  - Eldad Palachi, IBM Rational

Acronyms

ACD: Activity Diagram
BDD: Block Definition Diagram
CAS: Computer Algebra System
CPS: Cyber Physical Systems
DSL: Domain Specific Language
FMI: Functional Mockup Interface
IBD: Internal Block Diagram
INCOSE: International Council of Systems Engineering
MBSE: Model-Based Systems Engineering

MBSE: Model-Based Systems Engineering
OMG: Object Management Group
PCE: Parametric Constraint Evaluator
PD: Parametric Diagram
SysML: Systems Modeling Language
UCD: Use Case Diagram
UML: Unified Modeling Language

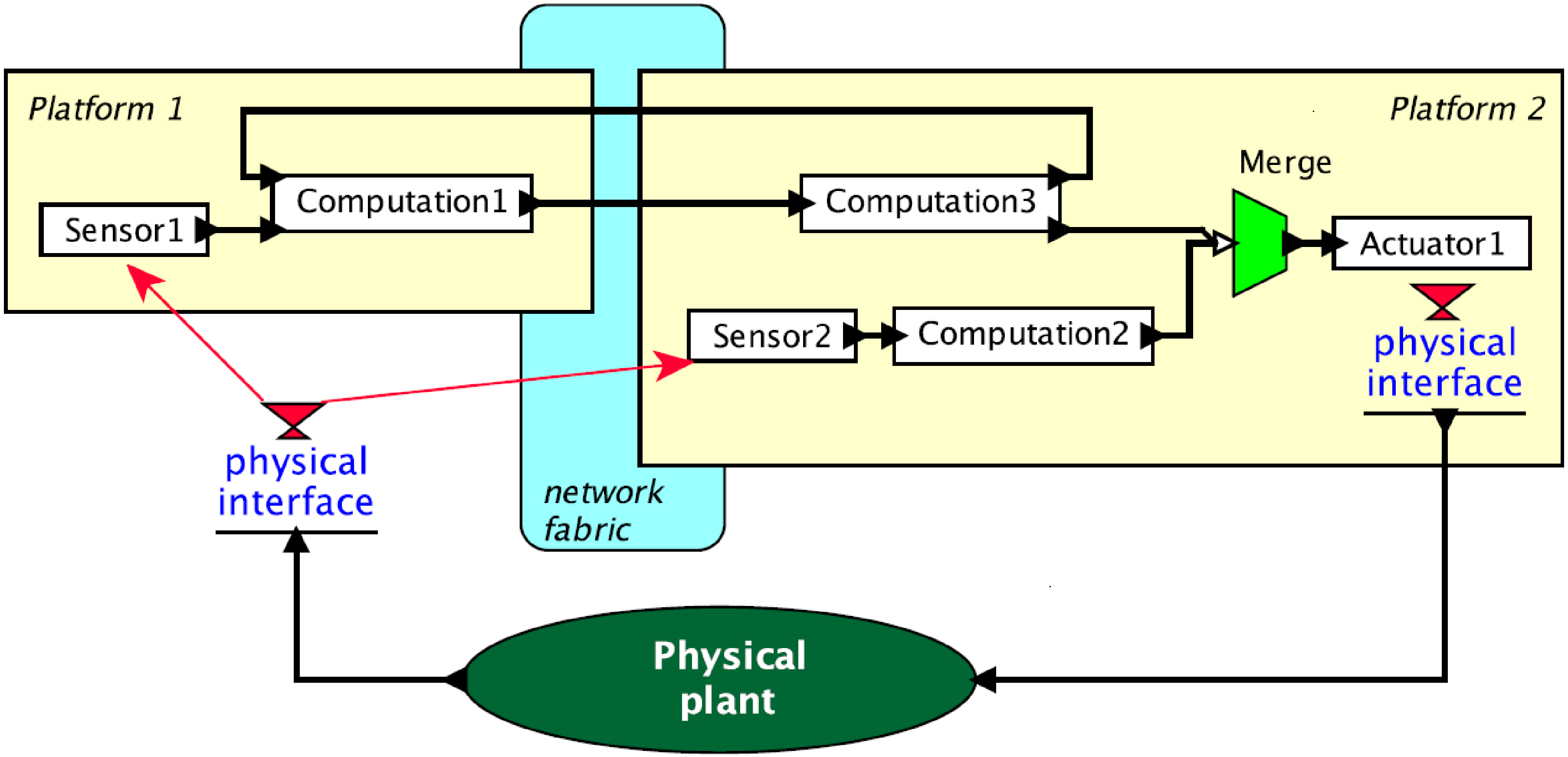
Presentation Outline

- <u>What is a Cyber Physical System?</u>
- A short overview of SysML
- Short overview of Simulink and Modelica
- How to model and simulate physical environments/plant?
- How to model and simulate CPS?
- Summary

Cyber Physical Systems (CPS)

- The term cyber physical system refers to the integration of computation with physical processes.
  - *"In CPS, embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa. The design of such systems, therefore, requires understanding the joint dynamics of computers, software, networks, and physical processes."* (*Edward A. Lee and Sanjit A. Seshia, Introduction to Embedded Systems, A Cyber-Physical Systems Approach, http://LeeSeshia.org, ISBN 978-0-557-70857-4, 2011*)

Typical Cyber Physical System (CPS)



Source: Edward A. Lee and Sanjit A. Seshia, Introduction to Embedded Systems, A Cyber-Physical Systems Approach, http://LeeSeshia.org, ISBN 978-0-557-70857-4, 2011

Developing CPS (usually) means doing Systems Engineering

- CPS are commonly complex multi-disciplinary systems:
  – Requires disciplined requirements analysis (functional analysis, trade-offs, etc.)
  – Requires coordination between domain specific engineering teams (managing engineering artifacts)
  – High risk of failure, esp. during integration, non-trivial emergent behavior -> simulations!

Role	Abbr.	Name
1	RO	Requirements Owner
2	SD	System Designer
3	SA	System Analyst
4	VV	Validation/Verification Engr.
5	LO	Logistics/Ops Engineer
6	G	Glue Among Subsystems
7	CI	Customer Interface
8	TM	Technical Manager
9	IM	Information Manager
10	PE	Process Engineer
11	CO	Coordinator
12	CA	Classified Ads SE

Table 1. The Twelve Roles

Source: Sheard, Sara, A.,Systems Engineering Roles Revisited, Proceedings of the 10th Annual International Council of Systems Engineering, 2000

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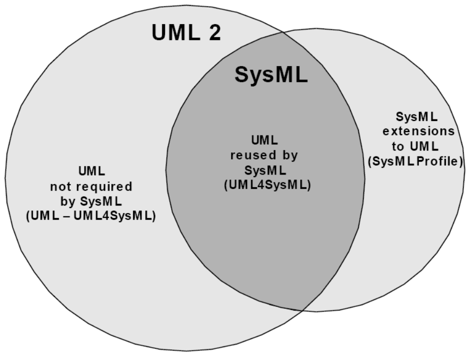
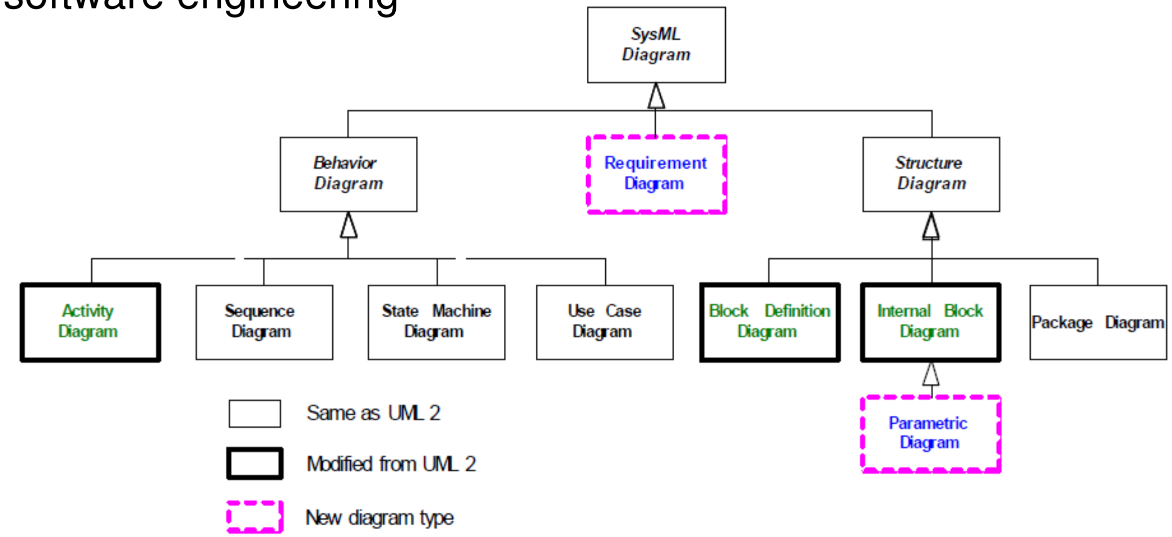
The Systems Modeling Language (SysML)

- SysML is a general purpose domain-specific language (DSL) for model-based systems engineering (MBSE)
- Originated as an initiative of the International Council of Systems Engineering (INCOSE) in January 2001
- Developed by Object Management Group (OMG)
- Current version: 1.3 (http://www.omg.org/spec/SysML/1.3/) – released in 2012
- Implemented as a UML profile
  – Allows easier hand-off for software engineering
- Subsets and extends UML

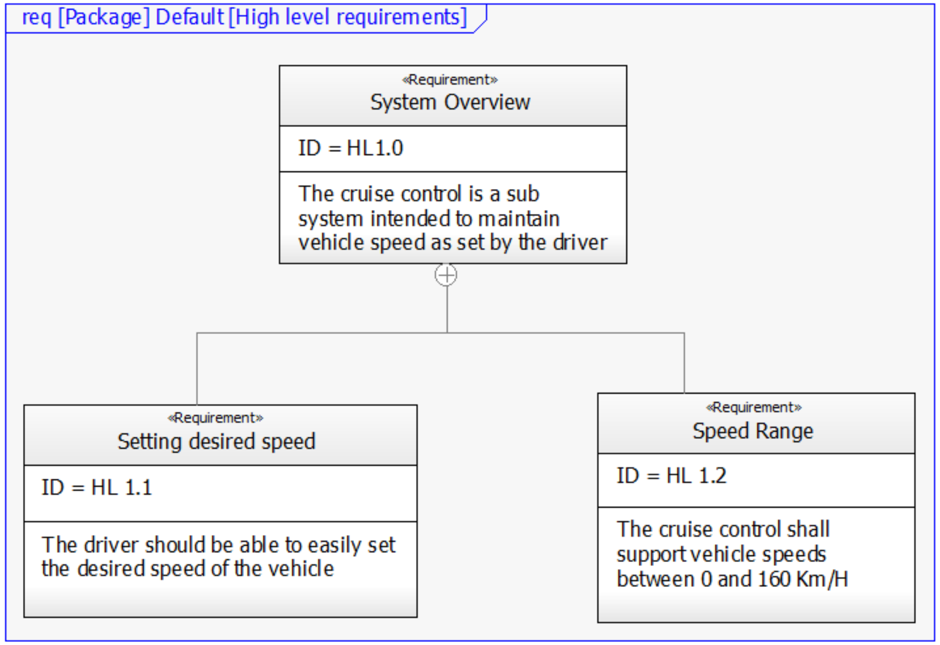




Source: SysML 1.3 Spec.

Requirement Diagram

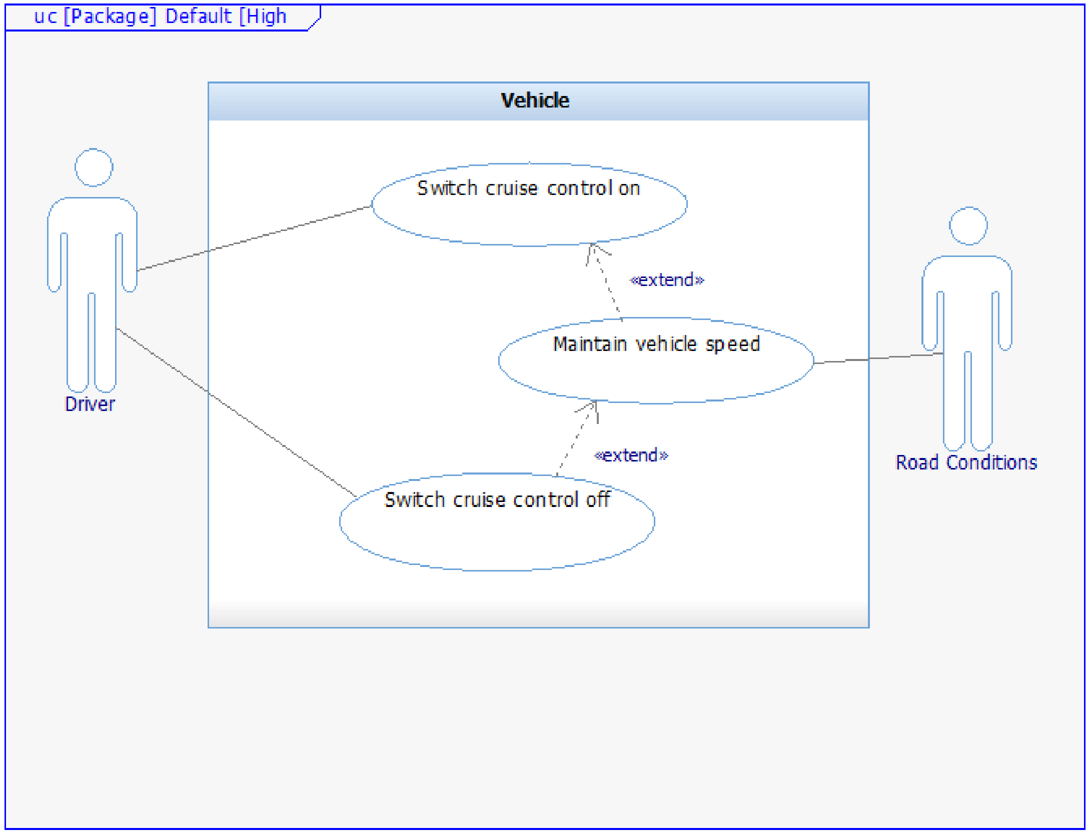
- Introduced in SysML
  - Along with the notion of Requirement
- Describes a hierarchy of textual requirements
- Allows tracing from design elements to requirements using various standard relationships (satisfy, derived, etc.)
- SysML also supports tabular notations for requirements
- Requirements might be imported from requirements management tools



ID	Name	Specification
HL1.0	System Overview	The cruise control is a sub system intended to maintain vehicle speed as set by the driver
HL 1.1	Setting desired speed	The driver should be able to easily set the desired speed of the vehicle
HL 1.2	Speed Range	The cruise control shall support vehicle speeds between 0 and 160 Km/H

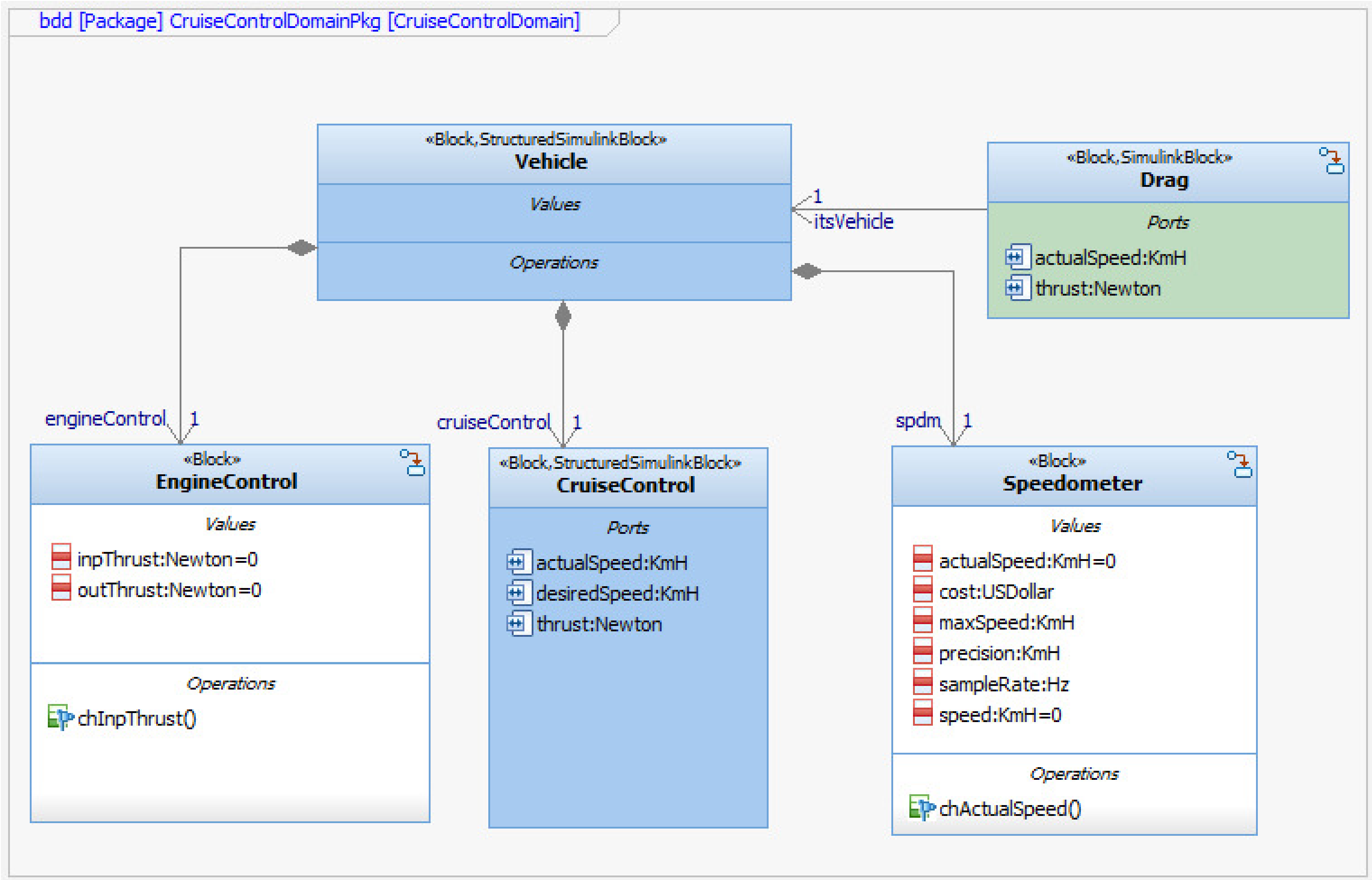
Use Case Diagram (UCD)

- Same as in UML
- Lists the capabilities of the systems (use cases) and how they relate to actors and to each other
- Use Cases are commonly considered as the “chapters” of the SysML model



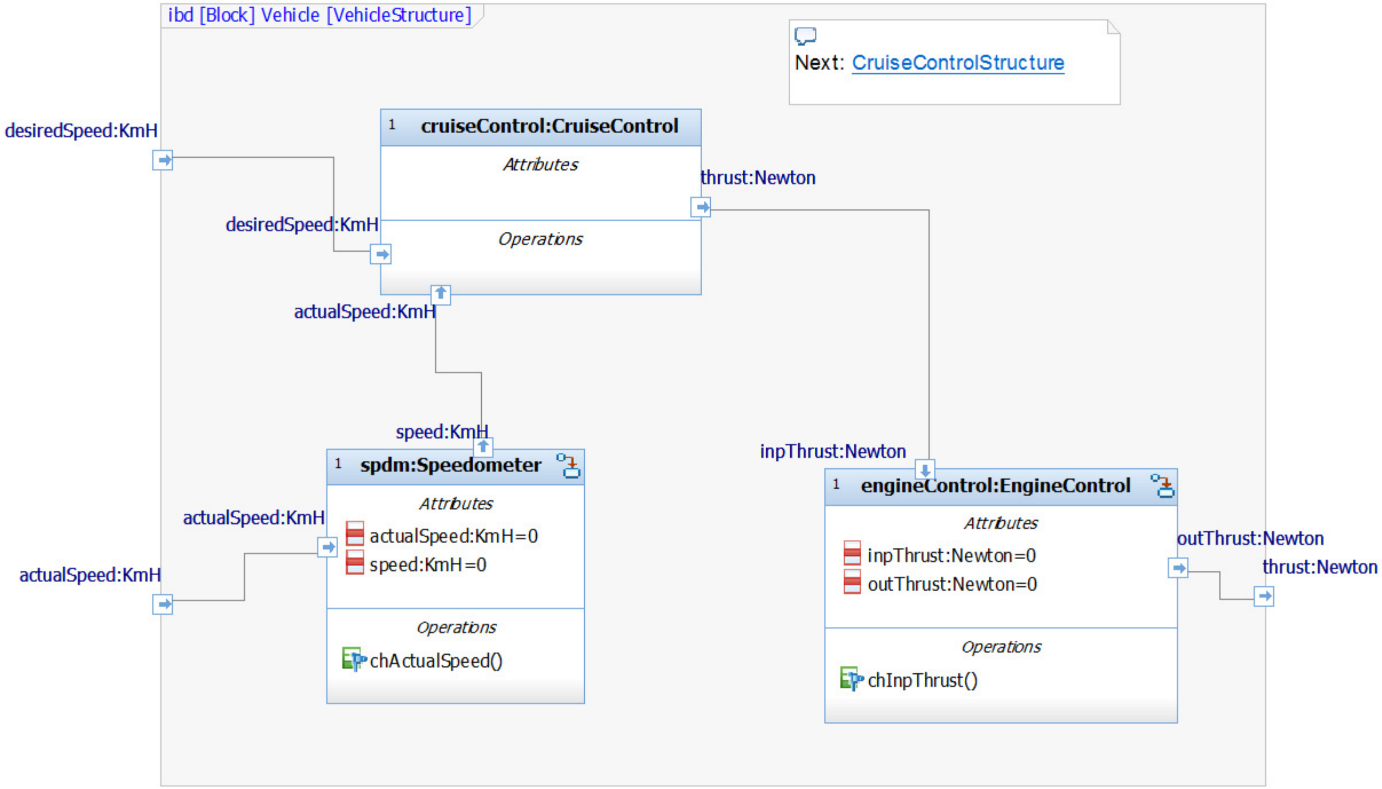
Block Definition Diagram (BDD)

- Based on UML Class Diagram
- Describes the system Blocks and their features (structural and behavioral)



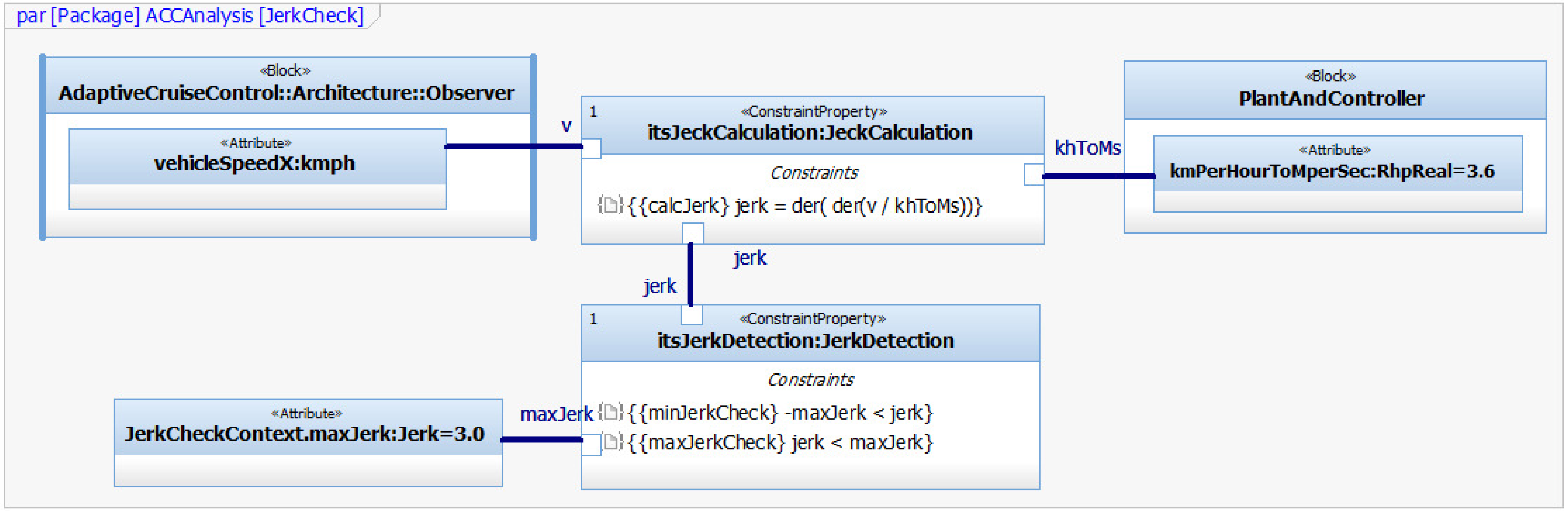
Internal Block Diagram (IBD)

- Based on UML Internal Structure Diagram
- Describes the internal structure of Blocks
- Main concepts: Part, Connector, Port (various kinds)



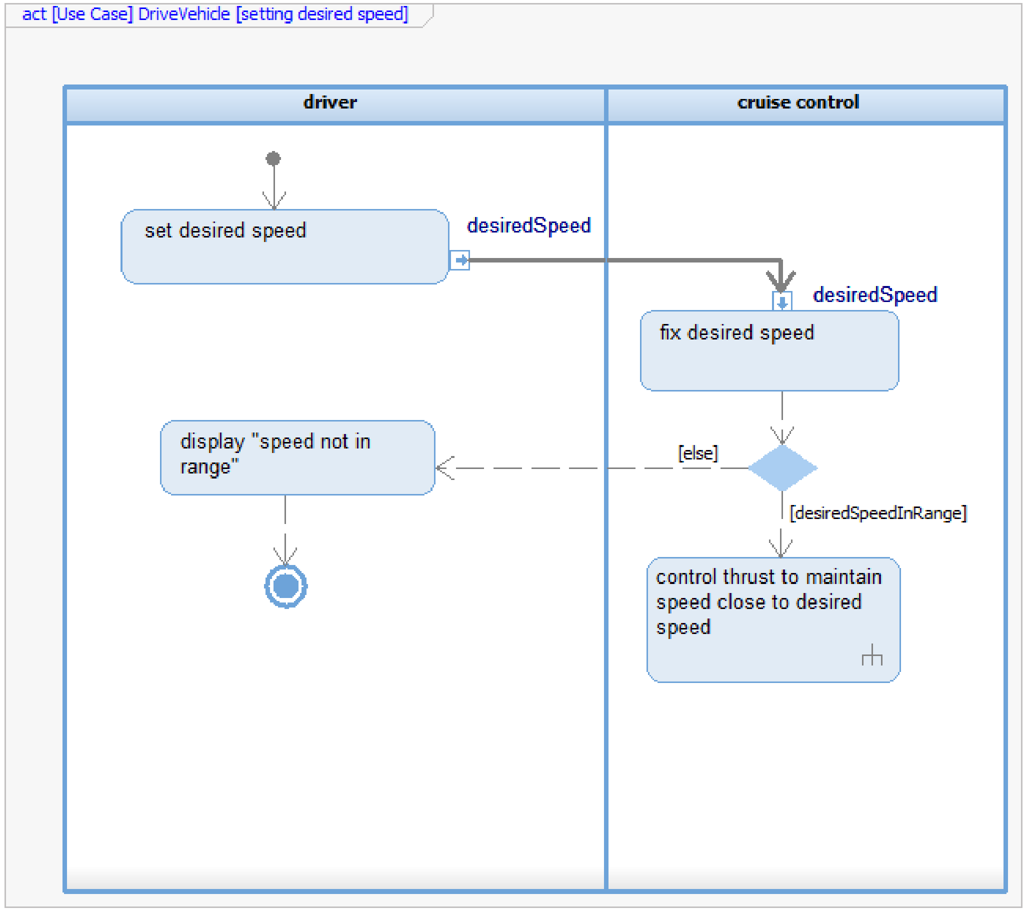
Parametric Diagram

- Introduced in SysML
- Imposes mathematical constraints on properties of Blocks (in system's context)
- Main concepts:
  - Constraint Block: groups non causal mathematical expressions (equations/inequalities)
  - Constraint Parameter: a variable of the math expressions that can be bounded to a design property
  - Constraint Property: a usage of a constraint block in a specific context
  - Binding Connector: declared that the value of the design property must be equal to the value of the constraint parameter



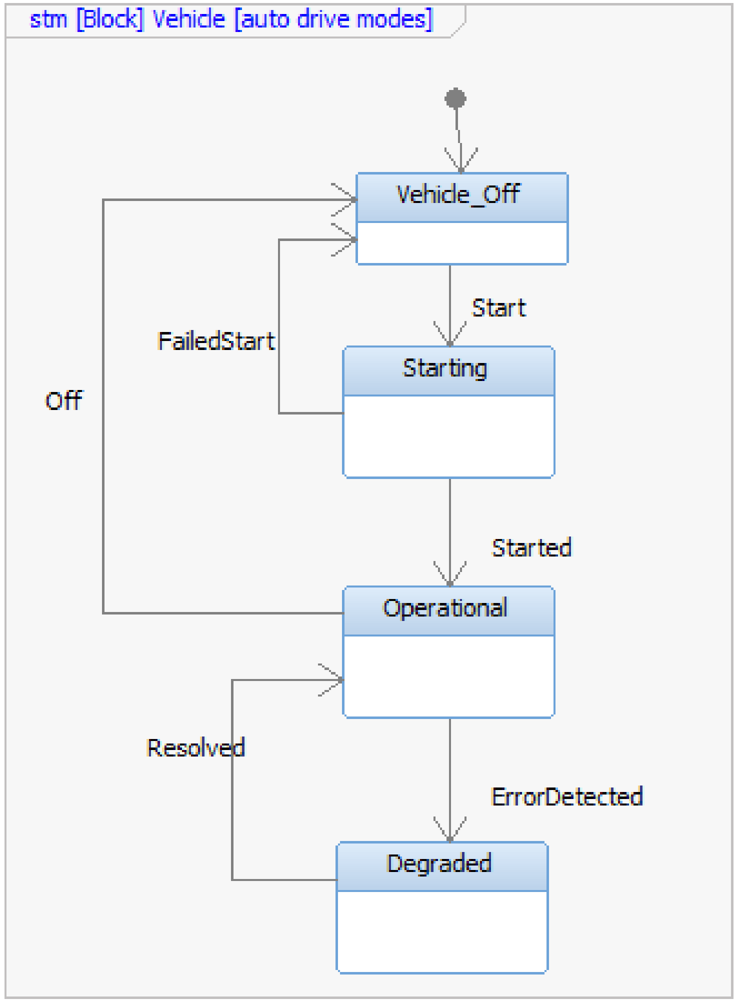
Activity Diagram

- Same as in UML 2 with a few extensions (mainly continuous flows)
- Token based semantics:
  - Every action has input/output pins through which control/object tokens flow
  - An action starts when all pins have tokens
  - As action offers its output tokens after the its computation is done
- Commonly describes behavior of:
  - Use Cases: system level processes
  - Operations: block level procedures ("flow charts")
- Continuous semantics is not precise
- Not well-suited for describing dynamic time-dependent processes



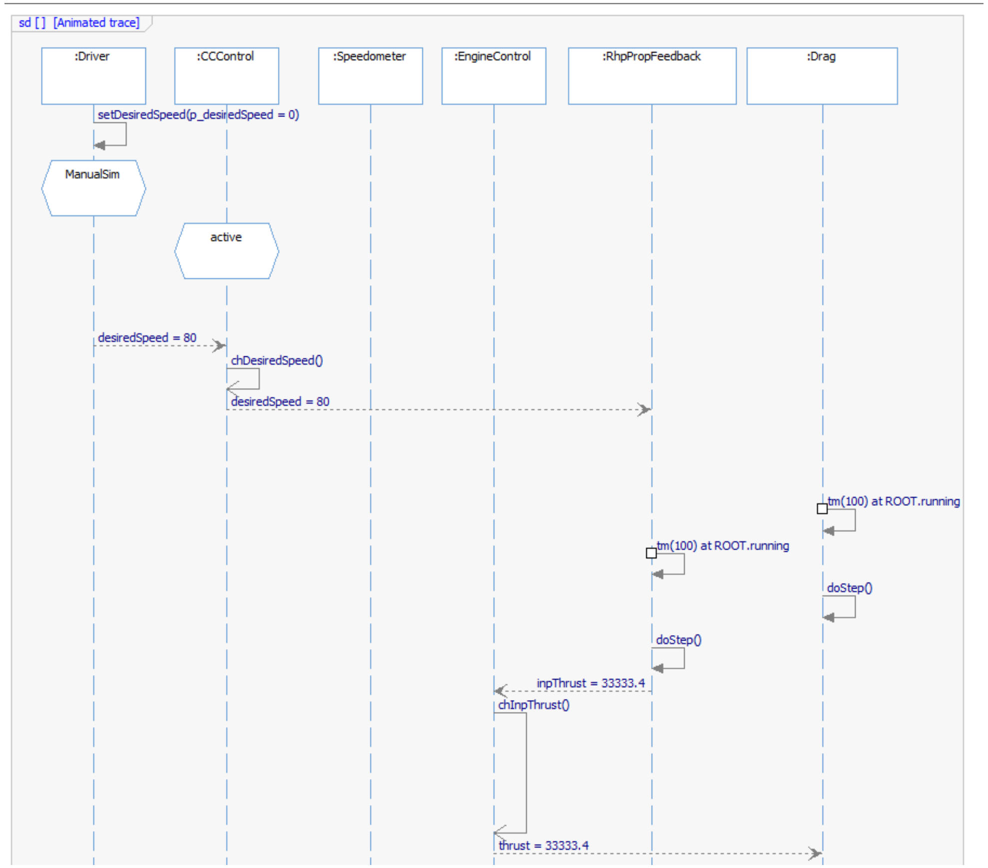
State Machine Diagram (statechart)

- Same as in UML
- Describes reactive state based behavior
- Run-to-completion semantics:
  - One event at a time
  - A run-to-completion computation step takes the state machine from one stable state to another
    - Stable state: a concrete state configuration of the classifier after all internal actions are completed
- Commonly used to describe behavior of Blocks



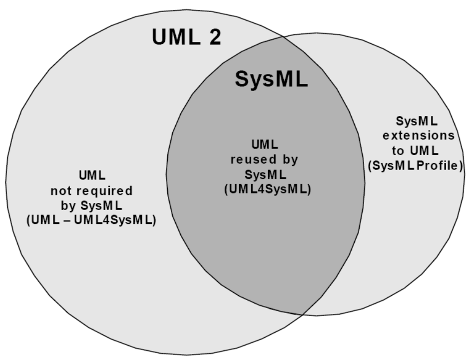
Sequence Diagram

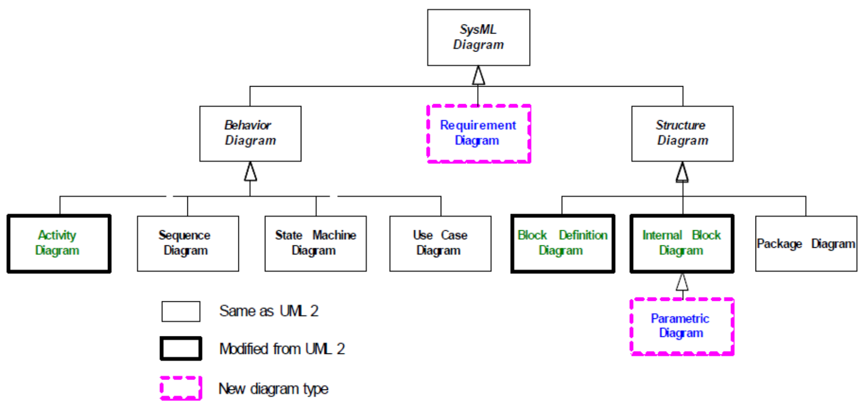
- Same as in UML
- Describes a specific interaction scenarios between parts
- Can be captured by model execution
- Commonly used to describe test cases in model-based testing (UML Testing Profile)



SysML overview summary

- Standardized language for model-based systems engineering
- Subsets and extends UML
- Consists of multiple diagram types to describe various aspects of the system
  - Requirements (requirement diagram, use case diagram)
  - Structure (block definition diagram, internal block diagram)
  - Constraints (parametric diagram)
  - Behavior (activity diagram, state machine diagram)
  - Interaction Traces (sequence diagrams)
- Lacks precise execution semantics
  - Not well suited for modeling plant and continuous control algorithms
- Parametric diagrams can be used to describe equations imposed on design attributes





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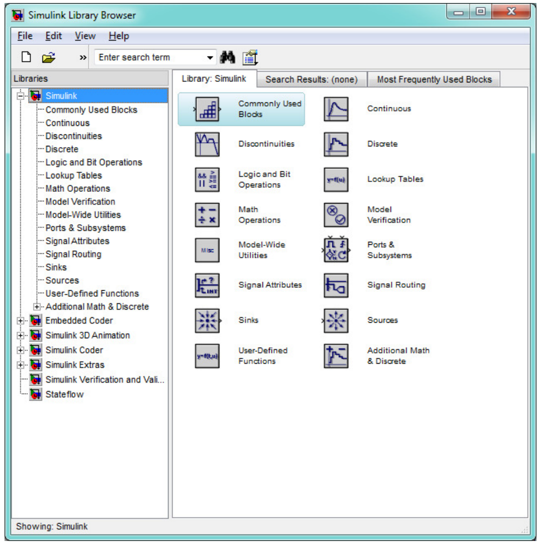
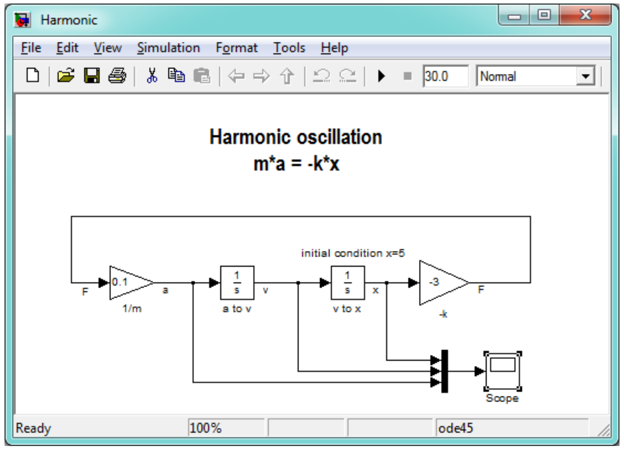
MATLAB Simulink

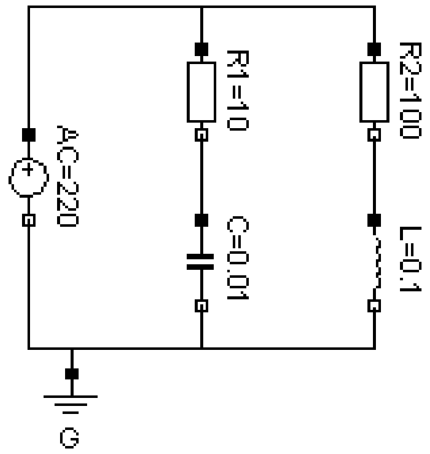
- Designed to model and simulate time-dependent transformational behavior
- Based on Block Diagrams
  - Every block transforms input signals to output signals
  - Signal: a time dependent function of a physical quantity
    - E.g. Amplitude of a radio signal, Voltage of an AC outlet, Car speed
- Simulink is widely used for control and signal processing designs
- Developed by Mathworks for modeling “multi-domain dynamic systems”
- Add-on to MATLAB
- For reactive behavior an add-on called Stateflow is used on top of Simulink
- Other add-ons:
  - Embedded coder: generate C and C++ code from models for real-time targets
  - HDL coder: generates VHDL
  - Simulink Design Verifier





Modelica

- A standardized textual language for modeling physical systems
  - Annotations are also standardized now and can be used to render diagrams
- Developed since 1996 by the Modelica Association https://www.modelica.org
  - Current version 3.3 (May 2012)
- Modelica is Object-Oriented (see right side)
- Has a large (~30) set of free and commercial libraries for different domains (source: https://www.modelica.org/ModelicaLibrariesOverview)
- Implemented by various free and commercial tools: (Dymola, Open Modelica, Math Modelica)
- The OMG SysML4Modelica profile extends SysML to model Modelica constructs in SysML (IBD) and roundtrip Modelica models back to SysML




```
model Circuit
  Resistor  R1 (R=10),   R2 (R=100);
  Capacitor C  (C=0.01);
  Inductor  L  (L=0.1);
  VsourceAC AC;
  Ground    G;
equation
  connect(AC.p, R1.p);  // Capacitor circuit
  connect(R1.n, C.p);
  connect(C.n,  AC.n);
  connect(R1.p, R2.p);  // Inductor circuit
  connect(R2.n, L.p);
  connect(L.n,  C.n);
  connect(AC.n, G.p);
end Circuit;
```

Source: https://modelica.org/publications/papers/Eurosim98Modelica.pdf

Simulink vs. Modelica

Simulink

- Transformational semantics of signals
  - Language is well-suited for control algorithms and signal processing
- Causal semantics (inputs -> outputs)
- Mature: more features, highly usable, a lot of add-ons
- Well integrated into the “MATLAB universe”
- Widely used in industry (standard de-facto)
- Many existing tool integrations
- Code generation to C/C++/VHDL/Verilog

Modelica

- Object oriented approach for modeling physical components (mechanical, electrical, etc.)
  - Language is better suited for physical modeling (plant)
- Causal and A-Causal semantics (equations)
- Open standard (of the textual language) with collaboration in research and standard bodies
  - SysML for Modelica profile
- Multi tool support (although Dymola is dominant)
  - Tools are less mature than Simulink
- Few industry deployments but a lot of interest
- No export regulation restrictions (relevant for defense systems development)
- Currently no production code generation (to the best of our knowledge)

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Describing plant behavior

- Plant is the physical environment in which the CPS operates
- Plants can be described using partial time-dependent differential equations
  - These equations are a-causal: no notion of inputs and outputs
- “Hello, World” example – one dimensional spring and mass performing harmonic oscillation

$$m * a = -k * x$$

$$a = \dot{v} = \ddot{x}$$

$$x(t = 0) = 5$$

$$v(t = 0) = 0$$

$$m = 10$$

$$k = 3$$

Analytic Solution: $x = A * \sin(\omega * t + \varphi)$

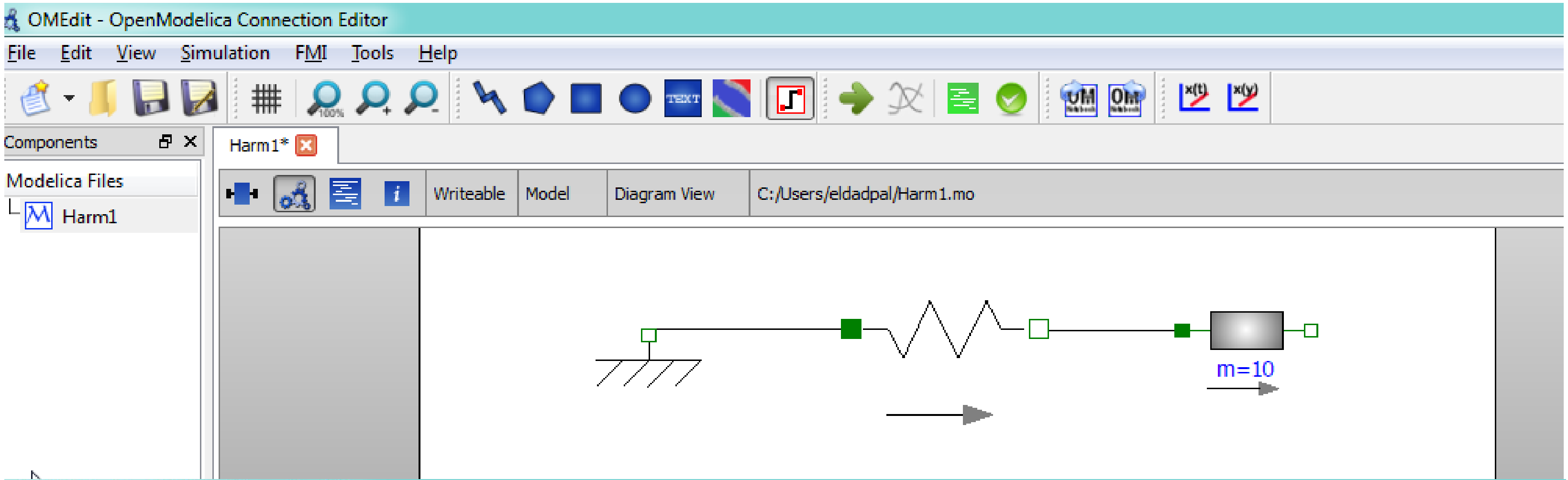
$$\omega = \sqrt{k / m}$$

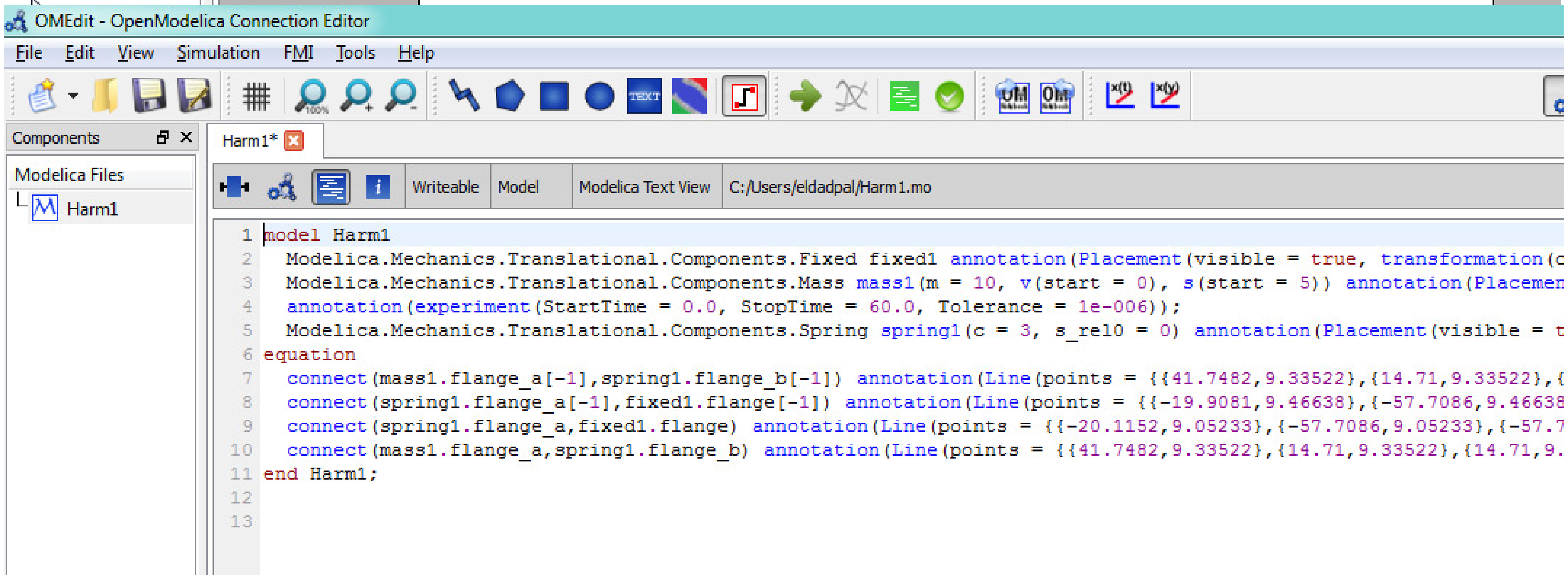
For our initial conditions: $A = 5$

$$\varphi = \pi / 2$$

$$\omega = \sqrt{3/10} = 0.577$$

Modeling spring and mass dynamics using Modelica





Modeling spring and mass dynamics using Simulink

$$m*a=-k*x$$

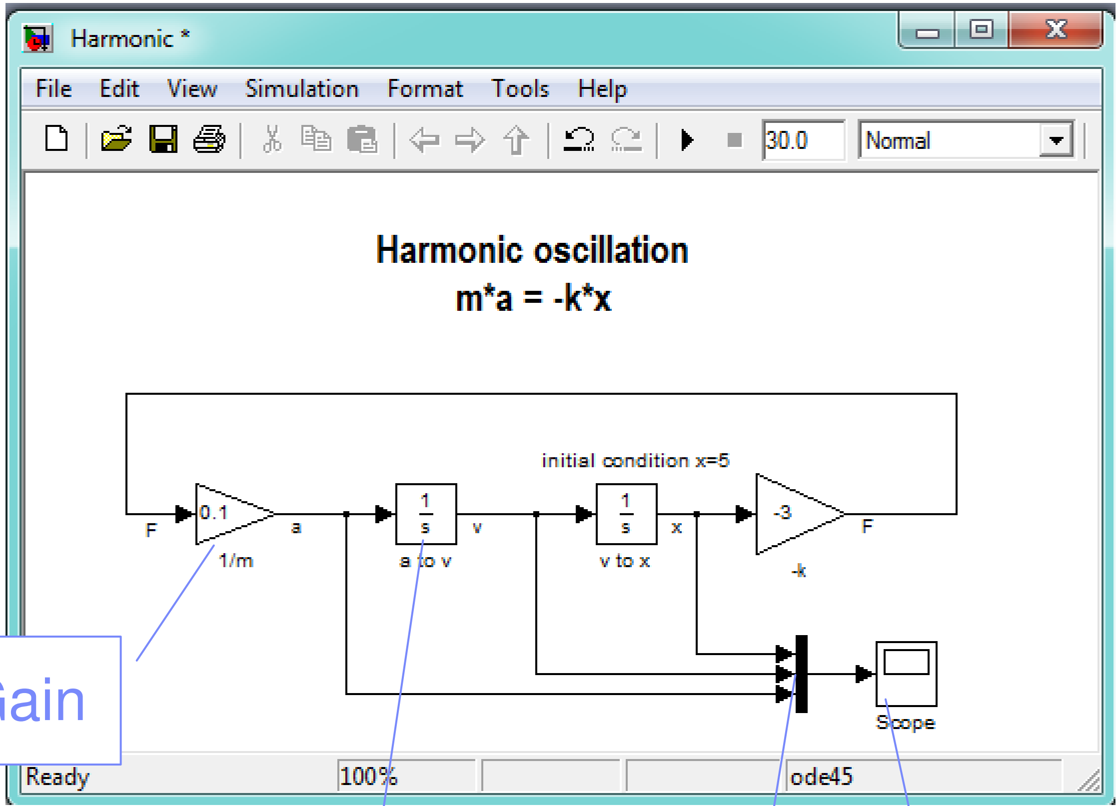
$$a=\dot{v}=\ddot{x}$$

$$x(t=0)=5$$

$$v(t=0)=0$$

$$m=10$$

$$k=3$$



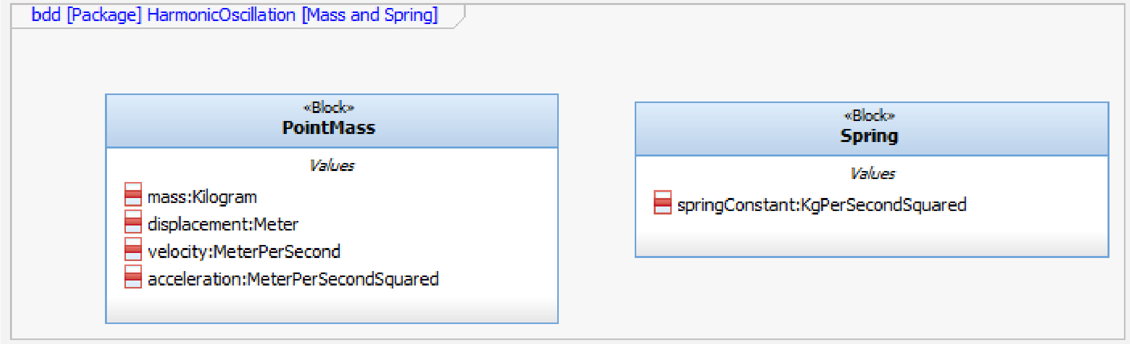
Gain

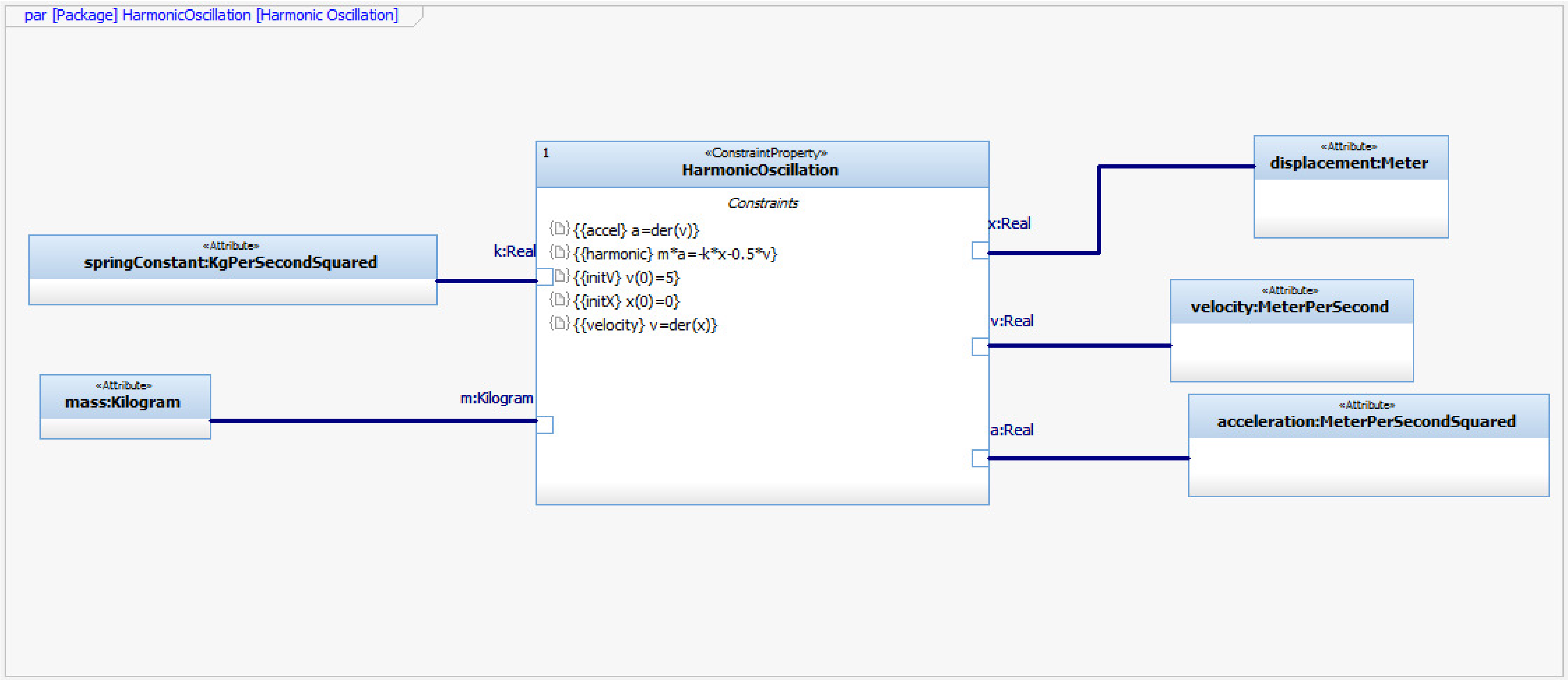
Time integration

Mux

Scope display

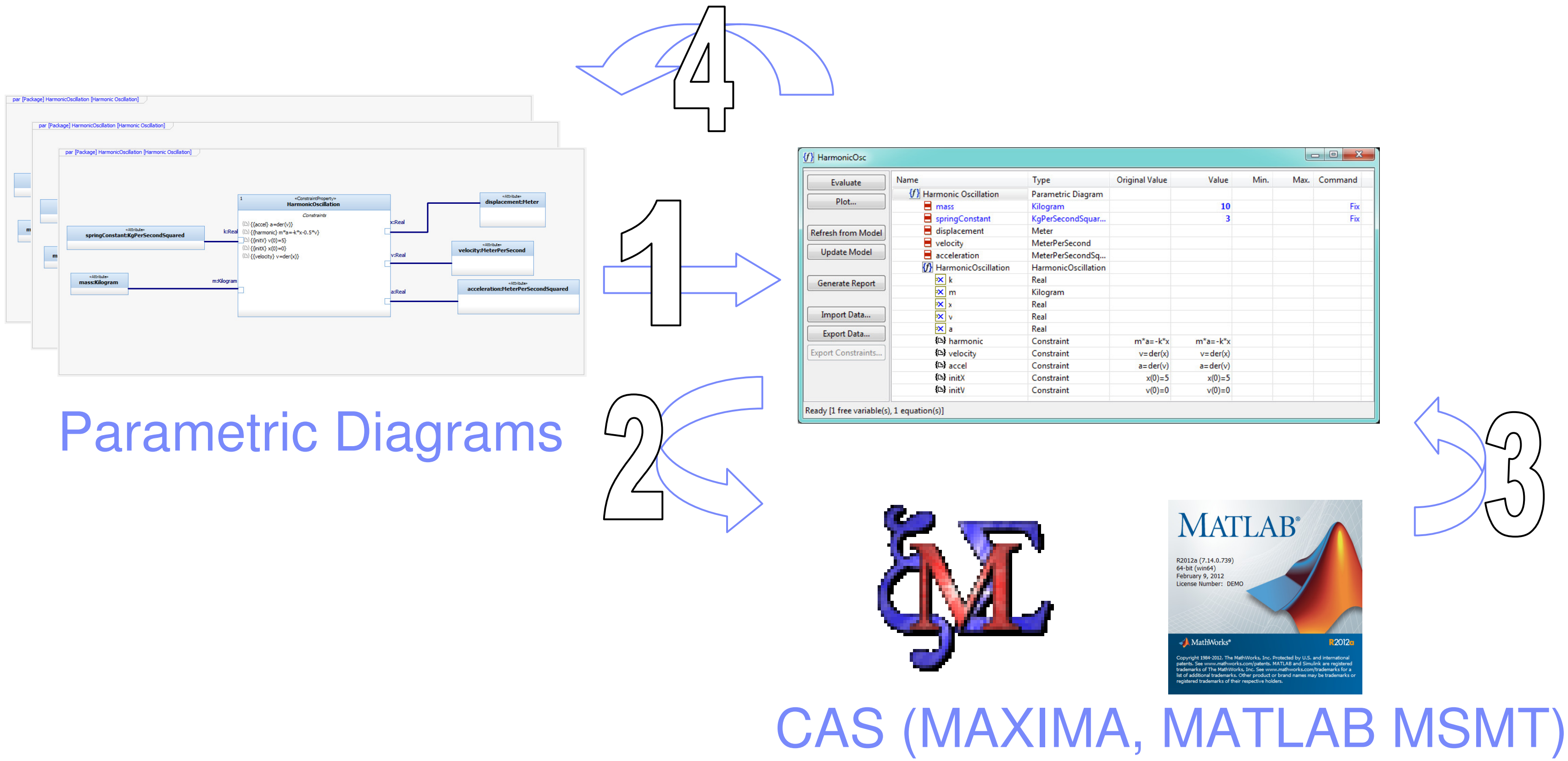
Modeling spring and mass dynamics using SysML parametric diagram





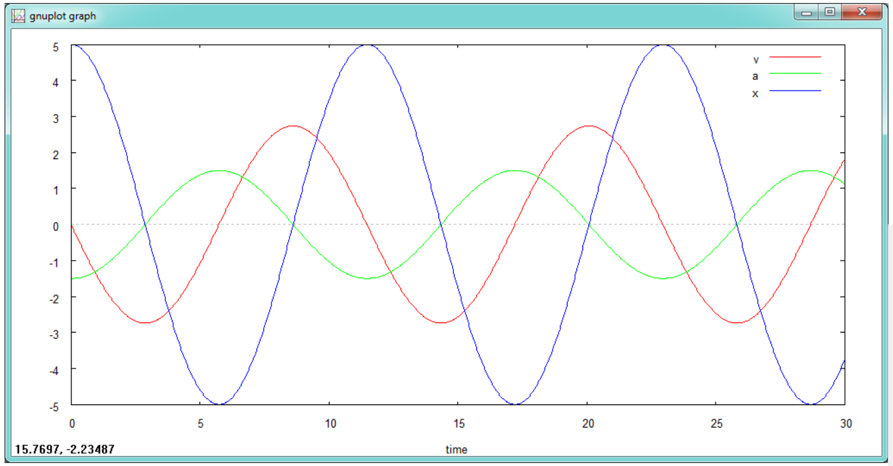
Rhapsody Parametric Constraint Evaluator (PCE)

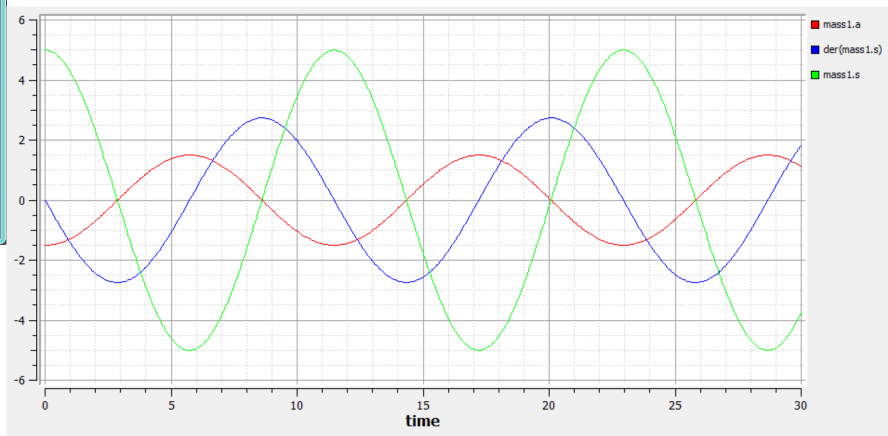
- IBM Rational Rhapsody is a modeling tool capable of specifying and executing SysML models
- PCE is an add-on to Rhapsody that allows solving sets of math expressions specified in parametric diagrams and update the design model based on the results



Plant modeling summary

- We have shown three simulations of a simple harmonic oscillator using three languages and three tools:
  - Modelica (Opem Modelica)
  - MATLAB Simulink
  - SysML Parametric Diagrams (Rhapsody PCE)
- PCE relies on having a symbolic solver (CAS)





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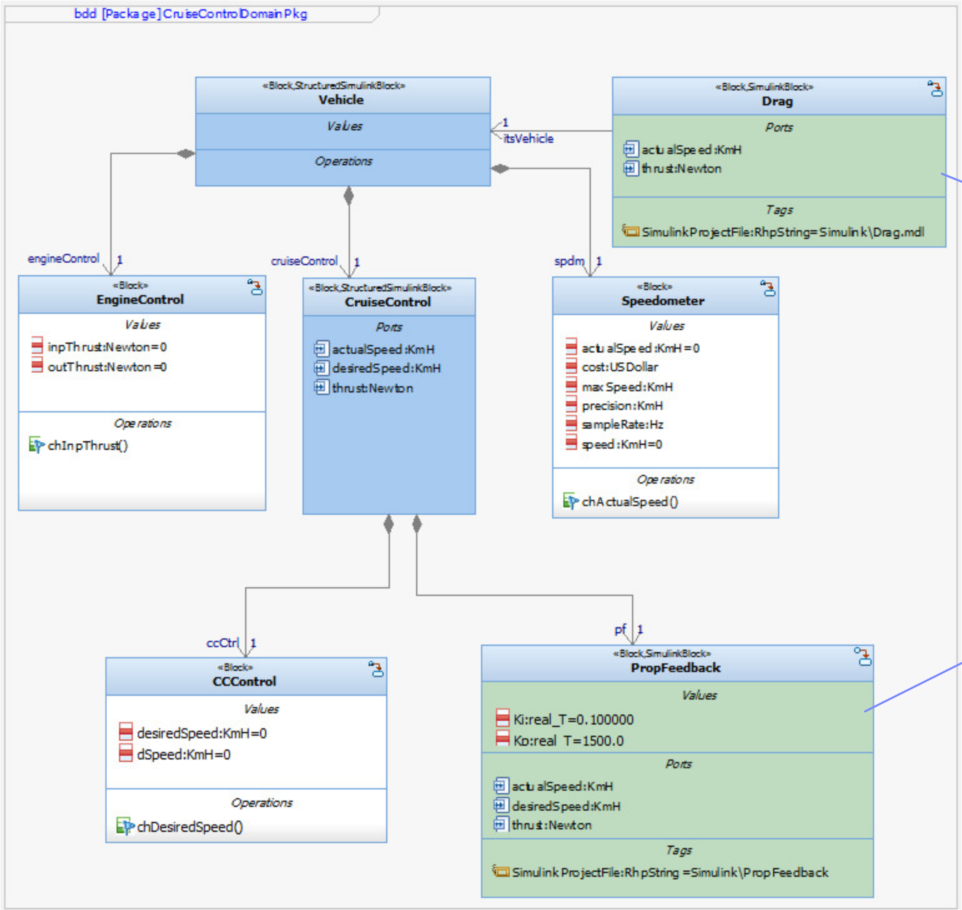
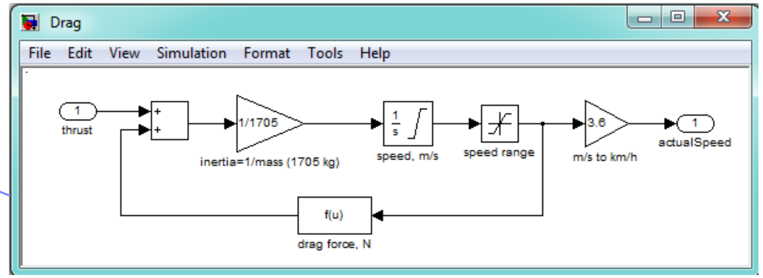
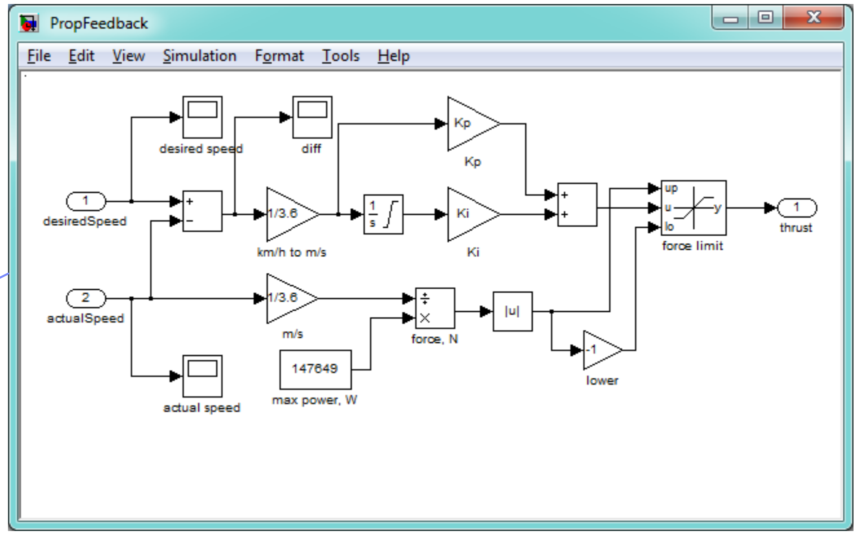
Extending SysML: «SimulinkBlock»

- The stereotype «SimulinkBlock» means the block's behavior is specified in a Simulink model
- Every input/output port in the Simulink model is represented as a SysML atomic flow port
- Type matching rules need to be applied

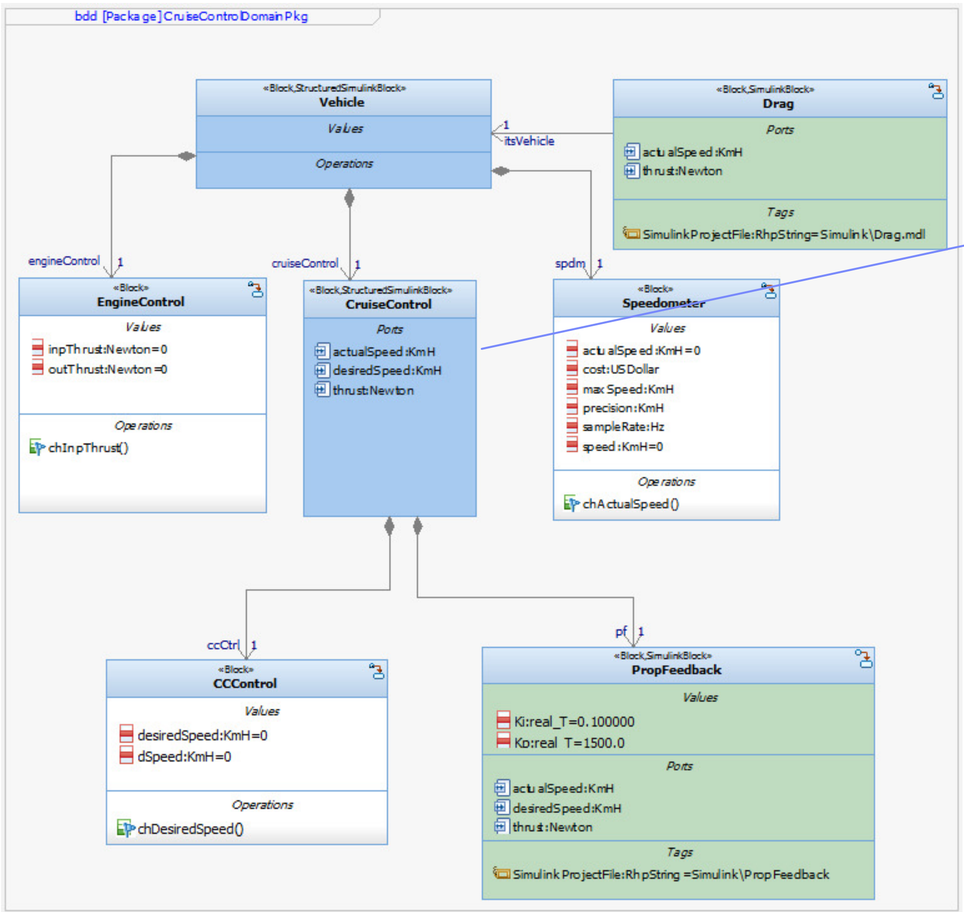


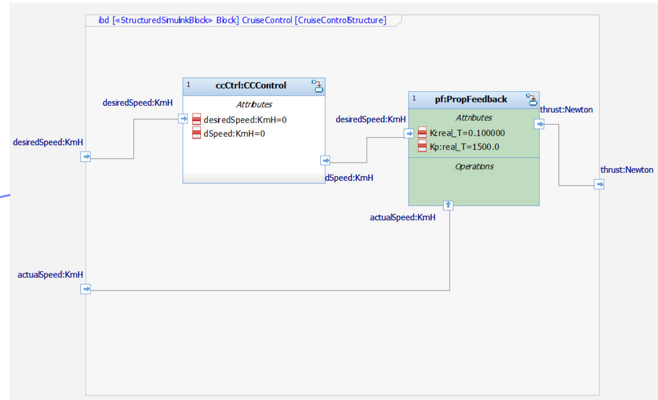


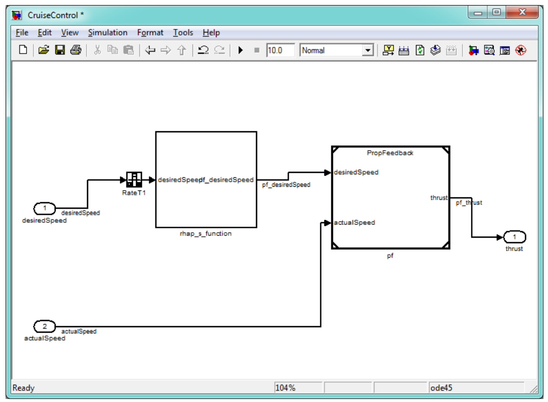


Extending SysML: «StructuredSimulinkBlock»

- The stereotype «StructuredSimulinkBlock» means the block has parts typed by Simulink blocks
  - A block that owns a part typed by a «StructuredSimulinkBlock» is also a «StructuredSimulinkBlock»
- A «StructuredSimulinkBlock» can be exported to Simulink for simulation
  - All non Simulink blocks are transformed to a single S-Function in Simulink

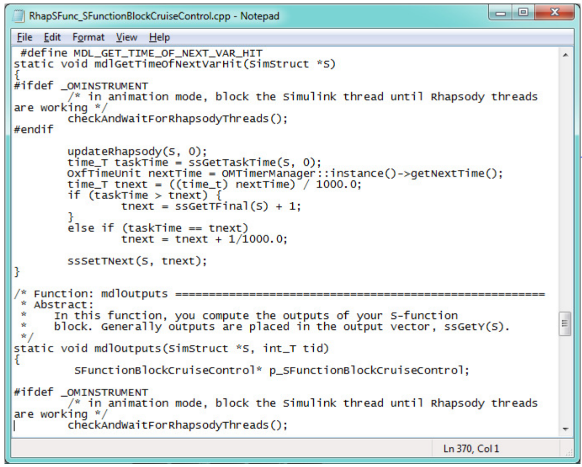




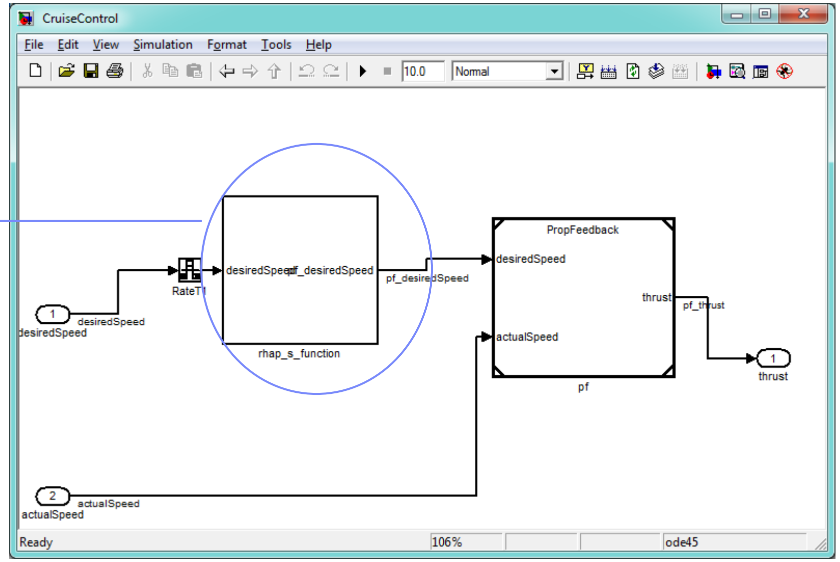


Simulink S-Function

- MATLAB/Simulink S-Function is a user defined block implemented in C/C++ or other programming language.
  - The S-Function code must conform to the S-Function standard in order for Simulink to understand its interfaces and to interact with it.
- Rhapsody can generate C/C++ code corresponding to blocks stereotyped «S-FunctionBlock» along with a mex option file to generate an S-Function simulink block
  - The generated code conforms to the S-Function standard and transforms the ports accordingly
- For more information on S-Function see http://www.mathworks.com/help/simulink/s-function-basics.html

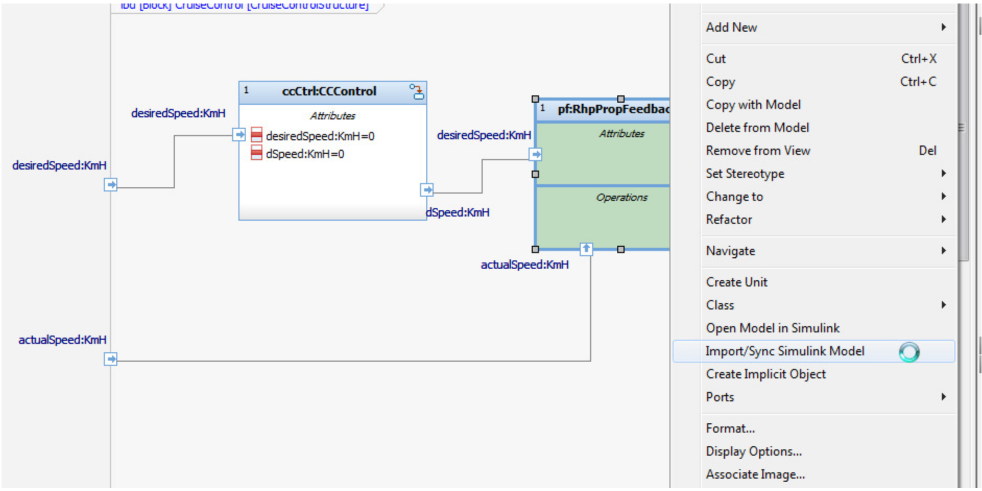


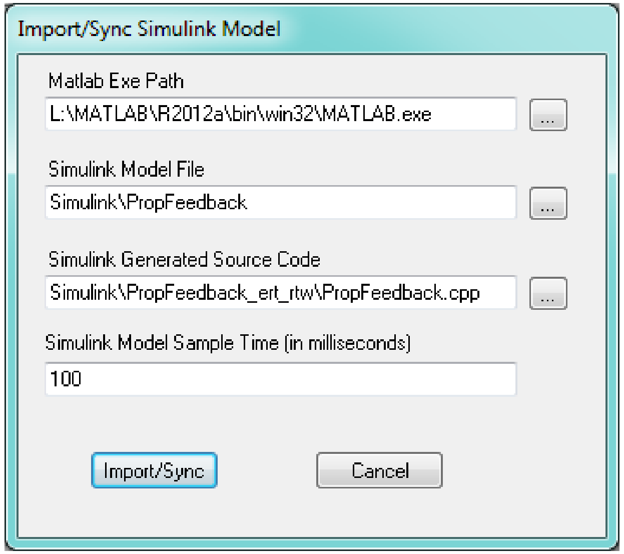

```
 #define MDL_GET_TIME_OF_NEXT_VAR_HIT
static void mdlGetTimeOfNextVarHit(SimStruct *S)
{
#ifdef _OMINSTRUMENT
        /* in animation mode, block the Simulink thread until Rhapsody threads
are working */
        checkAndWaitForRhapsodyThreads();
#endif

        updateRhapsody(S, 0);
        time_T taskTime = ssGetTaskTime(S, 0);
        OxfTimeUnit nextTime = OMTimerManager::instance()->getNextTime();
        time_T tnext = ((time_t) nextTime) / 1000.0;
        if (taskTime > tnext) {
                tnext = ssGetTFinal(S) + 1;
        }
        else if (taskTime == tnext)
                tnext = tnext + 1/1000.0;

        ssSetTNext(S, tnext);
}

/* Function: mdlOutputs =======================================================
 * Abstract:
 *    In this function, you compute the outputs of your S-function
 *    block. Generally outputs are placed in the output vector, ssGetY(S).
 */
static void mdlOutputs(SimStruct *S, int_T tid)
{
         SFunctionBlockCruiseControl* p_SFunctionBlockCruiseControl;

#ifdef _OMINSTRUMENT
        /* in animation mode, block the Simulink thread until Rhapsody threads
are working */
        checkAndWaitForRhapsodyThreads();
```



Exchanging behavior via generated code

- Our approach uses generated C/C++ code to generate behavior of blocks brought to the simulator
- «SimulinkBlock» may reference C/C++ code generated by MATLAB Embedded Coder
  - This code is compiled with the rest of the code into an executable used by Rhapsody simulation
- «StructuredSimulinkBlock» is transformed to a Simulink model with an auto-generated S-Function Block that encapsulates the behavior of the native SysML blocks
- Modelica has adopted the Functional Mockup Interface (FMI) standard (see https://www.fmi-standard.org/) to exchange behavior using generated C code
  - Unlike S-Function, FMI is non-proprietary





Demo: Modeling a Cruise Control Vehicle

- We will demonstrate two simulations of a cruise control system of a vehicle:
  - Exporting a hierarchy of IBDs to Simulink and running the simulation in Simulink
  - Importing Simulink models + generated code to Rhapsody and building an executable that can be simulated
- We will use the same two Simulink models in both simulations
  - A model specifying a proportional feedback setting the thrust based on the difference between the desired and actural speeds
  - A model simulating the drag force exerted on the vehicle
- SysML will be used to describe the composition of the system
  - The variant between the two SysML models is very small (will be explained)

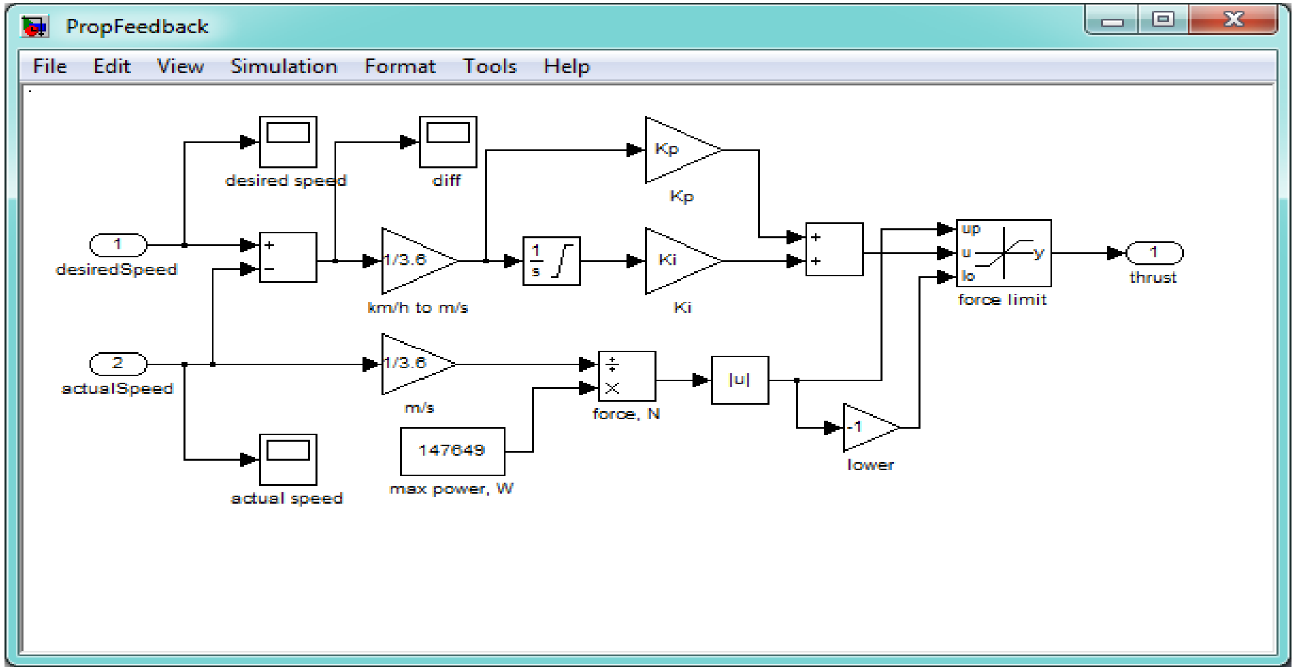
Proportional Feedback in Simulink

$$V_{diff} = \frac{V_{desired} - V_{actual}}{3.6}$$

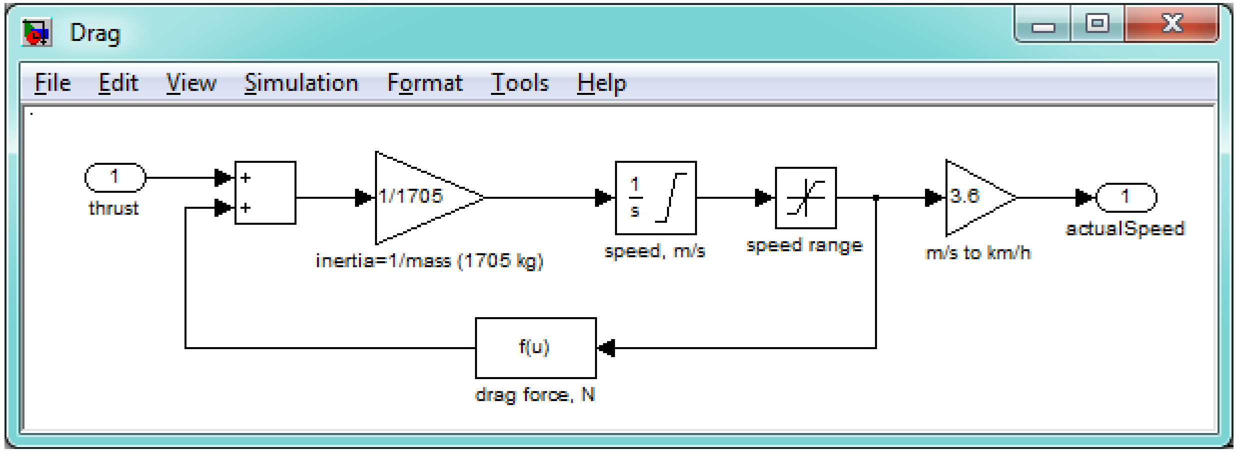
$$MaxThrust = \left| \frac{147649}{V_{actual} / 3.6} \right|$$

$$Th = Kp * V_{diff} + Kr * \int V_{diff} * dt$$

$$Thrust = \begin{cases} MaxThrust & Th > MaxThrust \\ Th & MaxThrust \geq Th \geq -MaxThrust \\ -MaxThrust & Th < -MaxThrust \end{cases}$$



Drag



- Thrust is converted to speed in m/sec, and then converted to Km/h
- Drag force is proportional to the square of the velocity

$$F_D = \frac{1}{2} \rho v^2 C_d A,$$

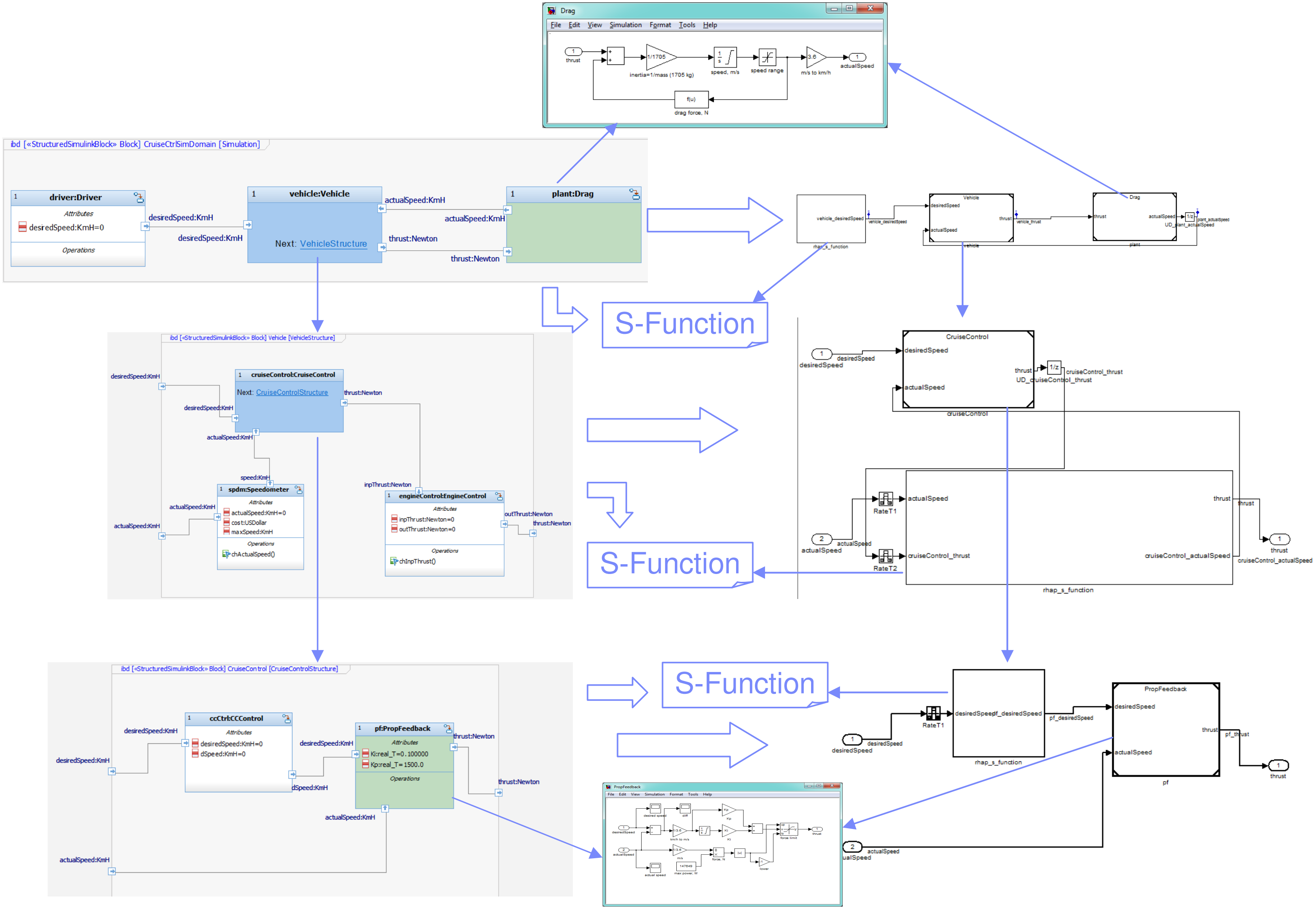
see derivation

where

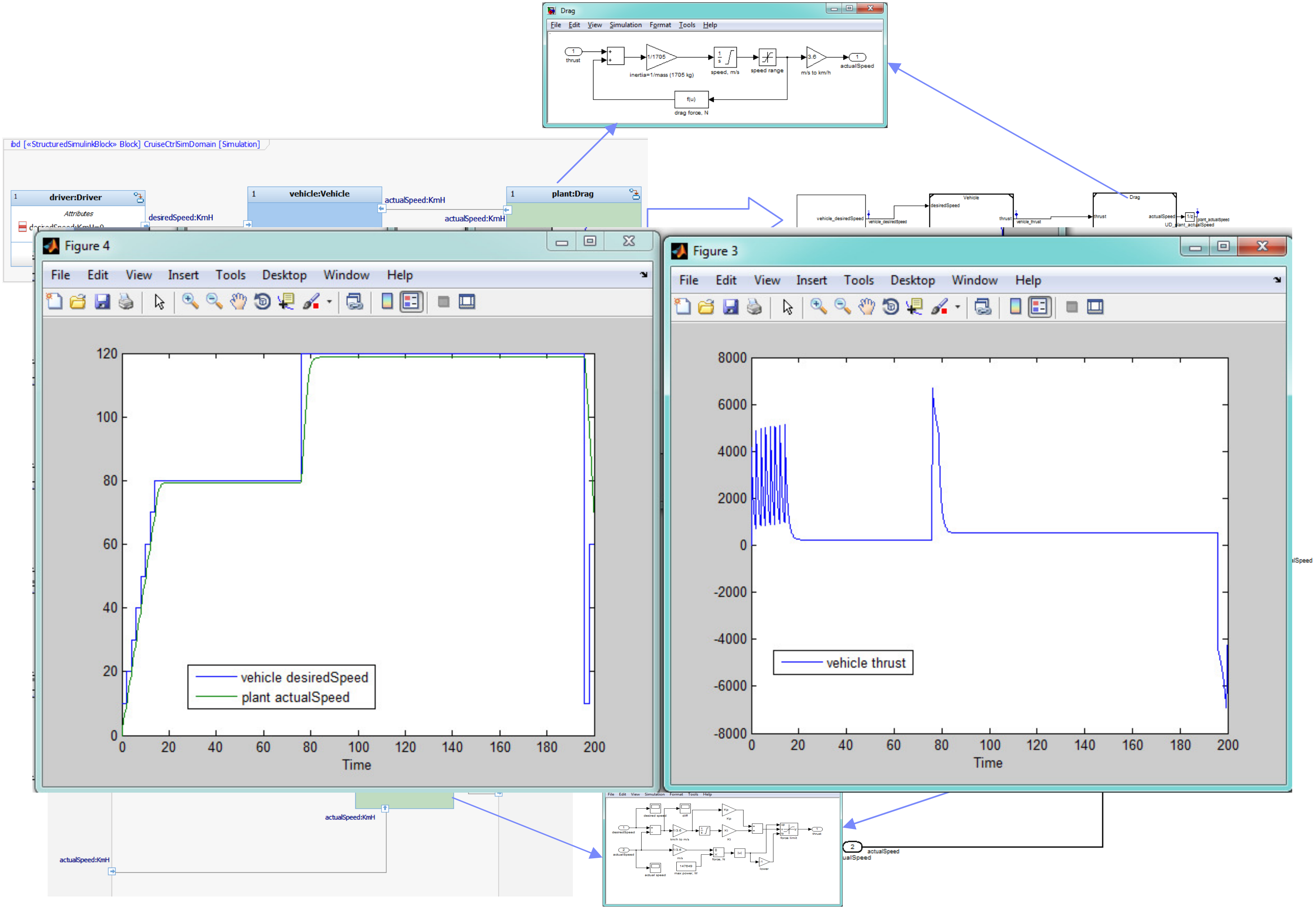
$\mathbf{F}_D$ is the force of drag,
ρ is the density of the fluid,[12]
v is the speed of the object relative to the fluid,
C_d is the drag coefficient (a dimensionless parameter, e.g. 0.25 to 0.45 for a car)
A is the reference area,

Source: http://en.wikipedia.org/wiki/Drag_%28physics%29

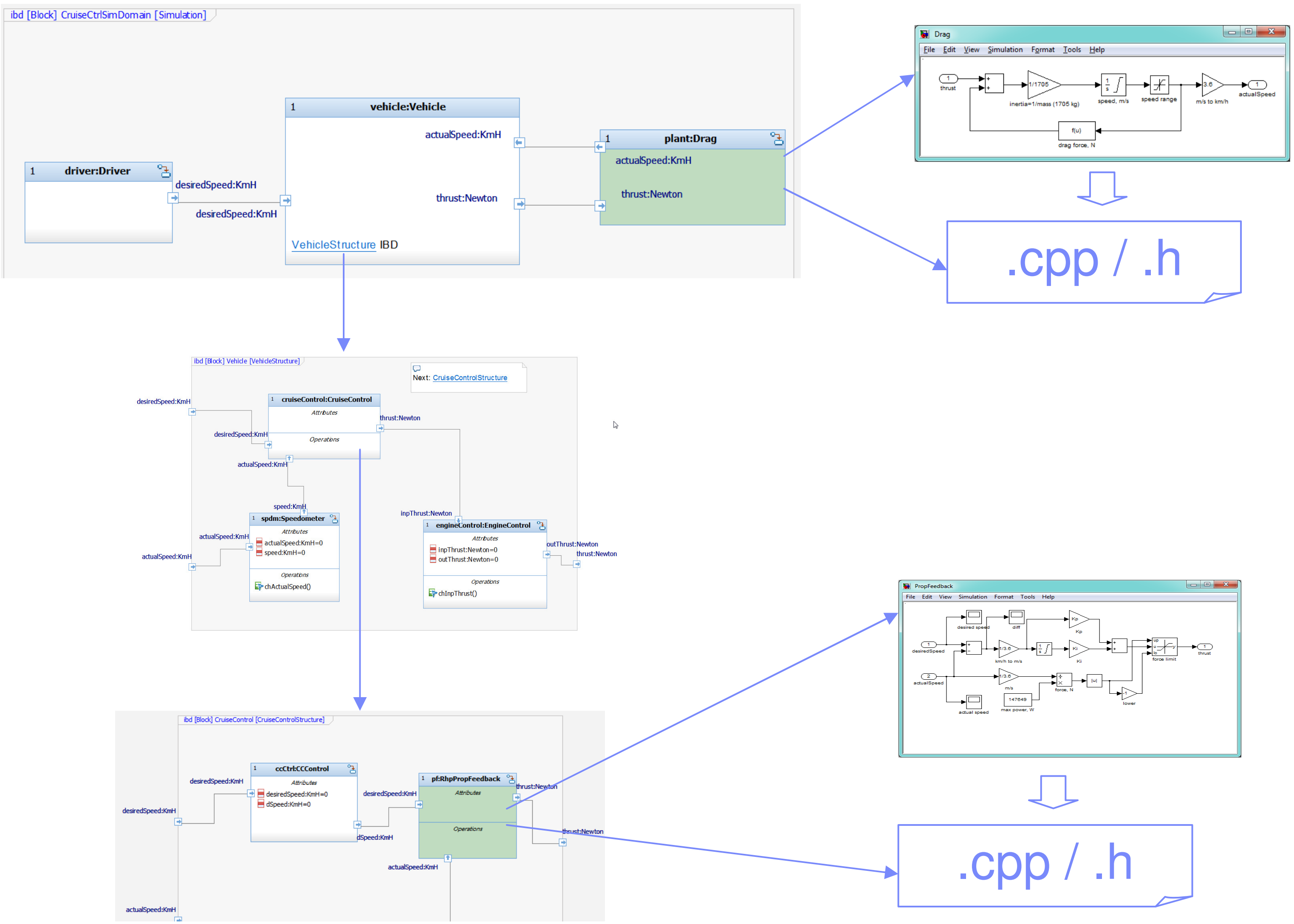
Demo 1: Vehicle Cruise Control, Simulation in Simulink



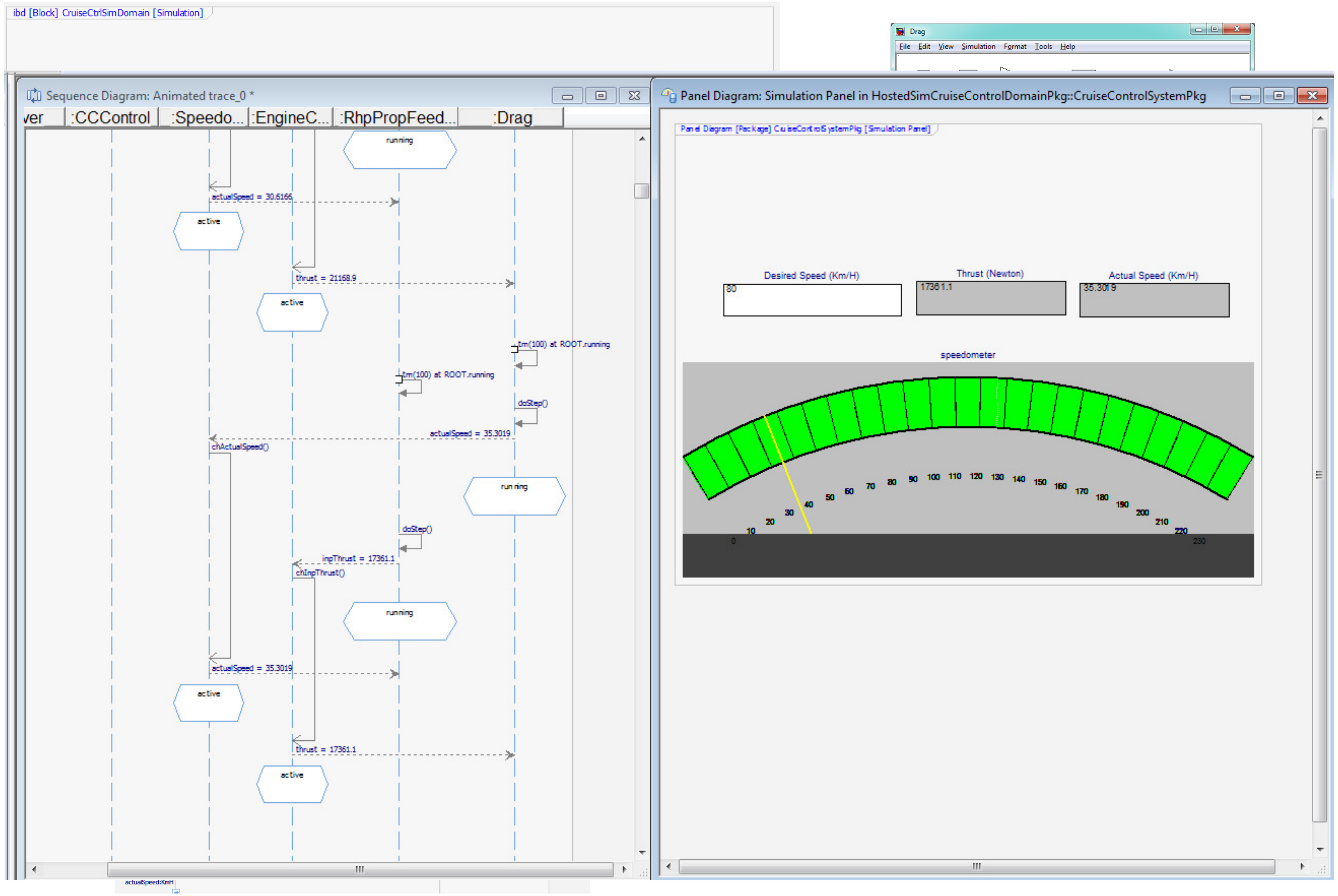
Demo 1: Vehicle Cruise Control, Simulation in Simulink



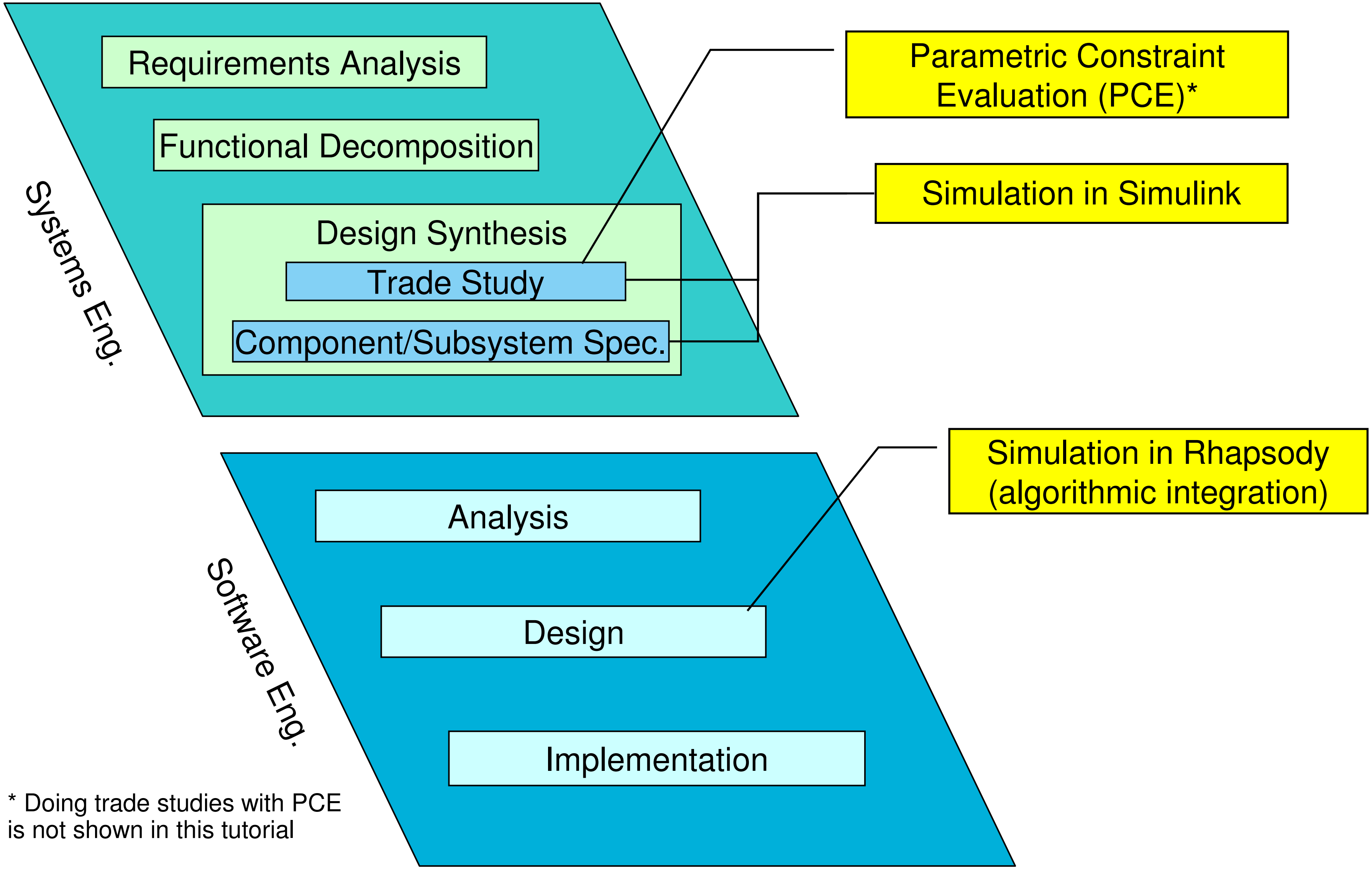
Demo 2: Vehicle Cruise Control, Simulation in Rhapsody



Demo 2: Vehicle Cruise Control, Simulation in Rhapsody



Demo summary: usage on the “V-Model”



* Doing trade studies with PCE is not shown in this tutorial

Presentation Outline

- What is a Cyber Physical System?
- A short overview of SysML
- Short overview of Simulink and Modelica
- How to model and simulate physical environments/plant?
- How to model and simulate CPS?
- <u>Summary</u>

Tutorial Summary

- CPS are computerized systems the operate and interact with physical environment
- Complex CPS designs require systems engineering techniques involving modeling and simulations
- SysML is a standardized modeling language defining multiple diagram types to describe various aspects of systems
- SysML needs to be complemented by tools/languages such as Simulink/Modelica to specify continuous algorithms and plant behavior
- We showed how to model physical environments using Simulink, Modelica and SysML Parametric Diagrams
- We demonstrated three integration points between SysML and numerical tools:
  - Evaluation of parametric diagrams using Rhapsody PCE
  - Simulation of structured block by exporting it to Simulink for simulation
  - Simulation of hybrid models in Rhapsody using code generated from Simulink models

Some References and Further Readings

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- Open Modelica: https://openmodelica.org/
- Rational Rhapsody: http://www-142.ibm.com/software/products/us/en/ratirhapfami/
- S-Function information: http://www.mathworks.com/help/simulink/s-function-basics.html
- FMI web site: https://www.fmi-standard.org

Thank You!

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