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Model-based multi-disciplinary co-simulation and co-modelling

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and

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MPM4CPS
IC 1404

Horizon 2020 Programme

Outline

Co-simulation

- Motivation for M&S in MSBE
- Co-simulation
- Remote simulators
- Functional-Mock-up Interface
- Competent co-simulation

The DESTECS project

- Embedded Control Systems
- Co-Modelling, Co-Simulation
- Fault tolerance and handling

The INTO-CPS project

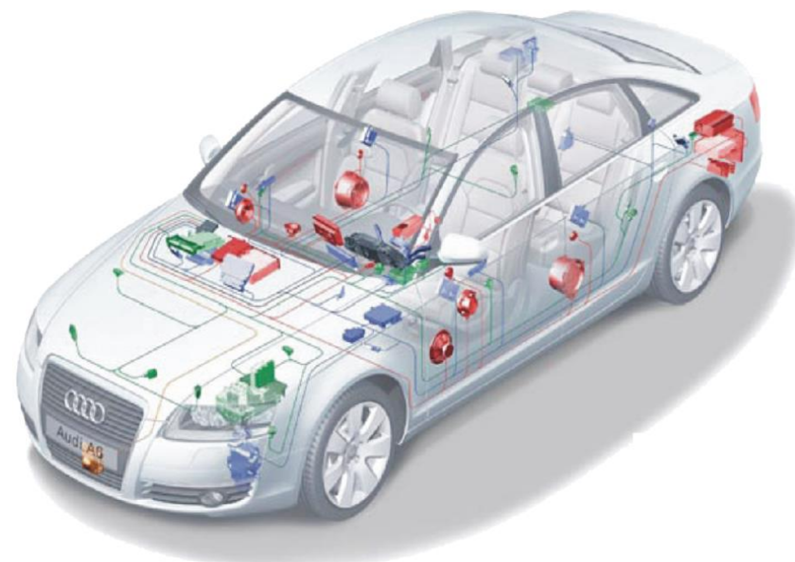
- Cyber Physical Systems (CPSs)
- System Vision
- Multi-modelling
- FMI-based co-simulation

The practical assignment

- A line-following robot
- Assumptions
- Development lines

The Modern Car

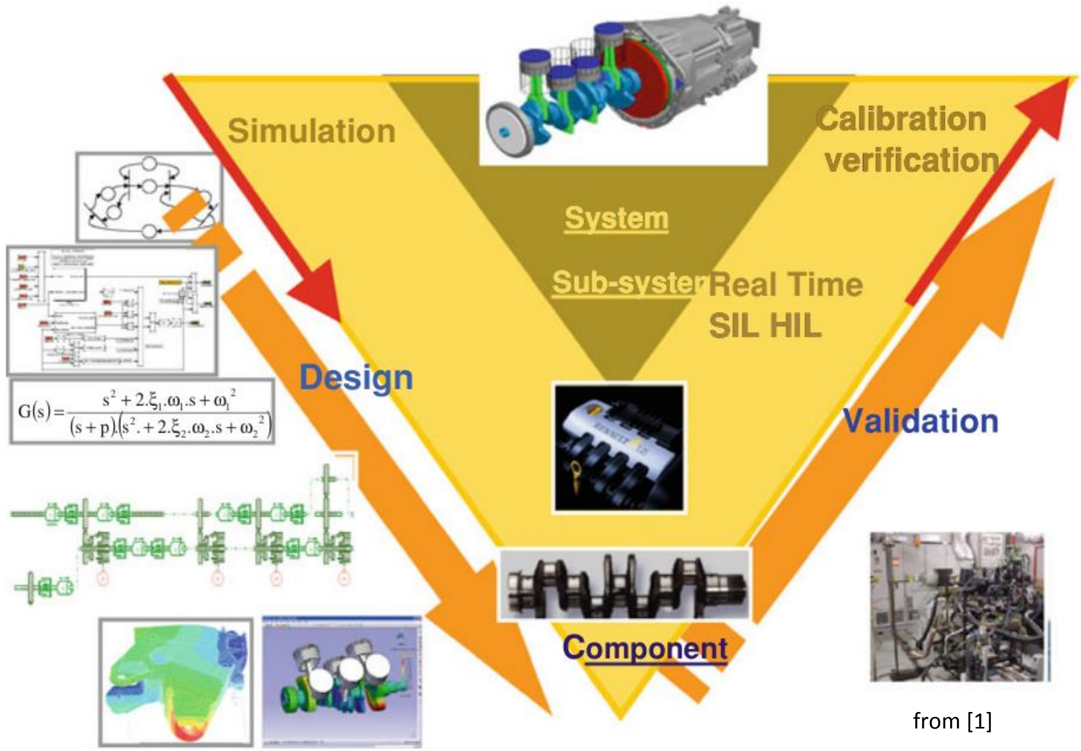
- Complexity
  - 40-100 subsystems
- Competitive Market
- Concurrent Development
  - Late Integration Problems
- Distributed Development
  - Specialized suppliers
  - OEM wants to
    - Evaluate multiple components
    - Perform early system integration
  - Supplier IP protection



from www.imes.uni-hannover.de/

M&S in MBSE

- V-Process
  - Design
    - Requirements (0D model)
    - Dynamics (1D model)
    - Mesh (3D model)
  - Validation
    - Reuse design experimentation results
- Simulation in all stages
- V-process also applies to more complex systems



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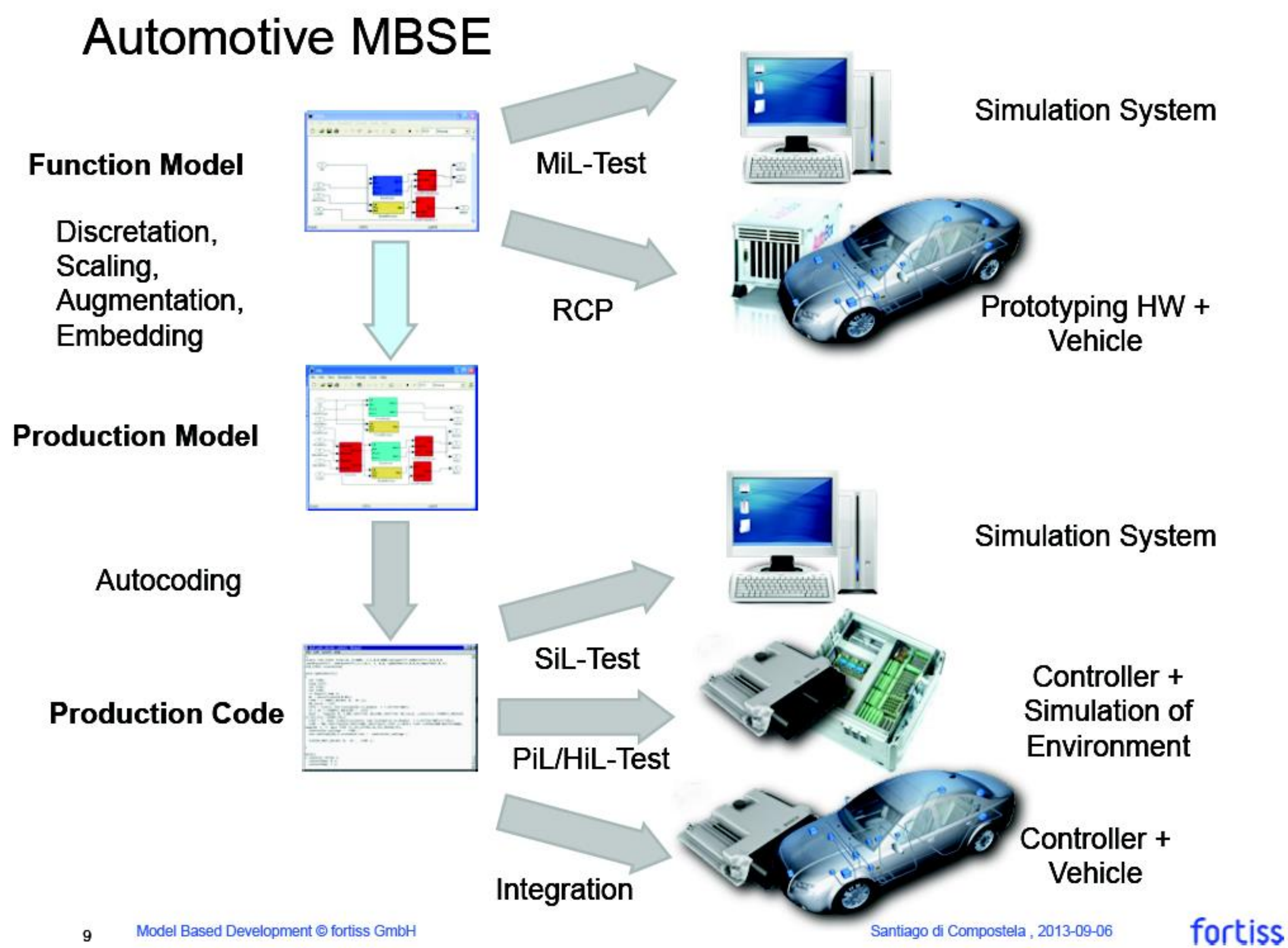
M&S in MBSE


Automotive MBSE
Function Model
Discretation,
Scaling,
Augmentation,
Embedding
Production Model
Autocoding
Production Code
MiL-Test
RCP
SiL-Test
PiL/HiL-Test
Integration
Simulation System
Prototyping HW +
Vehicle
Simulation System
Controller +
Simulation of
Environment
Controller +
Vehicle
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Model Based Development © fortiss GmbH
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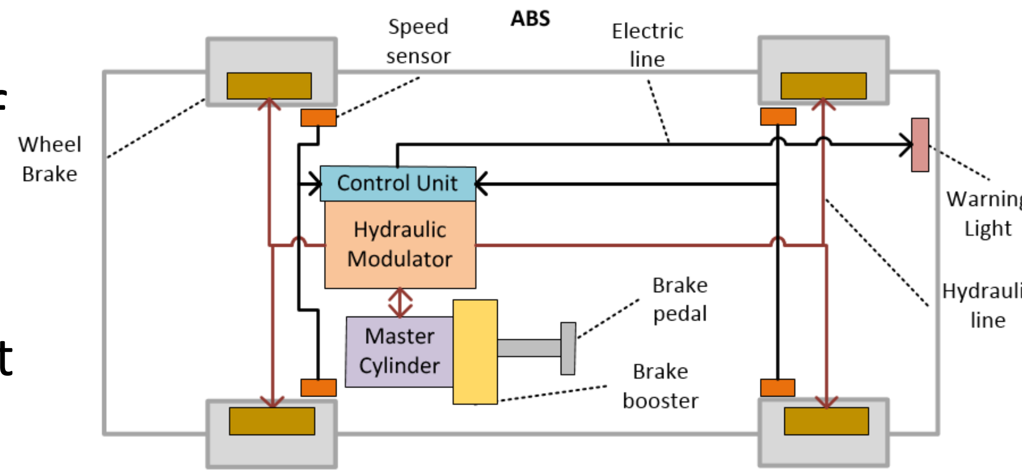
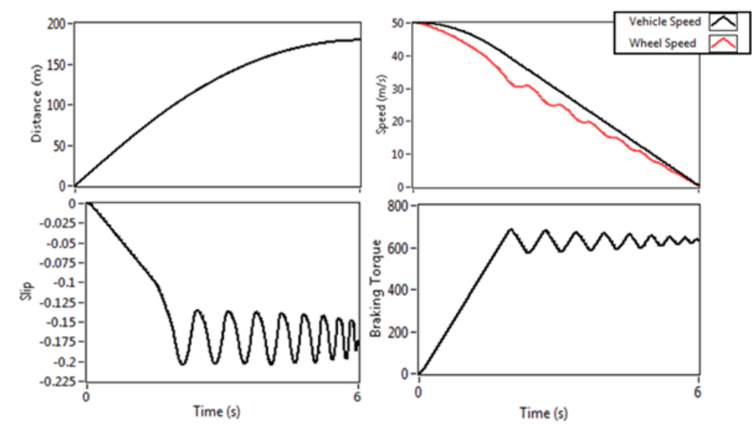
M&S in MBSE

- Early access to models of components.
  - Test different control approaches
  - Evaluate same component from different suppliers
- Challenges:
  - Different teams/suppliers use different modelling tools
  - IP Protection
- Exchange Models
  - Leads to Vendor Lock-in
  - Simulation tools must support import

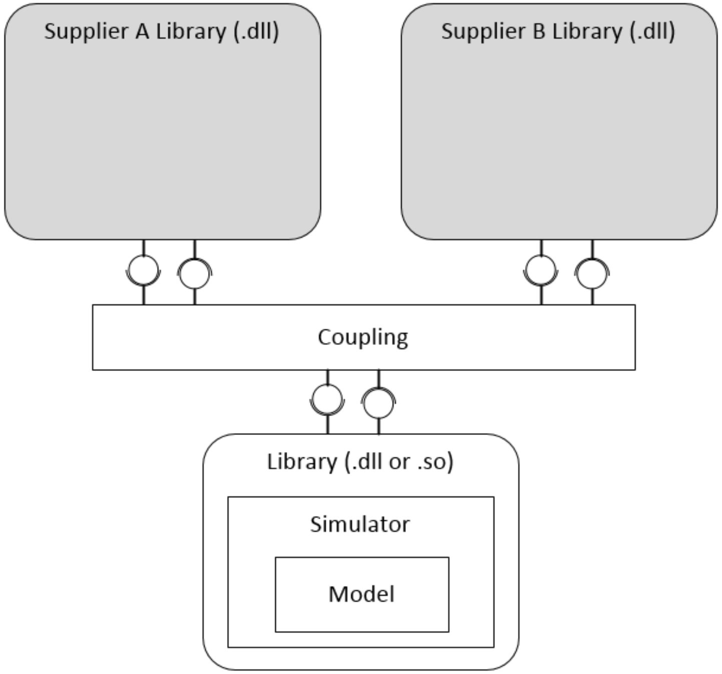




from www.ni.com/

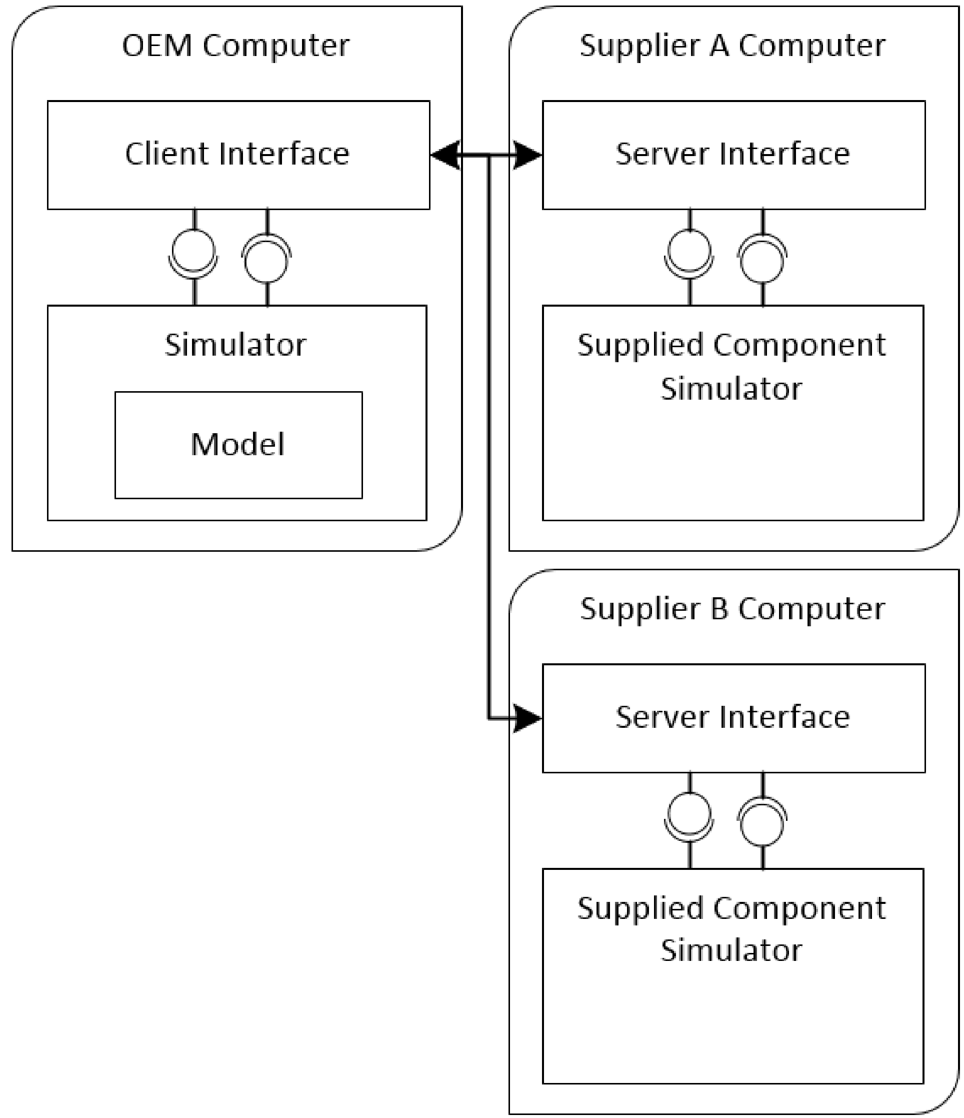
Co-simulation

- Simulation of a system
  - Coupling of multiple simulators
  - Optionally as black-boxes
  - Each simulating one or more models
  - Built with different formalisms/tools.
- Co-simulation scenario
  - Description of the system
  - The simulators and their dependencies
  - Data about the capabilities of each simulator.



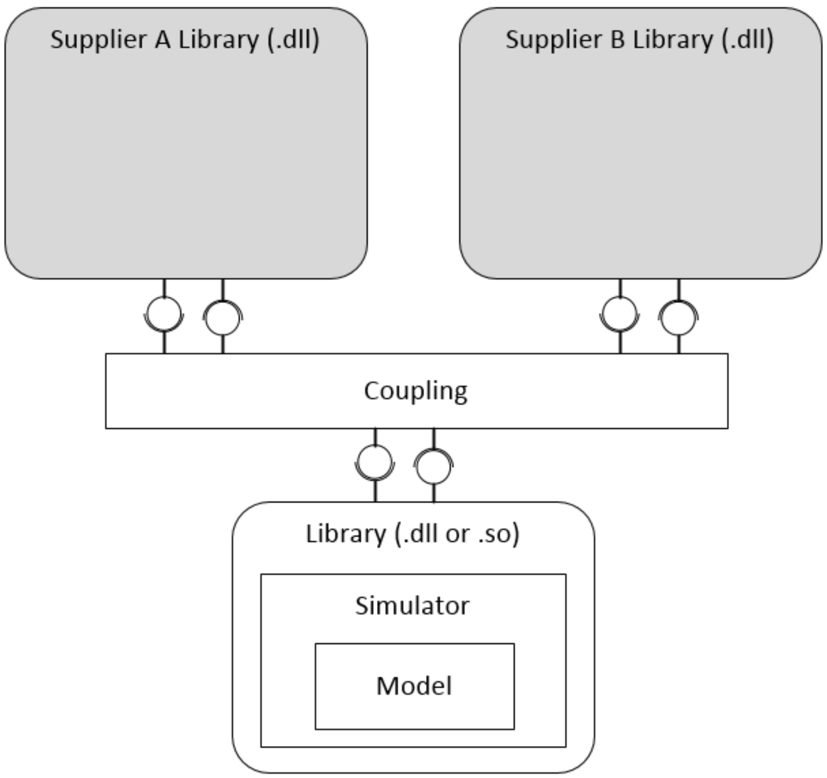
Remote Simulators

- Suppliers make a simulator available through an API
  - Integrator takes care of programming an interface
  - Good IP Protection
  - Different suppliers require different interfaces



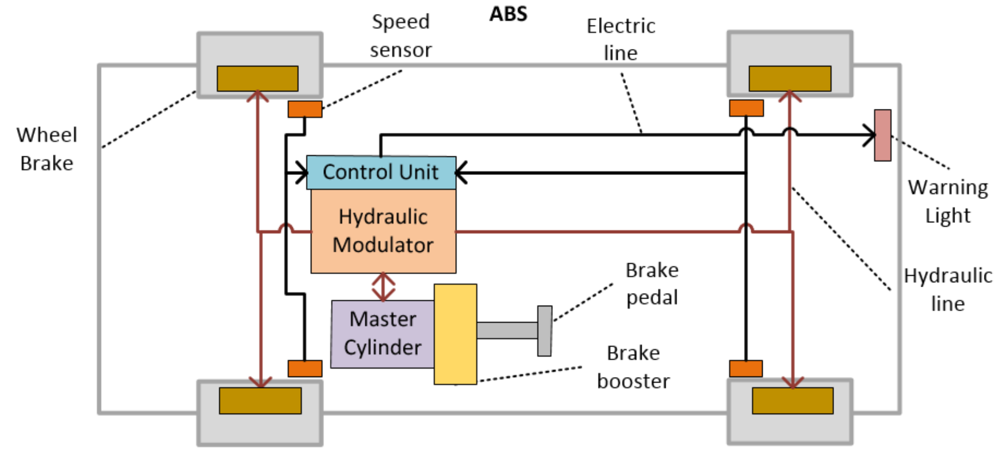
Functional Mock-up Interface Standard

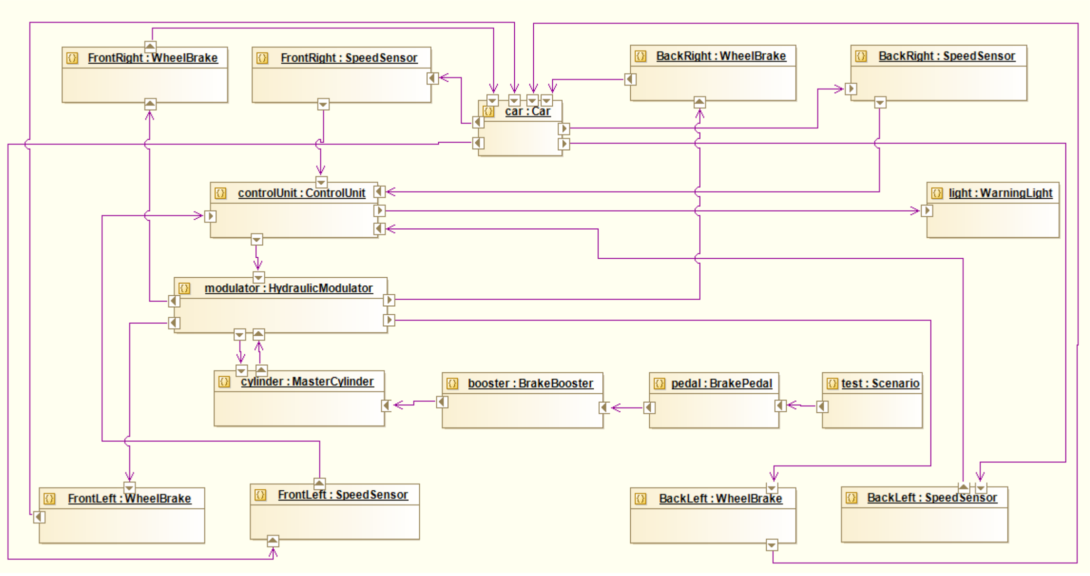
- Simulator and model exported as a standardized C library
- Standard interaction with any simulator
- Every simulator is a black box.
  - Executed locally but can communicate with a remote server



Functional Mock-up Interface Standard

- A Functional Mockup Unit is a zip-file (.fmu) consisting of
  – C Library (.dll or .so)
  – XML file (metadata)
- The coupling (master algorithm) must be provided





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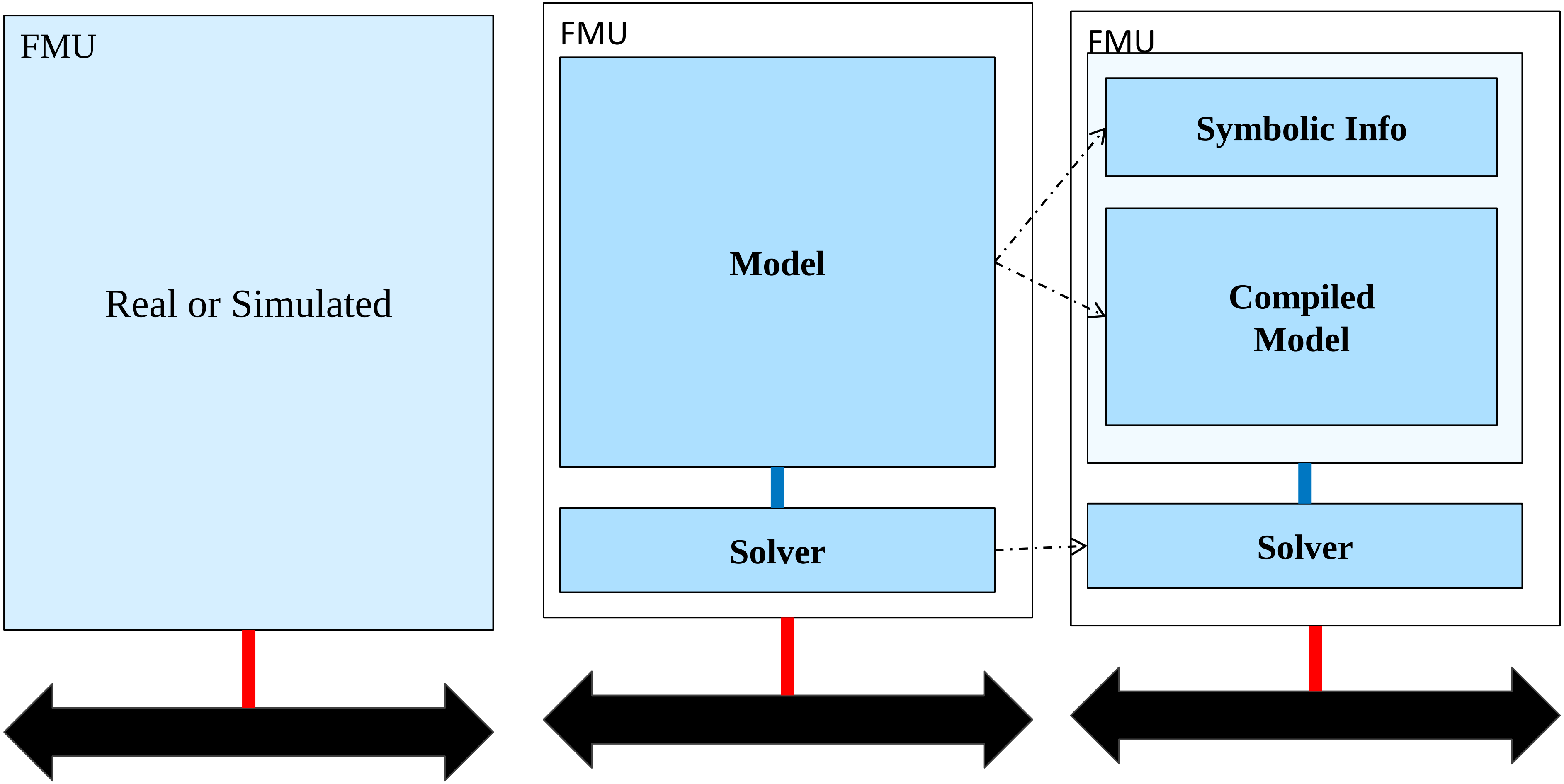
Inside an FMU



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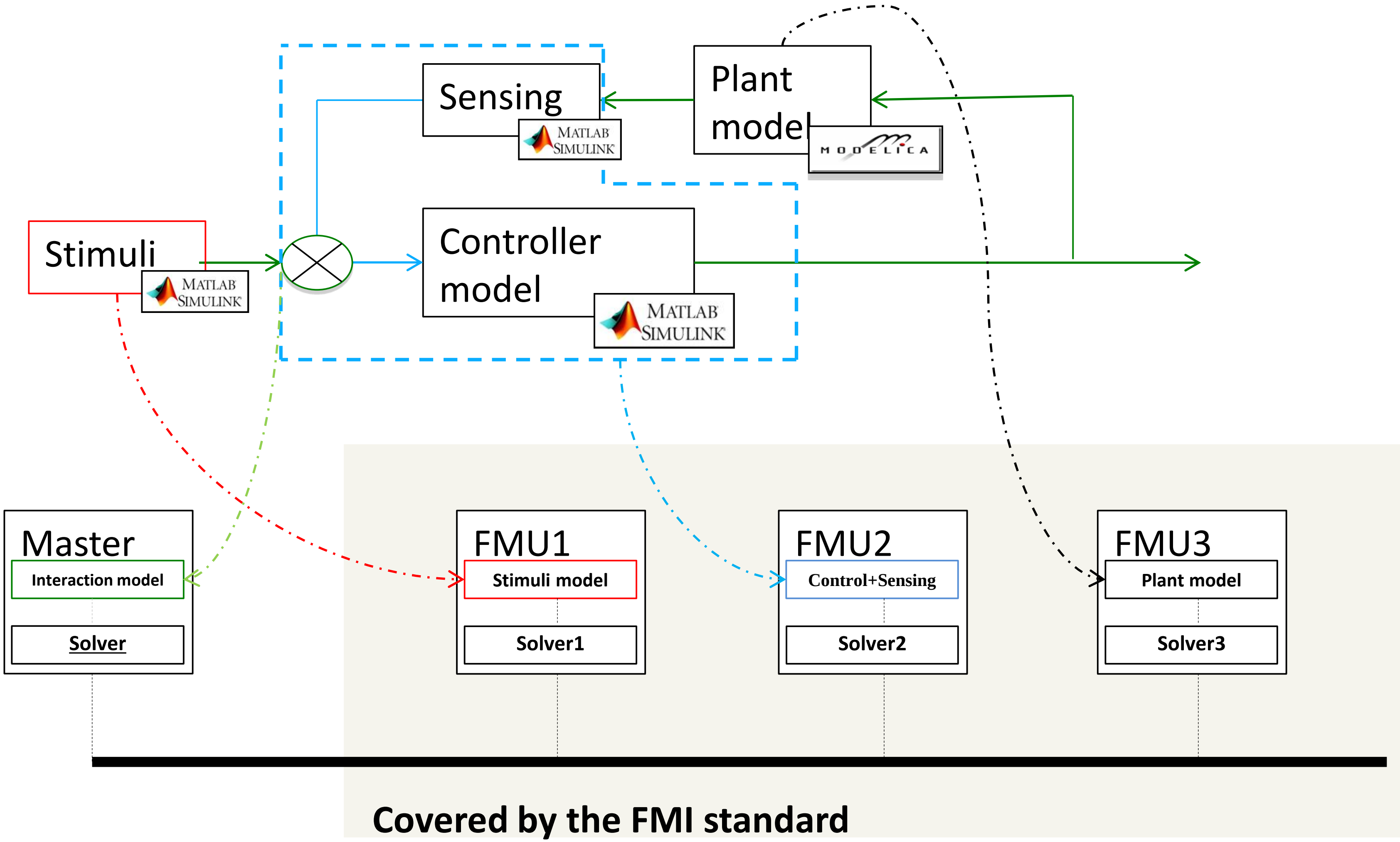
FMU Example

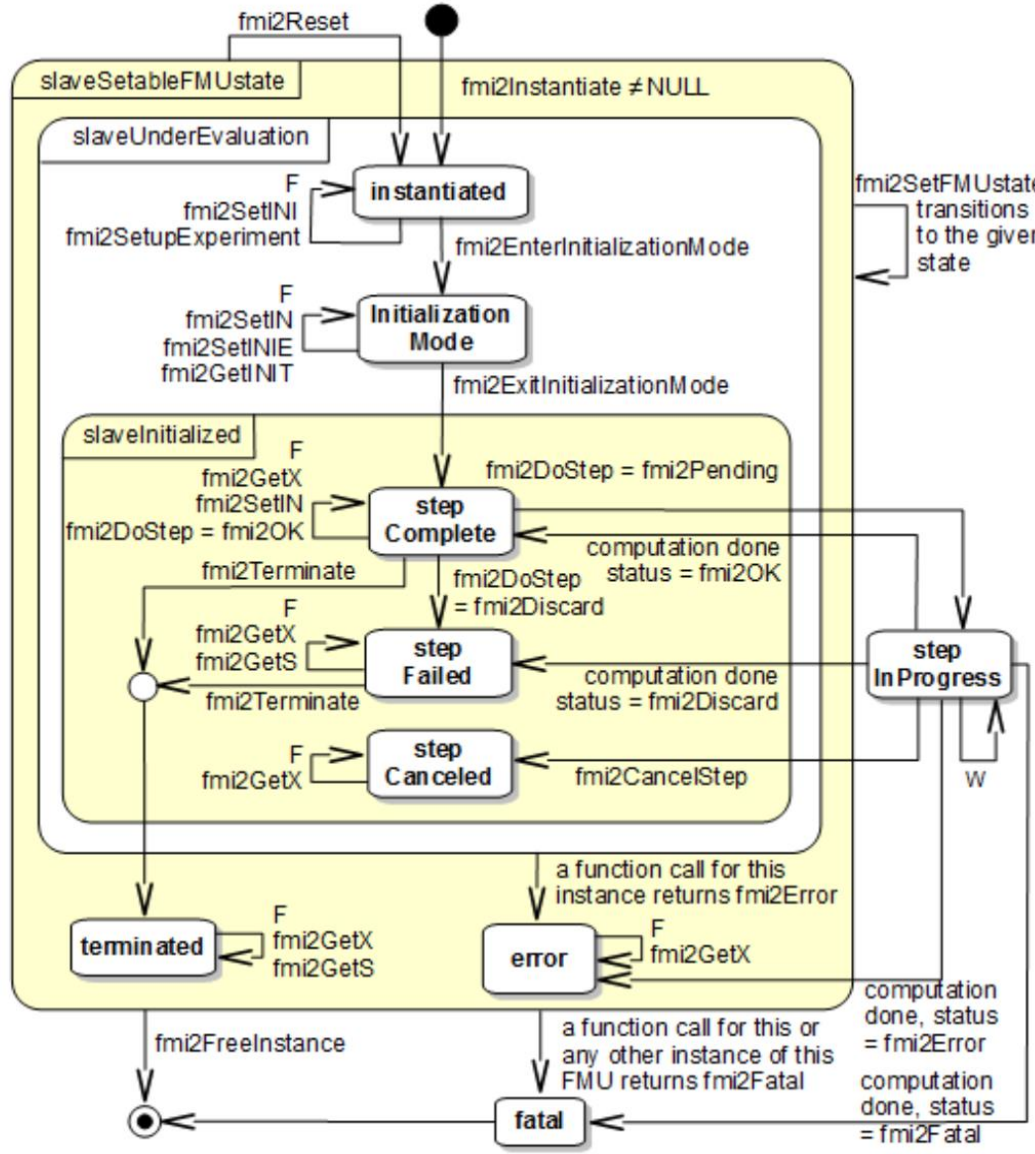
```
fmi2Status fmi2DoStep(fmi2Component fc , fmi2Real currentCommPoint, fmi2Real commStepSize, fmi2Boolean
    noPrevFMUState)
{
    FMUInstance* fi = (FMUInstance *)fc;
    fmi2Status simStatus = fmi2OK;
    printf("%s in fmiDoStep()\n",fi->instanceName);
    fi->currentTime = currentCommPoint + commStepSize;
    printf("Motor_in: %f\n", fi->r[_motor_in]);
    printf("slave CBD_PART2 now at time: %f\n", fi->currentTime);

    fi->r[_position] =  fi->r[_position] + fi->r[_velocity] * commStepSize;
    fi->r[_velocity] = fi->r[_velocity] + fi->r[_acceleration_after_friction] * commStepSize;
    fi->r[_friction] = fi->r[_velocity] * 5.81;
    fi->r[_motor_acceleration] = fi->r[_motor_in] * 40;
    fi->r[_acceleration_after_friction] = fi->r[_motor_acceleration] - fi->r[_friction];

    return simStatus;
}

fmi2Status fmi2GetReal(fmi2Component fc, const fmi2ValueReference vr[], size_t nvr, fmi2Real value[])
{
    FMUInstance* comp = (FMUInstance *)fc;
    int i;
    for (i = 0; i < nvr; i++)
    {
        value[i] = comp->r[(vr[i])];
    }
    return fmi2OK;
}
```

FMI Co-Simulation Scenario



FMU States

- Synchronization algorithm (master)
  - Communicates with each individual simulator
  - Moves data from one simulator to the other
  - Coordinates time

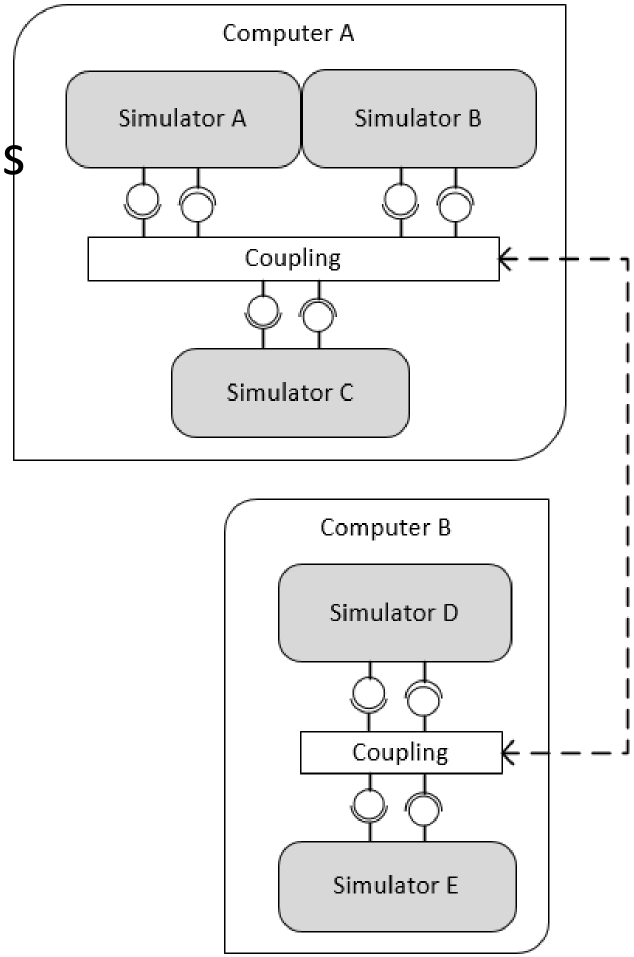


Research Challenges

- Can we trust the co-simulation results?
  - Computer Science
  - Numerical
  - Physics

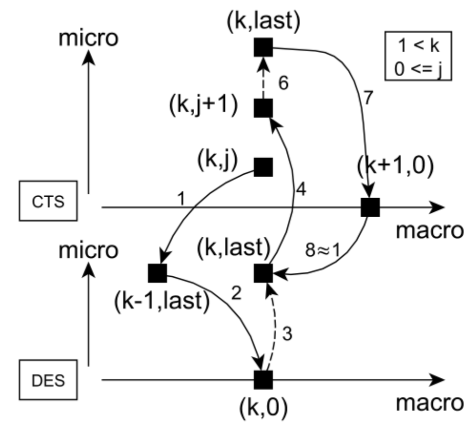
Research Challenges: Computer Science

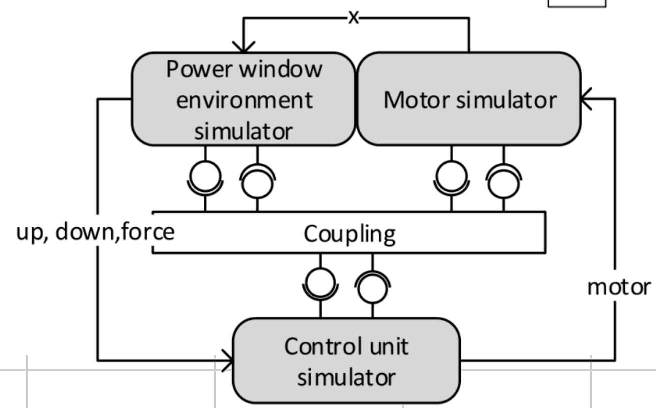
- Real-time constraints
  - E.g., Hardware (HiL)
- Make the most of heterogeneous capabilities
  - Fixed or adaptive time-step
  - no/single/multiple rollback support
- Hierarchical co-simulation
- Different information exposed about each simulator
  - IO Dependencies
  - Numerical algorithm
  - Recommended step size
  - Jacobian matrices
  - Operating conditions (e.g., range of stability)
- Parallelism
  - Determinism
  - Deadlocks
  - Fairness

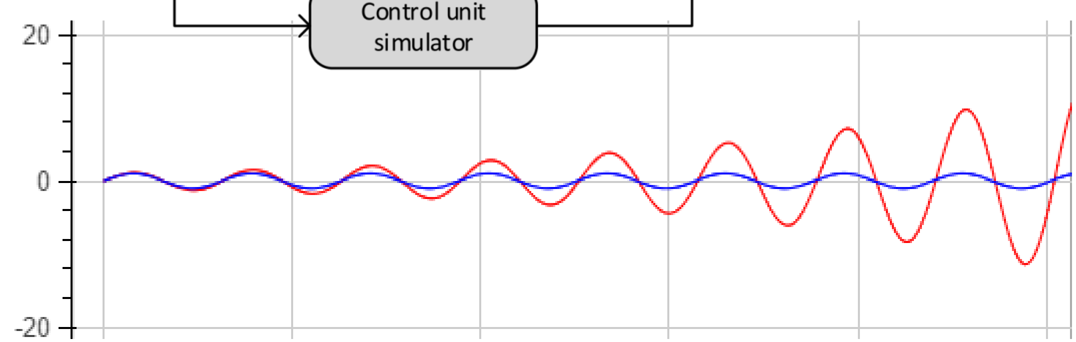


Research Challenges: Numerical

- Time synchronization
  - Correct interleaving of the execution of each simulator.
  - Including data dependencies.
- Time progression
  - Handle Zeno behaviours
- Algebraic (instant) dependencies
  - Detect and solve.
- Compositionality
  - State event location
  - Stability







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Research Challenges: Physics

- Extra coupling equations might be necessary
  - E.g., c^2 = 0.5 ⇔ c = 0.25 or c = -0.25
- Inconsistent values
  - E.g., Voltage

Validation in Industry

Abstraction/Refinement:

$$M_i \sqsupseteq_P M_{i+1} \equiv \forall p \in P, M_i \models p \implies M_{i+1} \models p$$

Engineering process:

$$M_0 \sqsupseteq_P M_1 \sqsupseteq_P \cdots \sqsupseteq_P M_n \sqsupseteq_P R$$

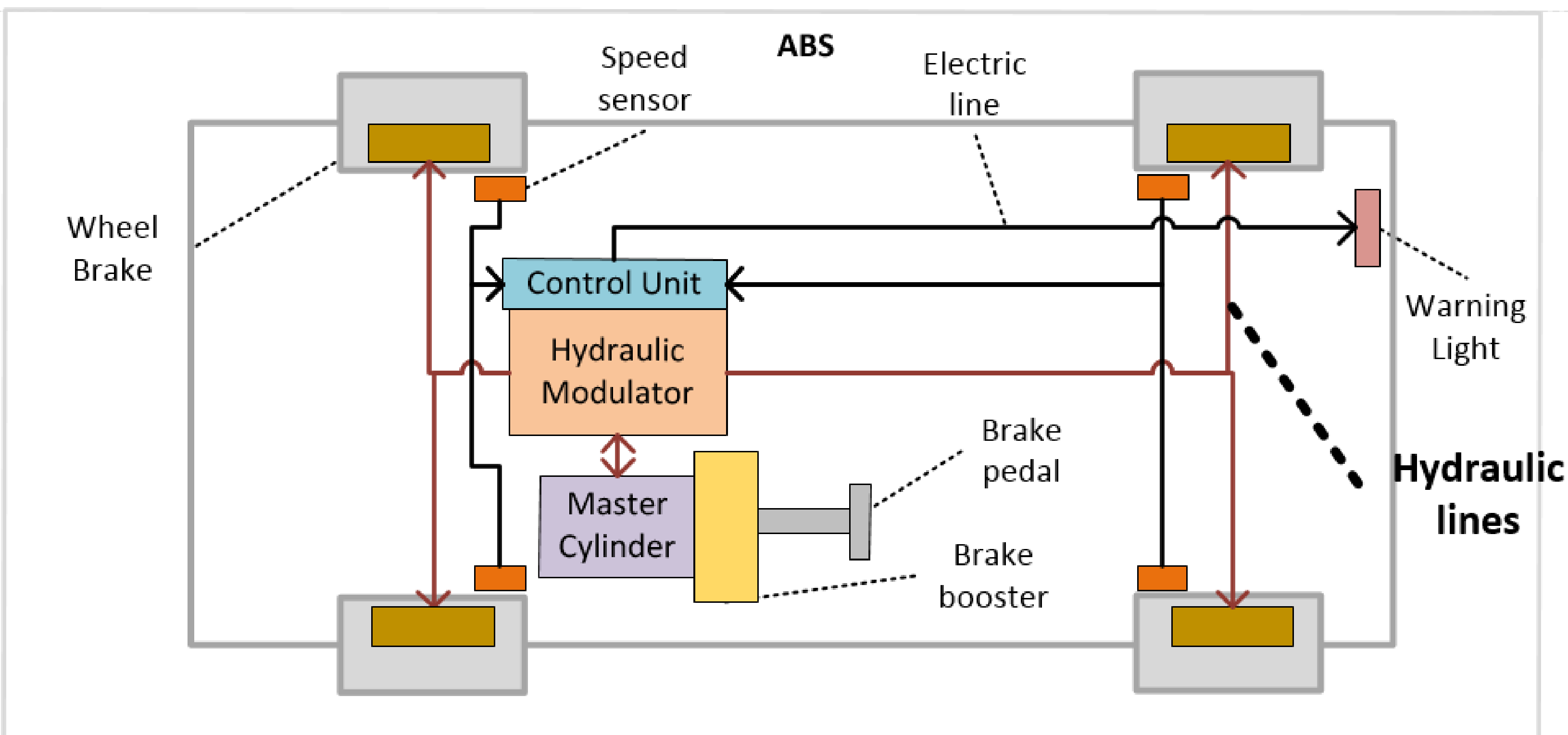
Verification ($M_i \models p$) is approximate: $M_i \mathrel{|}\!\approx p$

Validation becomes: $M_i \mathrel{|}\!\approx p \implies M_{i+1} \mathrel{|}\!\approx p$

Competency ($M_i \mathrel{|}\!\approx p \implies R \mathrel{|}\!\approx p$) becomes the goal

Validation in Industry (Example)

- Hydraulic connection introduces delay.
- If not modeled, refinements may be valid but not competent.



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References

[1] - Van der Auweraer, H., Anthonis, J., De Bruyne, S., & Leuridan, J. (2013). Virtual engineering at work: the challenges for designing mechatronic products. *Engineering with Computers*, *29*(3), 389–408. http://doi.org/10.1007/s00366-012-0286-6

[2] - Blochwitz, T., Otter, M., Åkesson, J., Arnold, M., Clauss, C., Elmqvist, H., … Viel, A. (2012). Functional Mockup Interface 2.0: The Standard for Tool independent Exchange of Simulation Models. In *Proceedings of the 9th International MODELICA Conference* (pp. 173 – 184). Munich, Germany: The Modelica Association.