The Challenge of Model-Based Integration for Cyber-Physical Systems

MPM4CPS Conference, Pisa, Italy, 18-23 November 2018

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Prelude

Internet of Things

Definition of Multi-Paradigm Modeling:

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-
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-
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Ok, then let's talk about what is really interesting for MPM in our CPSLab ...

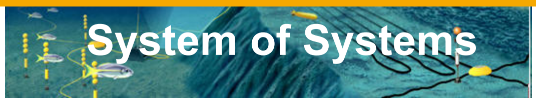
but then I realized ...

(Networked)
Cyber-Physical S

ge-Scale Systems

Smart Home

Smart Factory
E.g. Industry 4.0



E-Health

Smart Logistic

http://oceanservice.noaa.gov/news/weeklynews/nov13/ioos-awards.html

Micro Grids

Ambient
Assisted Living

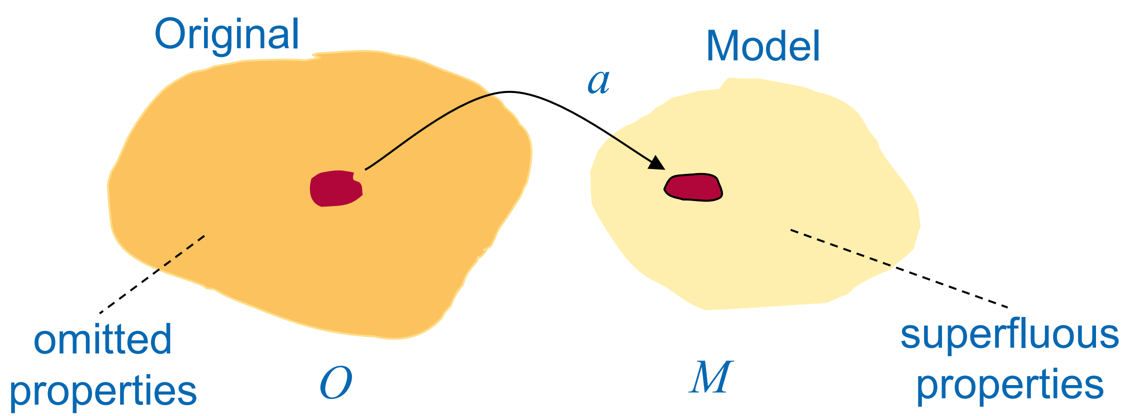
Outline

1. Foundations
(1) What are Models?

Herbert Stachowiak; *Allgemeine Modelltheorie*, Springer-Verlag, Wien 1973.

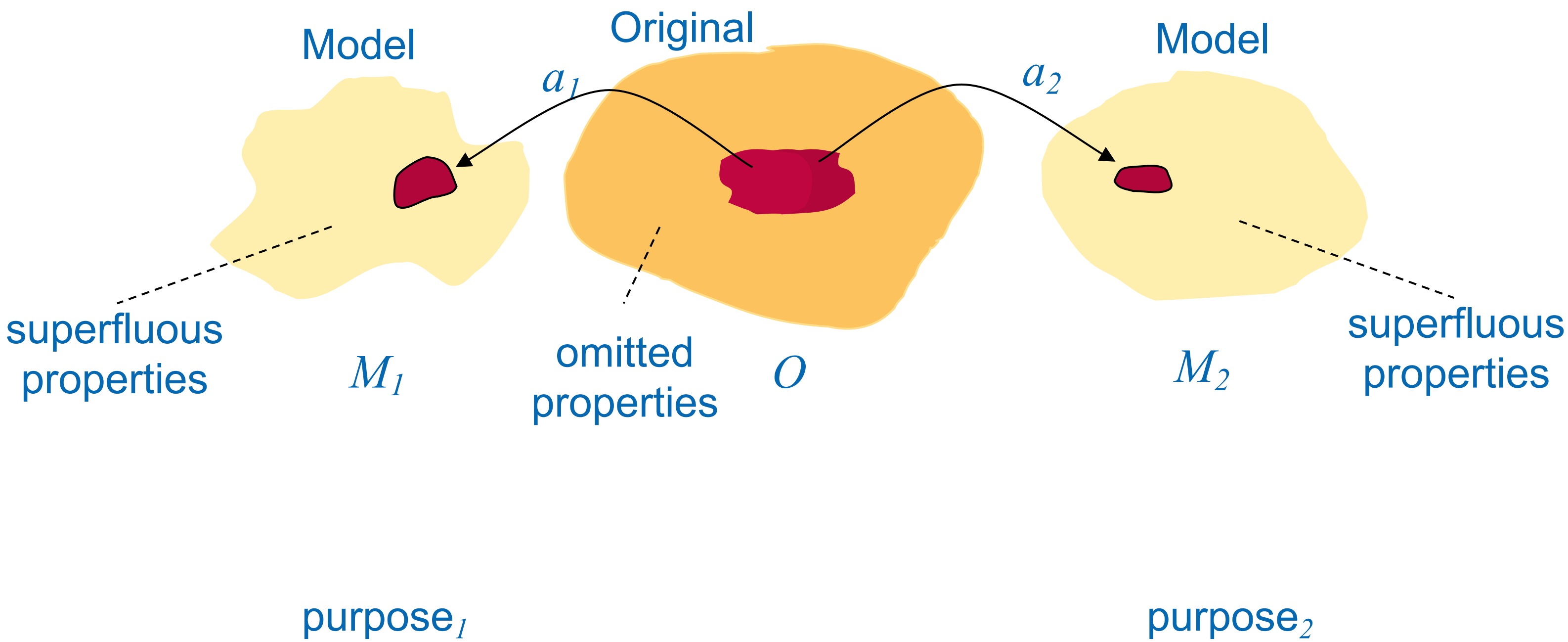
Models are in general abstract representations of existing or envisioned originals

- **Representation** of an original: it exists always a point of reference
  - A function a which assign a model M to the original O (**abstraction**).
  - A not unique backward mapping i assigns originals O to each model M (**interpretation**).
- **Reduction:** not all **properties** are represented
- **Pragmatics:** replaces the original only for a specific **purpose**



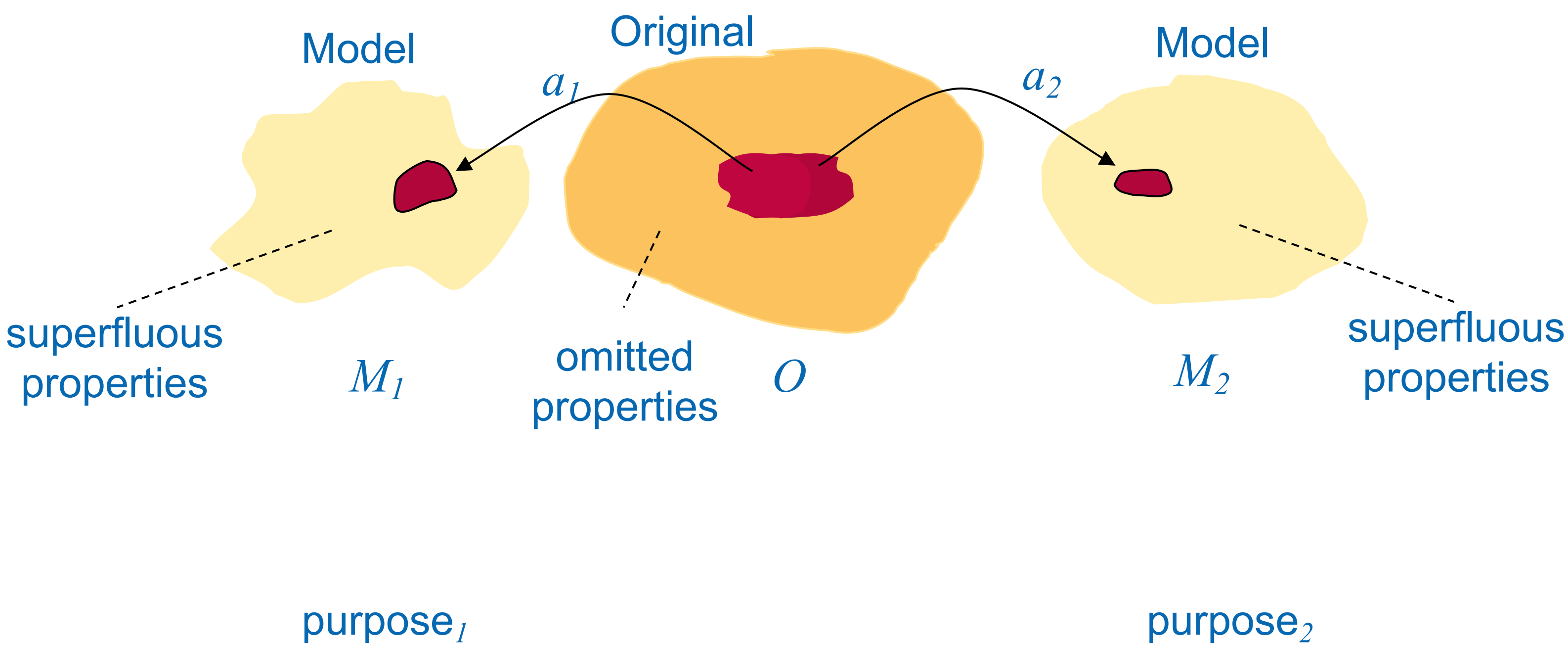
But Nowadays we often have Multiple Models?

Each **model** M_j is an abstract representations of of a part or multiple parts of an existing or envisioned original used for a specific purpose.



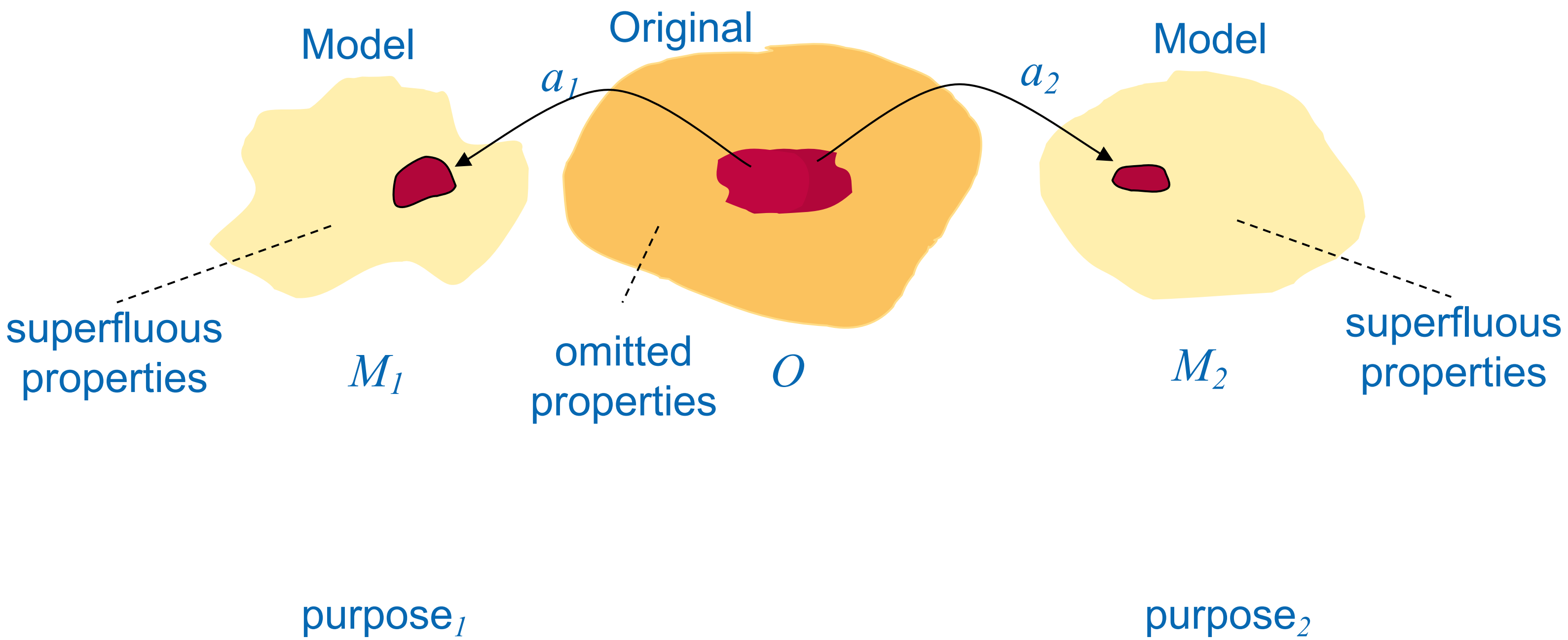
Benefits of Multiple Models?

Benefit: For purpose$_j$ we replace the original O by a suitable model M_j that does not contain any irrelevant information (**reduced complexity**!)



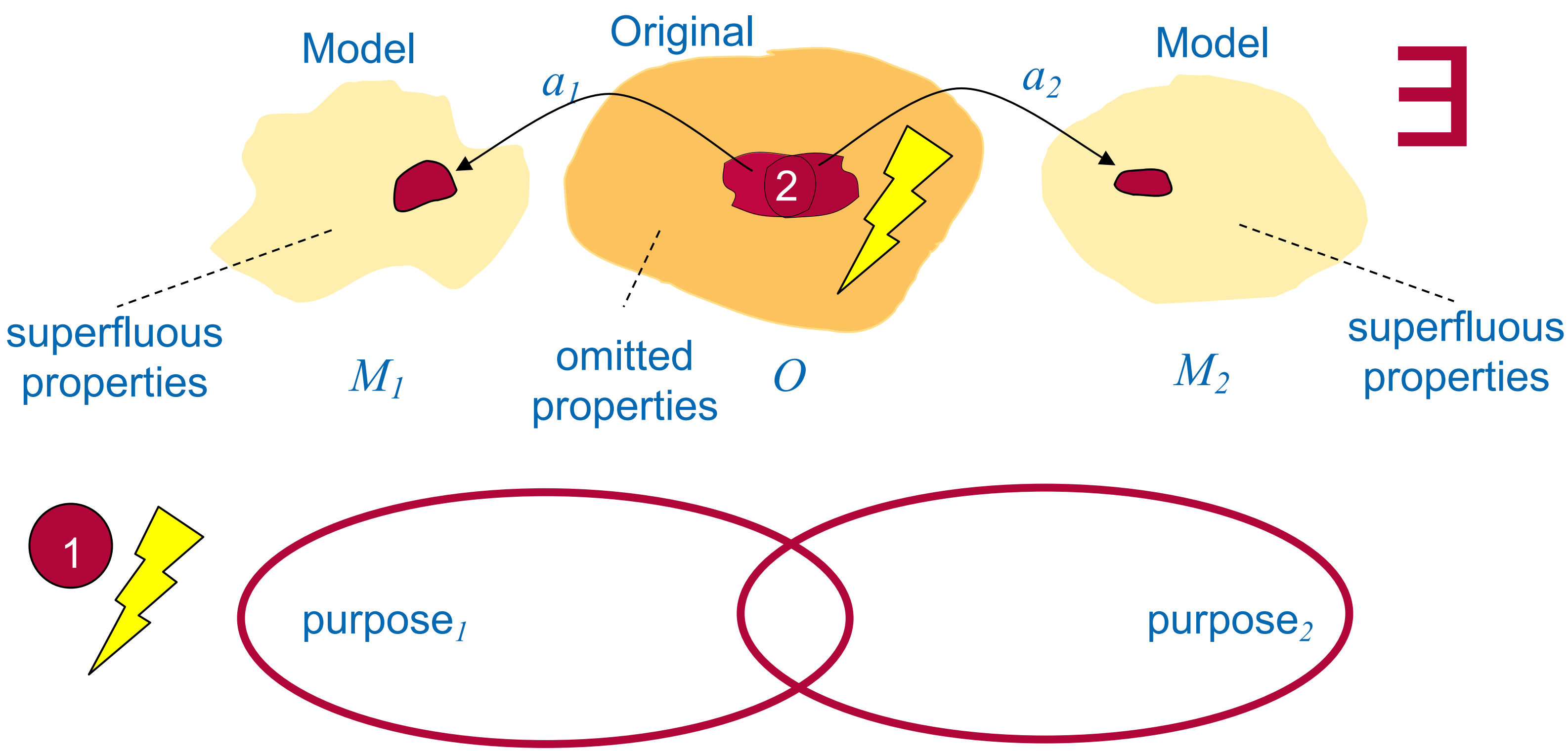
Drawback of Multiple Models?

Drawback: Does an original O consistent with both models M_1 and M_2 really exist (**consistency**)?



How to Handle Multiple Models?

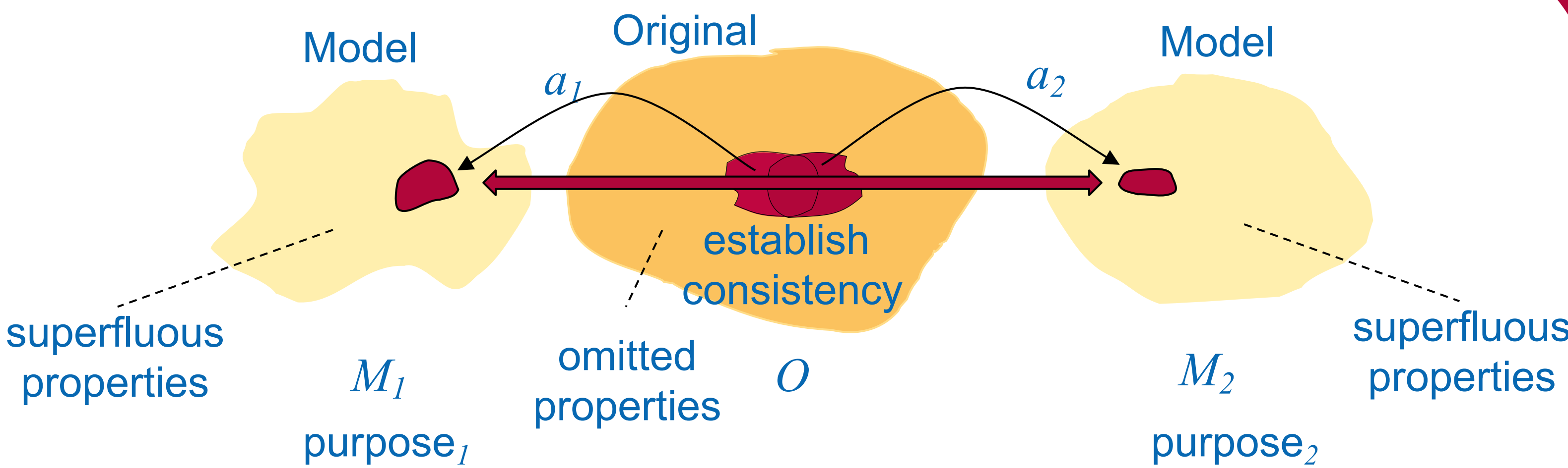
Idea 1: Try for each purposes to find a model M_j that replace the original O, does not contain any irrelevant information (reduced complexity!), and is **completely orthogonal** to all other model.



How to Handle Multiple Models?

Why this focus?
This is the heart of the matter of MPM4CPS!

Idea 2: Try for each purposes to find a model M_j that replace the original O, does not contain any irrelevant information (reduced complexity!), and **integrate** the models systematically to establish consistency.



Key questions:

- How many models are helpful (tradeoff benefits vs. integration effort)?
- When and how is integration happen for these models?

(1) How Many Models? Multi-Formalisms

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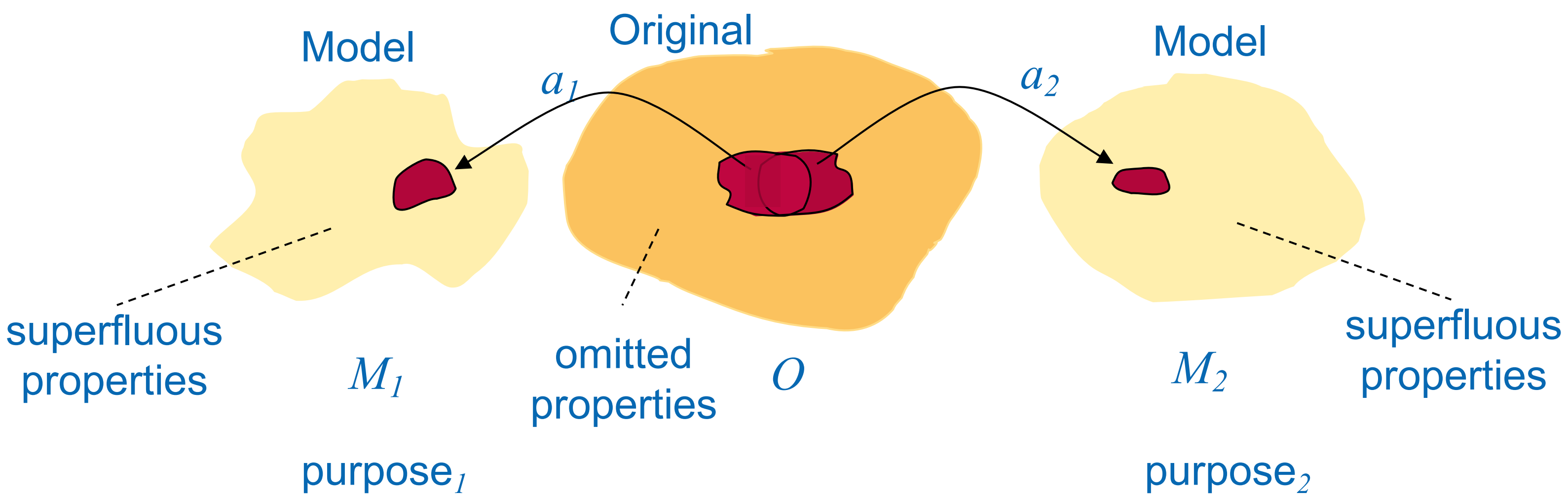


Specific for purpose$_1$:

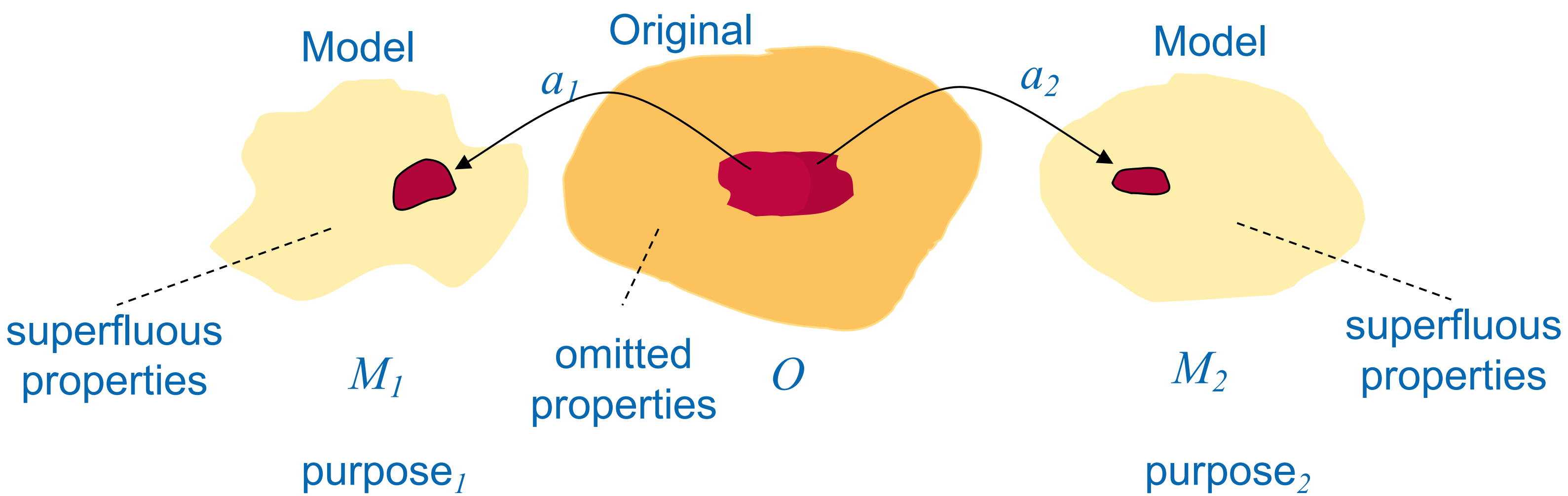
- Chosen formalism (semantics)
- Chosen level of detail

Specific for purpose$_2$:

- Chosen formalism (semantics)
- Chosen level of detail

Integration has to consider more ...

How Many Models? Multiple Paradigms



Specific for purpose$_1$:

- Chosen paradigm
  - Formalism(s) + semantics
  - Workflows and tools used
  - Local consistency needs

Specific for purpose$_2$:

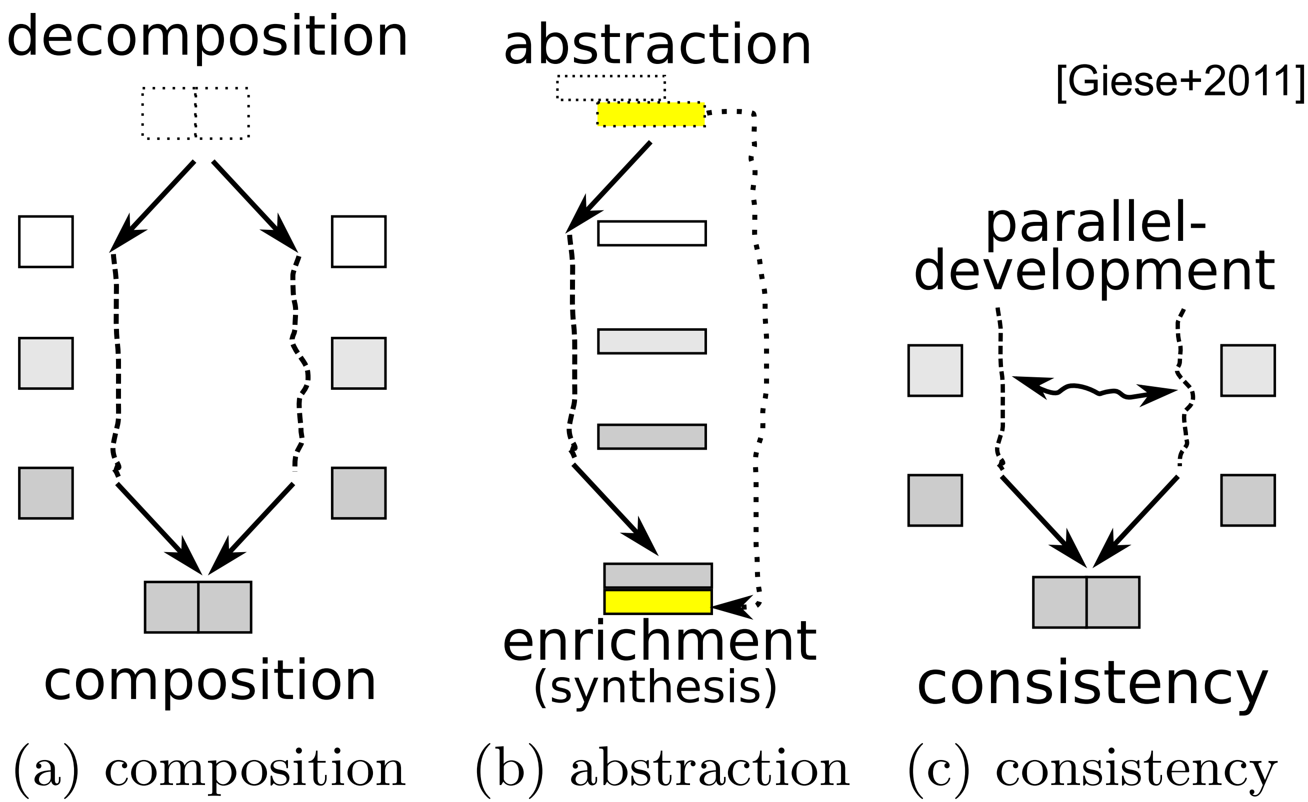
- Chosen paradigm
  - Formalism(s) + semantics
  - Workflows and tools used
  - Local consistency needs

Integration has to bridge/link the paradigms

(2) Integration: When & How

Warning: We use a less restricted notion of integration than many others ...

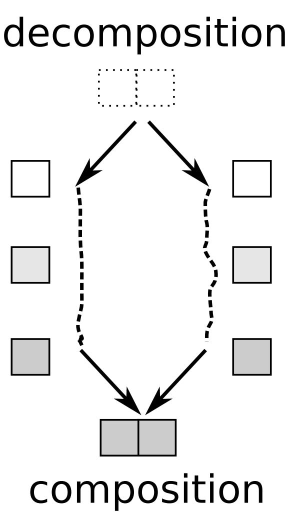
Fundamental Techniques for Integration:



Holger Giese, Stefan Neumann, Oliver Niggemann and Bernhard Schätz. **Model-Based Integration**. In *Model-Based Engineering of Embedded Real-Time Systems - International Dagstuhl Workshop, Dagstuhl Castle, Germany, November 4-9, 2007. Revised Selected Papers*, Vol. 6100:17-54 of *Lecture Notes in Computer Science*, Springer, 2011.

Integration via Explicit De-composition & Composition

[Giese+2011]



(a) composition

- explicit (horizontal) decomposition
- constant level of abstraction
- subsystems can be developed in parallel

Point in time:

- **Decomposition**: interfaces guarantees integration during the later composition (e.g., syntax-level for programming languages)
- **Composition**: risk that integration problems are detected rather late
- **Synthesis**: automated techniques that can generate a solution that solves the integration problem (if possible)

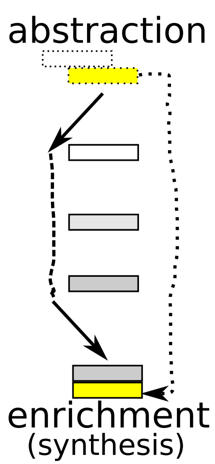
Remarks:

- Ideal case: all relevant characteristics are guaranteed for composition
- Real case: only a few relevant characteristics are guaranteed for composition
- Separation of concerns may not be enough to exclude that concern span multiple models
- Emergent phenomena can only be observed for the composition (e.g., deadlock)

Integration via Vertical Abstraction & Enrichment

[Giese+2011]

- change of the abstraction level
- implicit separation by omitting the details for a certain time
- Vertical enrichment can happen in two fundamentally different forms:
  - unconstrained enrichment (orthogonal characteristics)
  - constrained enrichment (refinement/approximation)



(b) abstraction

Point in time:

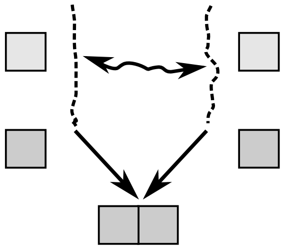
- **During abstraction**: can be employed to ease development when there is only a unidirectional dependency between the upfront-addressed details and the omitted ones
- **During enrichment**: the integration problem has to be addressed late when the enrichment happens, as the initial abstraction step does not provide any guarantee for the later enrichments.
- **During enrichment by synthesis**: used to automatically apply enrichment (if possible)

Examples:

- Architecture layers with std. interface (operating system, hardware)

Integration via Consistency & Synchronization

[Giese+2011]



(c) consistency

- approach the dependencies between the different artifacts throughout the parallel development
  - check consistency & resolve issue immediately
  - synchronization ➜ automatically keep consistent

Point in time:

- Frequently: do a horizontal integration of models that evolve in parallel

Remarks:

- the in parallel developed models can more freely evolve
- consistency resp. synchronization covers usually not all integration problems later on (example co-simulation and scheduling)

Kind of Integration (to Bridge Paradigms)

- **Formalism-based**: Having a single formalism in a paradigm that includes multiple paradigms (e.g., hybrid automata contain differential equations and automata)
- **Composition-based**: We compose formalism supporting different paradigms into a single paradigm by a suitable model of computation that composes the multiple formalisms (e.g., Simulink/Stateflow)
- **Tool-based**: We consider formalisms supporting different paradigms together via tools (e.g., co-simulation of a Simulink model and a plant specific simulator)

Level of Integration

- **Representation-level**: integration efforts only guarantee that a joint representation is reached
- **Syntax-level**: integration efforts lead to correct syntax
- **Semantics-level**: integration efforts lead to compatibility at the level of the semantics

Examples from software engineering:

- Merge is usually only ad hoc achieving representation-level integration and compilation is expected to ensure syntax-level integration
- Continuous integration = fully automated regression testing ensures some degree of semantic-level integration (changes do not break the semantic needs encoded in the tests)

Outline

1. Foundations
2. **Cyber-Physical Systems**
3. HPI CPSLab & Integration
4. Future Needs for Integration
5. Conclusion & Outlook

3. Cyber-Physical Systems & Integration

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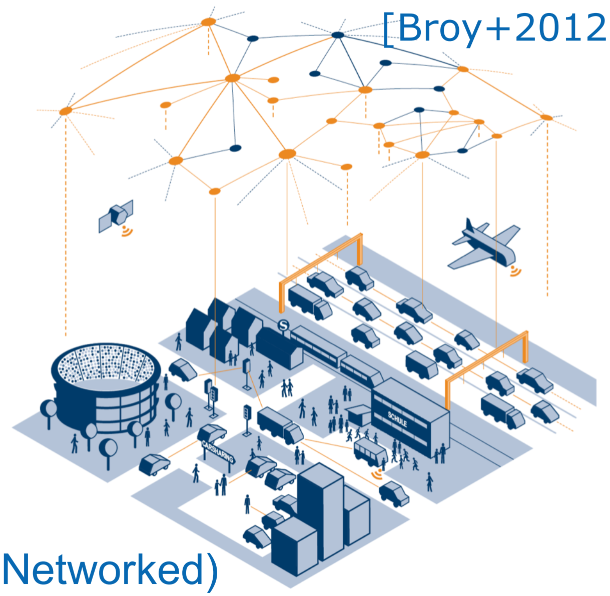
[Broy+2012]

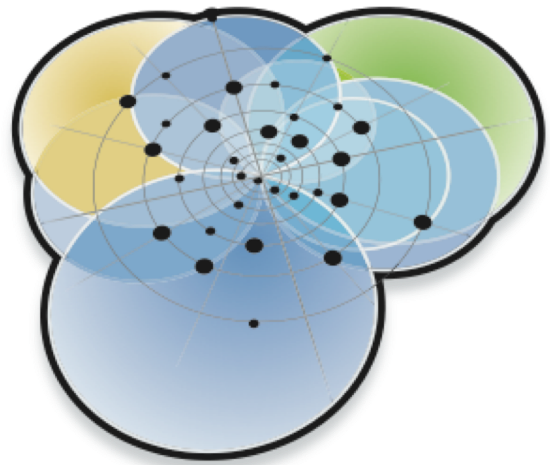


(Networked)
Cyber-Physical Systems

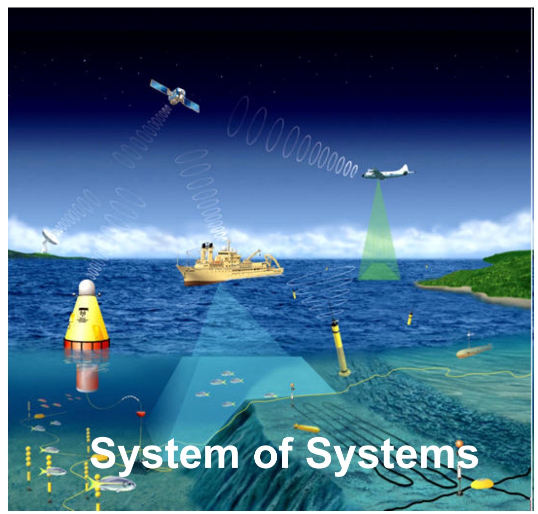
Internet of Things

Smart City

[Northrop+2006]



Ultra-Large-Scale Systems



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E-Health

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E.g. Industry 4.0

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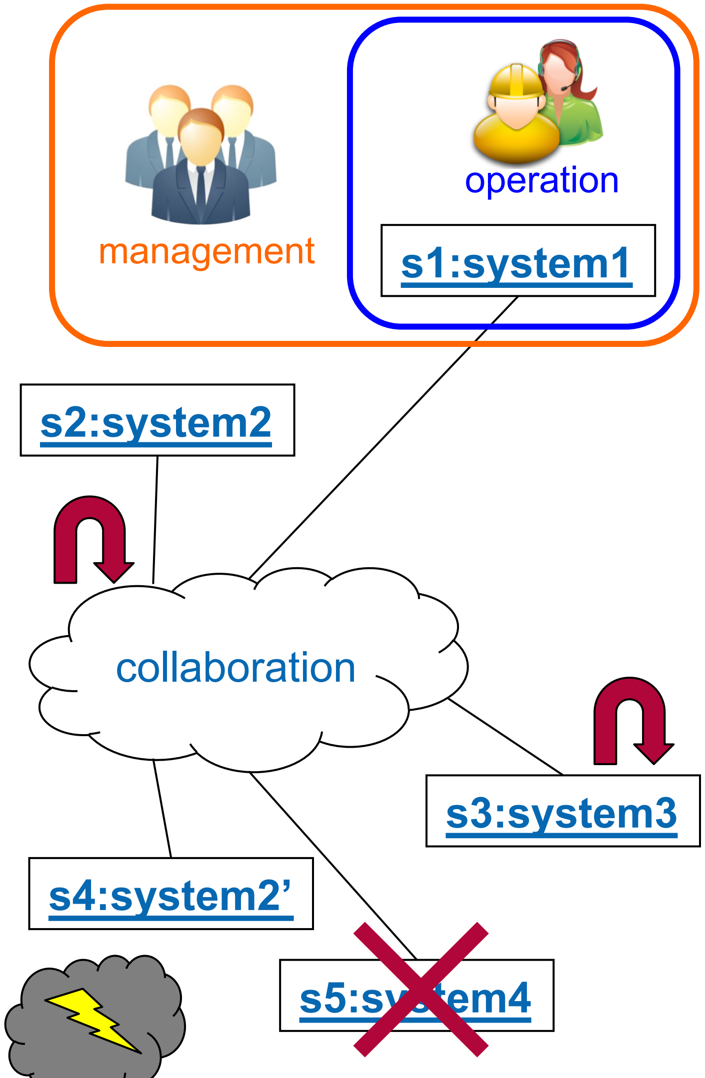
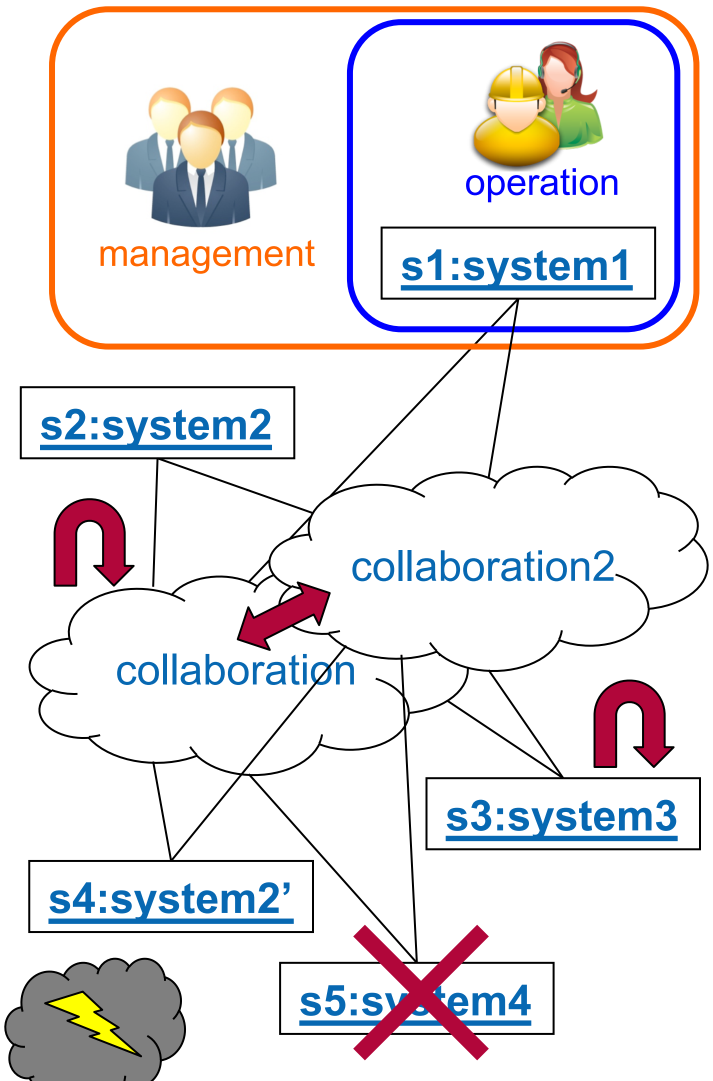
A Selection of Critical Future Challenges



- **Operational** and **managerial independence**
  - operated independent from each other without global coordination
  - no centralized management decisions (possibly confliction decisions)
- **Dynamic architecture** and **openness**
  - must be able to dynamically adapt/absorb structural deviations
  - subsystems may join or leave over time in a not pre-planned manner
- **Advanced adaptation**
- **Resilience**

A Selection of Critical Future Challenges



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- **Cross-Domain Integration**

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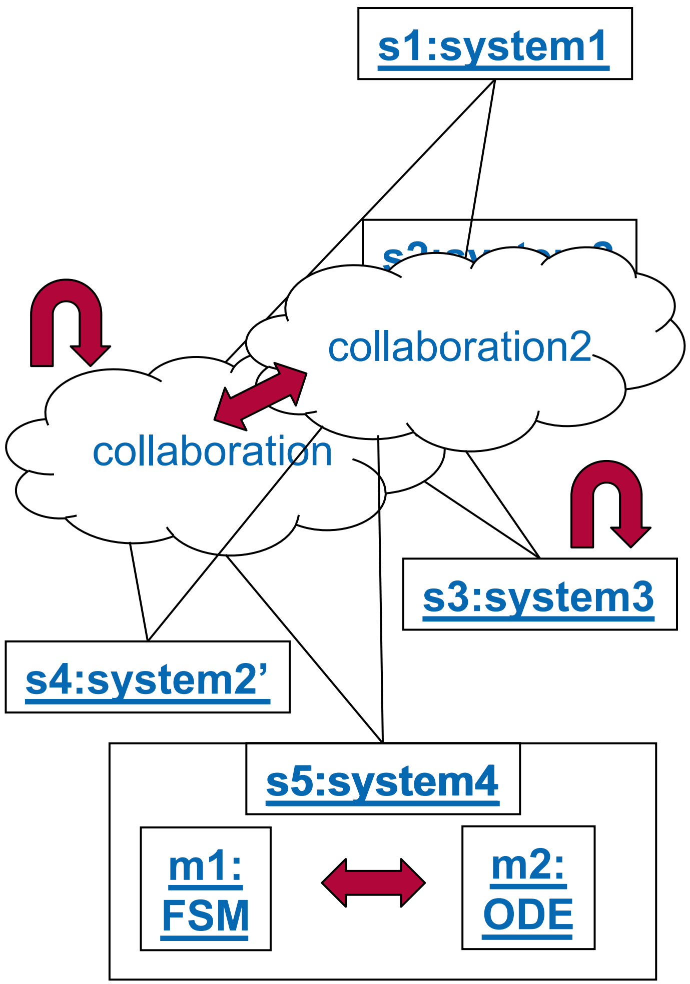

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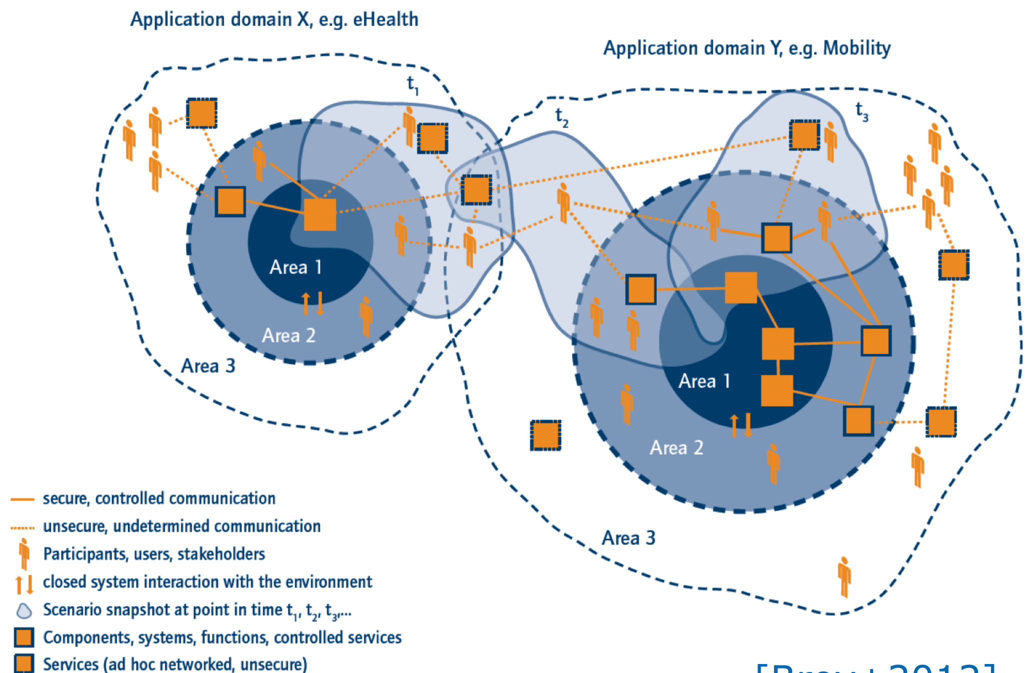
- **Advanced adaptation**
- **Resilience**
- **Cross-Domain Integration**
- **Integrate Models of Computation**

Challenge: Cross-Domain Integration

Example: A convoy of fully autonomous cars abandons the premium track in order to give way to an ambulance (intersection of CPS specific for **traffic** and **health care**)



[Broy+2012]

CPS of different domains have to be connected:

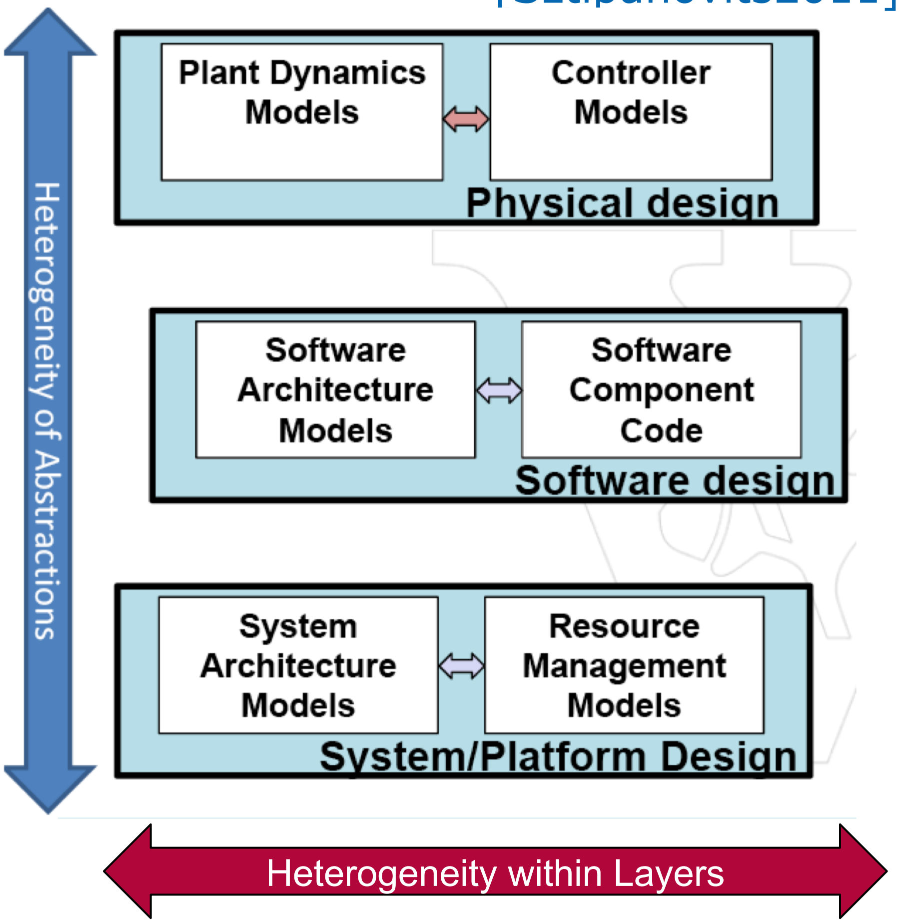
- According to social and spatial network topologies, CPS operate across different nested spheres of uncertainty
- CPS dedicated to different domains have to to interact and coordinate.

Integration has to cover multiple domains and their **paradigms**

Challenge: Integrate Models of Computation

- Problem to integrate models within one layer as different **models of computation** are employed
- Leaky abstractions are caused by lack of composability across system layers. Consequences:
  - intractable interactions
  - unpredictable system level behavior
  - full-system verification does not scale

[Sztipanovits2011]

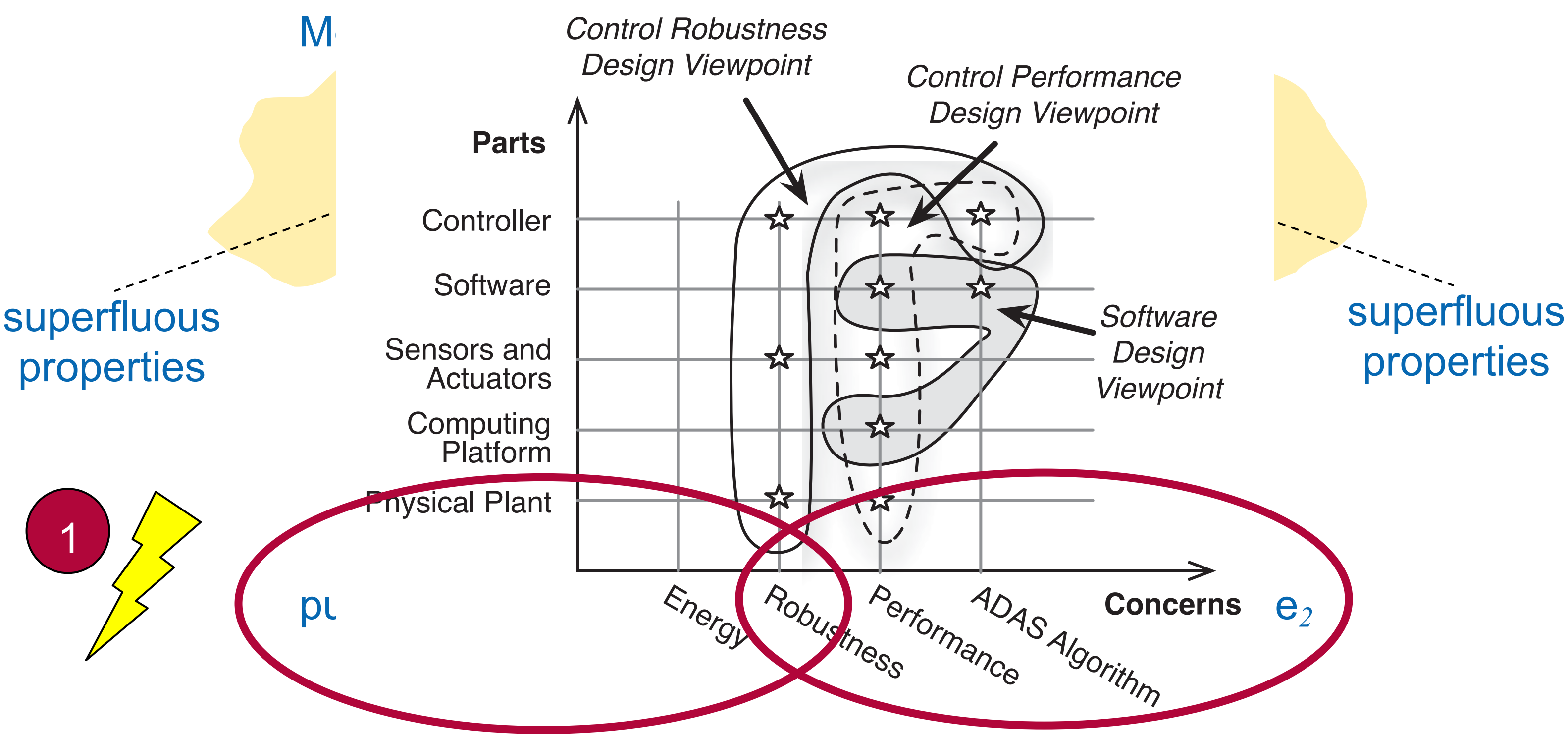


Integration has to cover multiple layers and their paradigms

How to Handle Multiple Models?

Check: Is integration unavoidable for complex CPS?

Idea 1: Try for each purposes to find a model M_j that replace the ... does not contain any irrelevant information (reduced complexity!), and is **completely orthogonal** to all other model.



[Broman+2012]

How to Handle Multiple Models?

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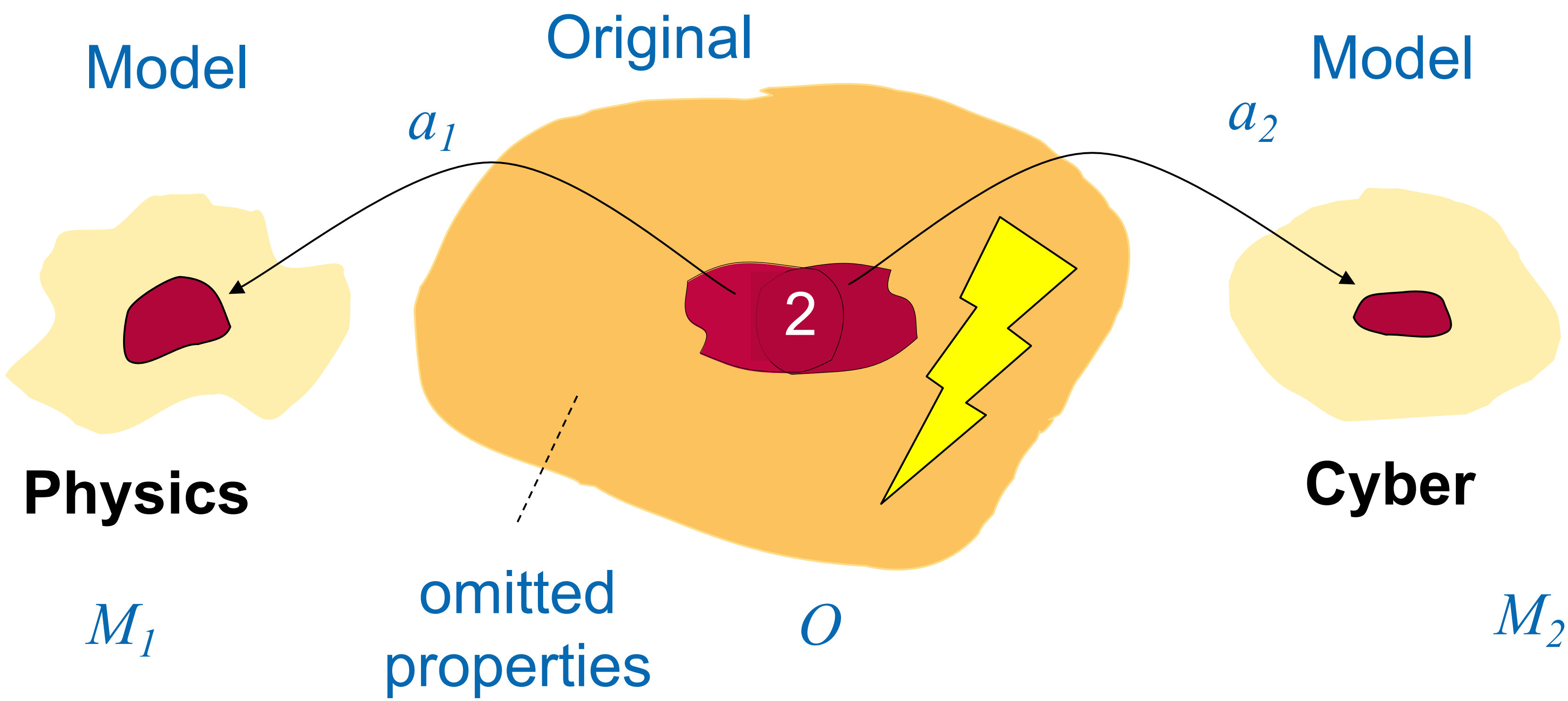
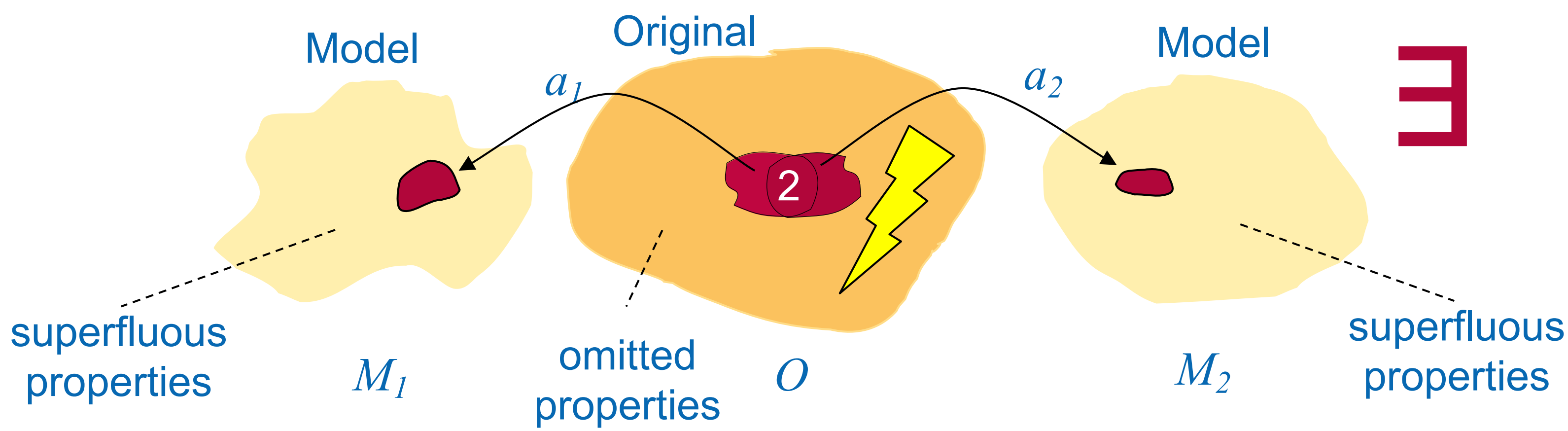
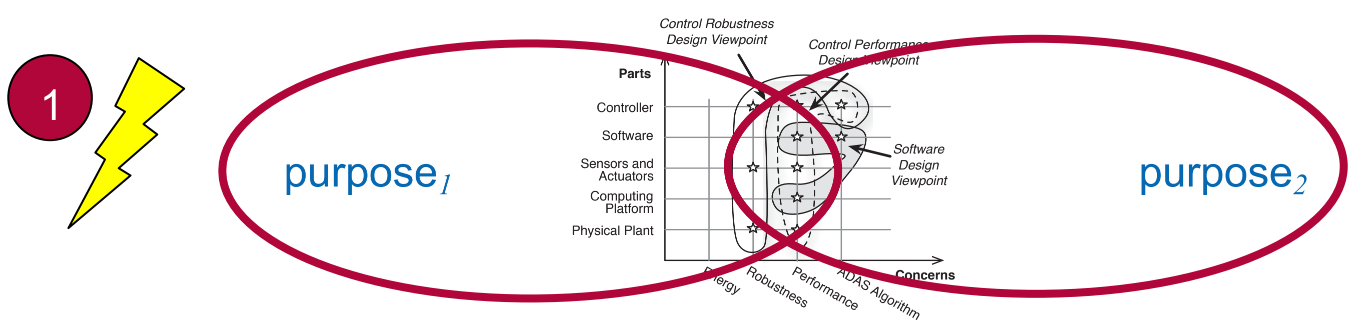


How to Handle Multiple Models?

Conclusion: Integration seems unavoidable for complex CPS!

Idea 1: Try for each purposes to find a model M_j that replace the original, does not contain any irrelevant information (reduced complexity!), and is **completely orthogonal** to all other model.





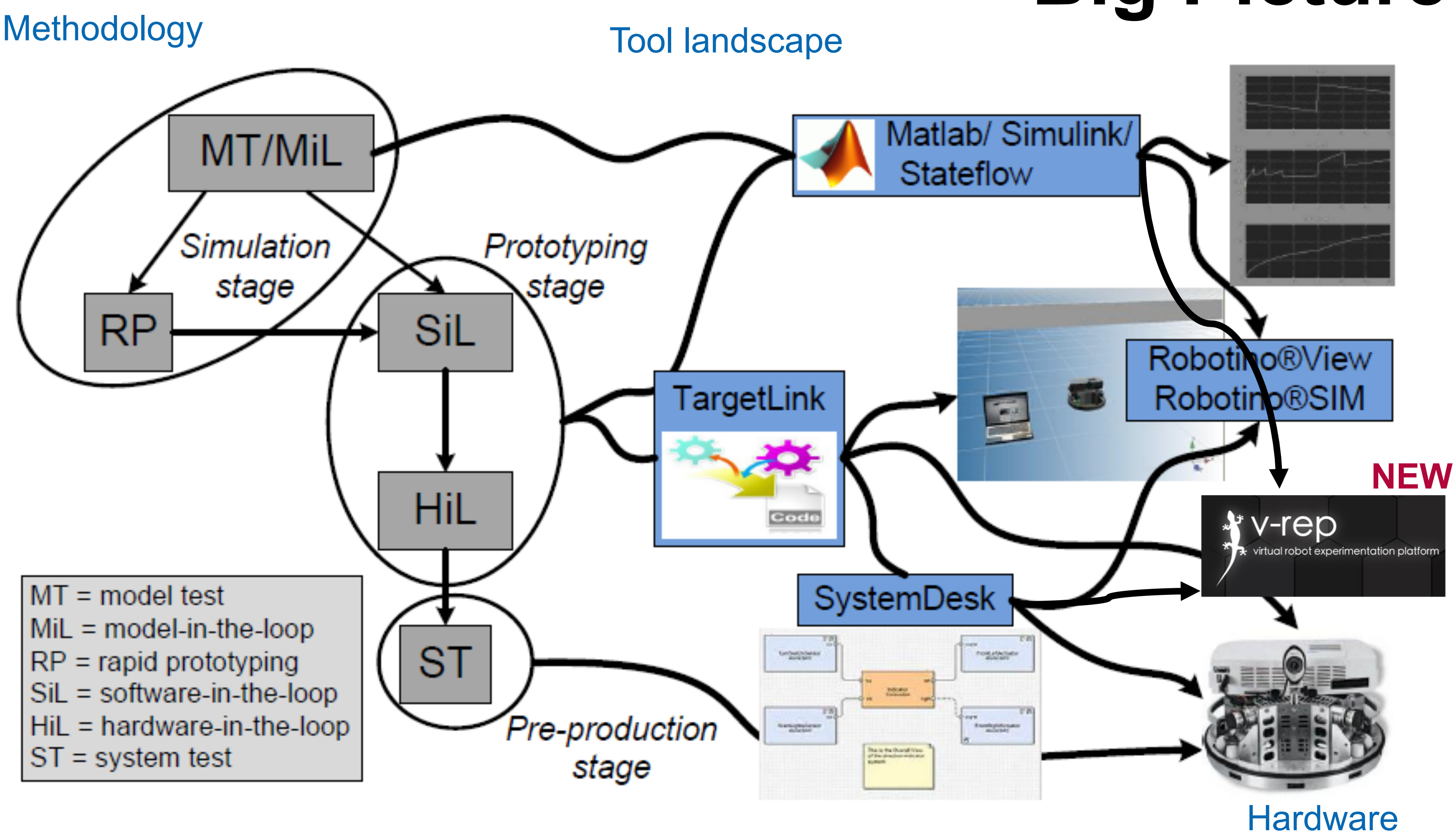
[Broman+2012]

Outline

1. Foundations
2. Cyber-Physical Systems
3. **HPI CPSLab & Integration**
4. Future Needs for Integration
5. Conclusion & Outlook

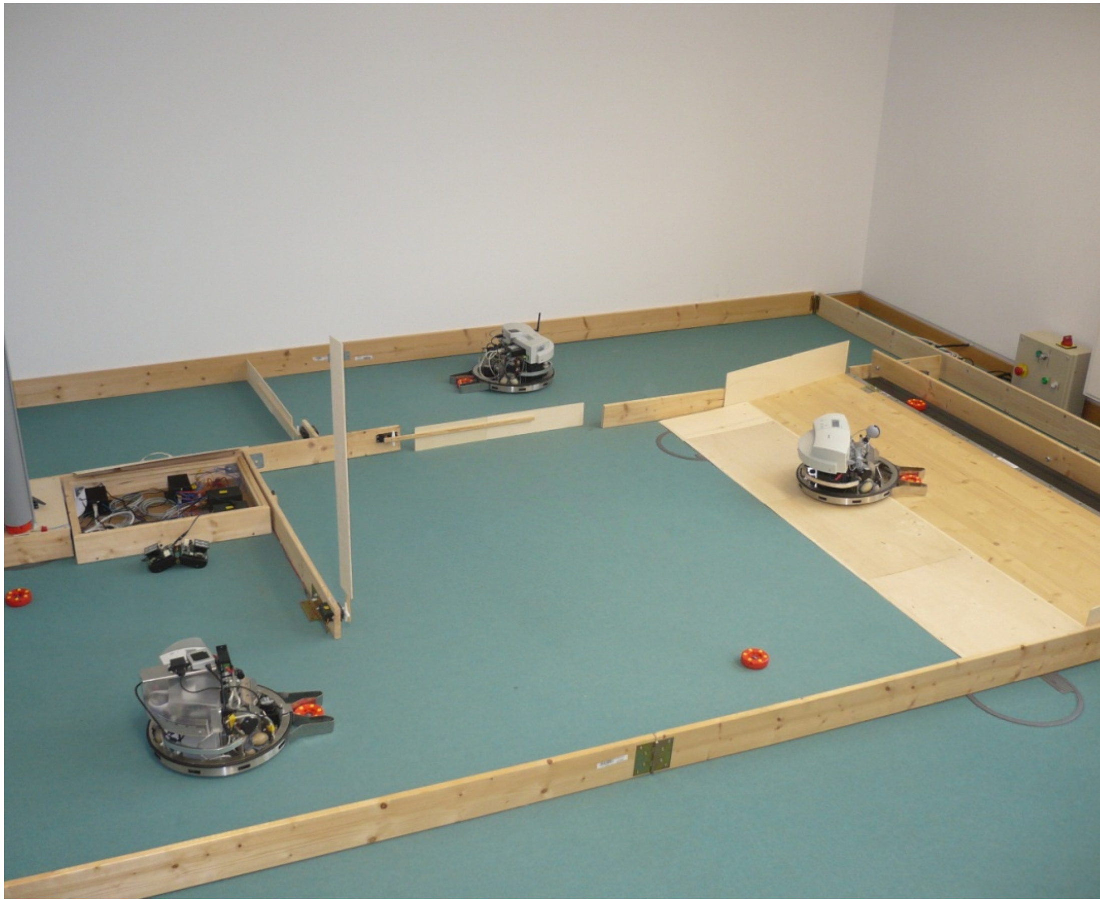
3. HPI CPSLab & Integration:

Big Picture



HPI CPSLab: Industry 4.0 Production

- Robots in Production Setting
- Transportation of Goods
  - represented by Pucks
- Different Production Locations
  - Puck Dispenser
  - Conveyor Belt
  - "Rooms"
- Obstacle Avoidance
  - Walls
  - Doors
  - Other Robots



HPI CPSLab: Industry 4.0 Production

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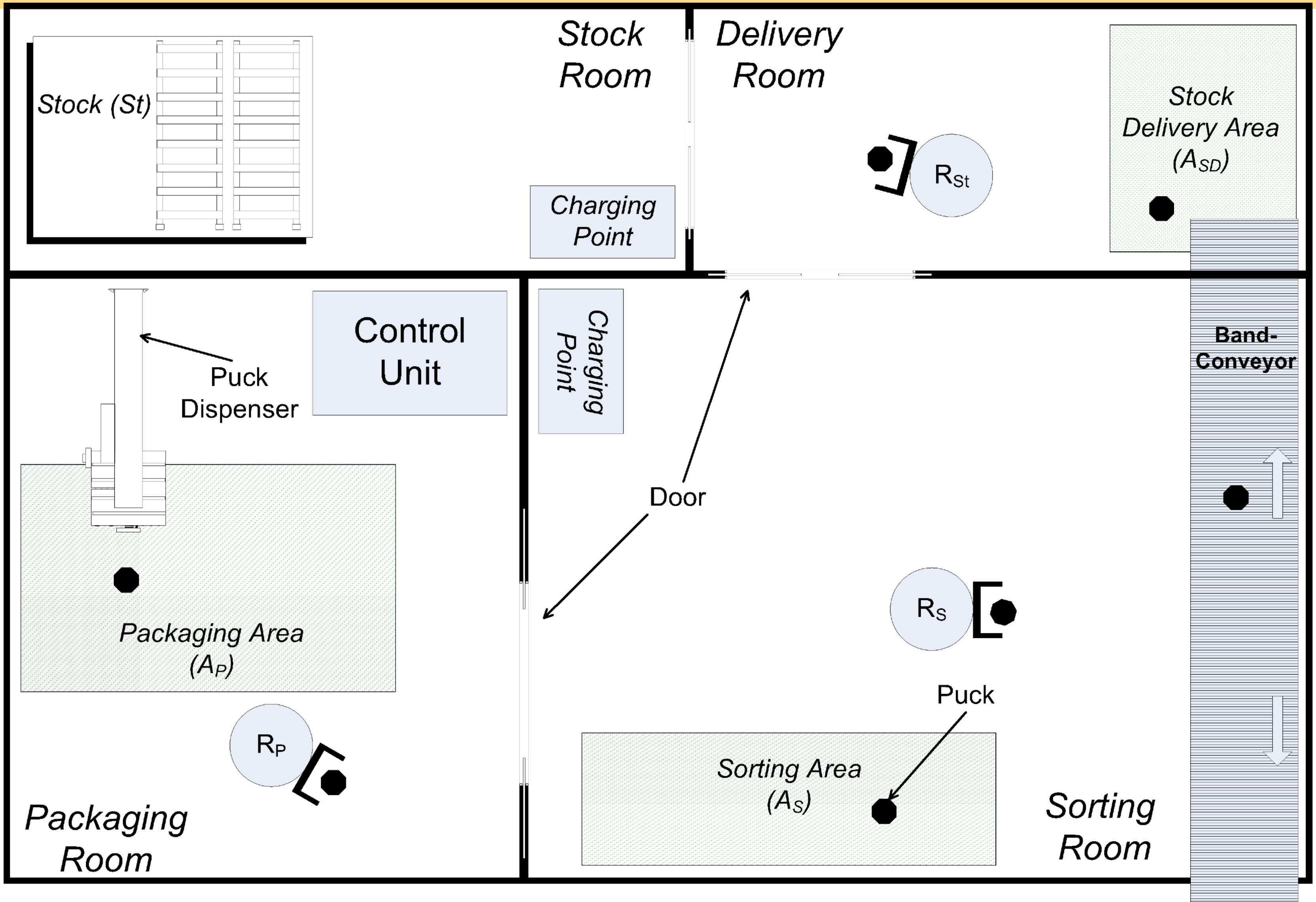


HPI CPSLab: Robotino Robot - Overview

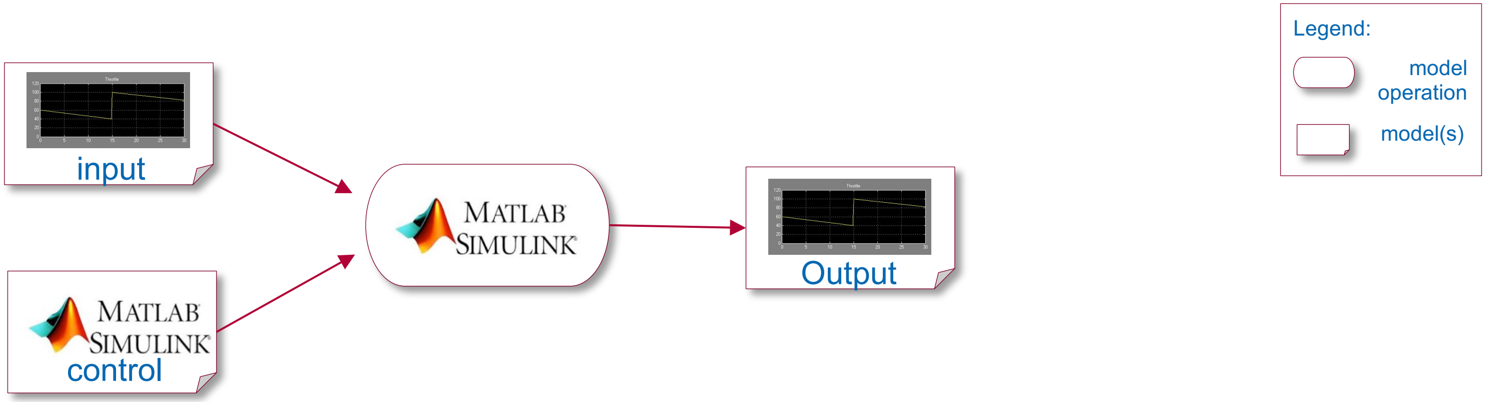
Basic Robotino Robot:

- Omni directional drive permits to move in all directions
- Distance / obstacles sensors
- Bumper to detect collisions
- Coordination via W-LAN

Extensions:

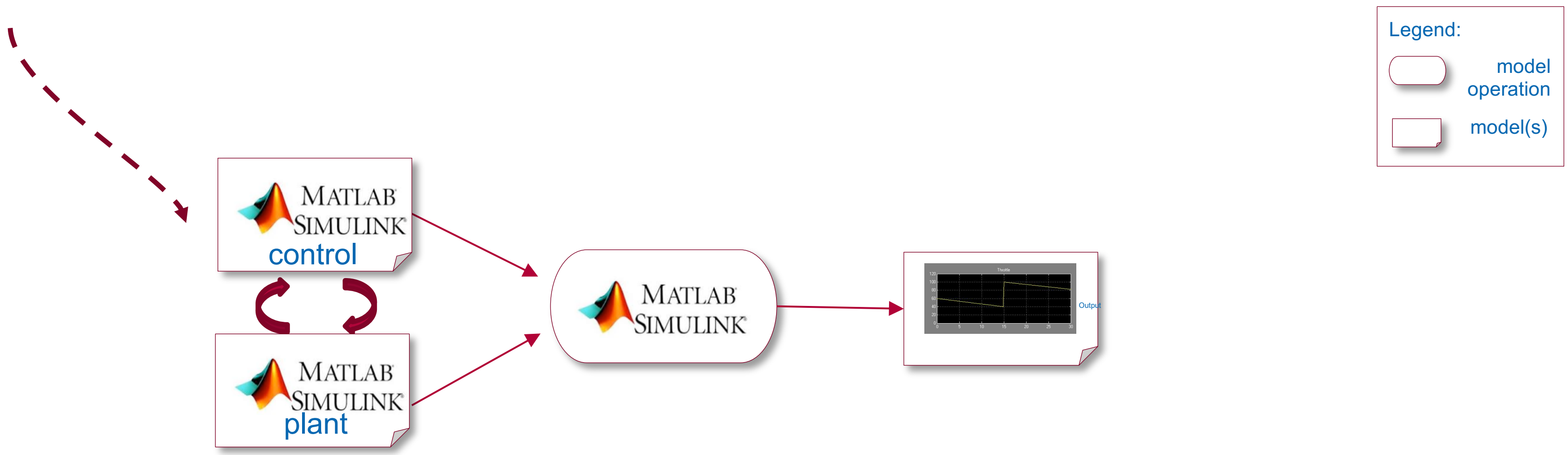
- GPS-like system: Northstar
- Camera & Vision
- Metal detector
- Gripper
- …

Model Test (MT)



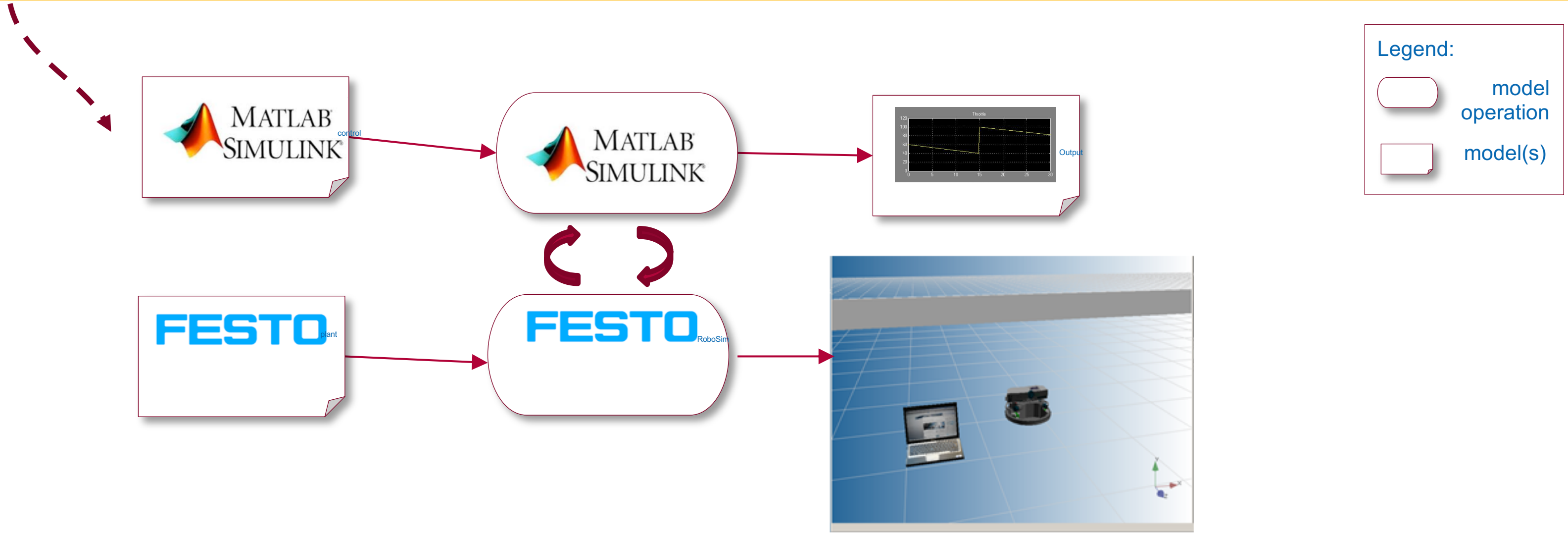
- Layer: Abstract Control Algorithm
- Domains: Control/Software (+ Physics)
- Multi-Paradigm: Yes, if control is discrete and input continuous
- Cyber-Physical system: Yes, as control is cyber and input is (conceptually) from the physical world
- Integration: Decomposition and composition-based

Model in the Loop (MiL)



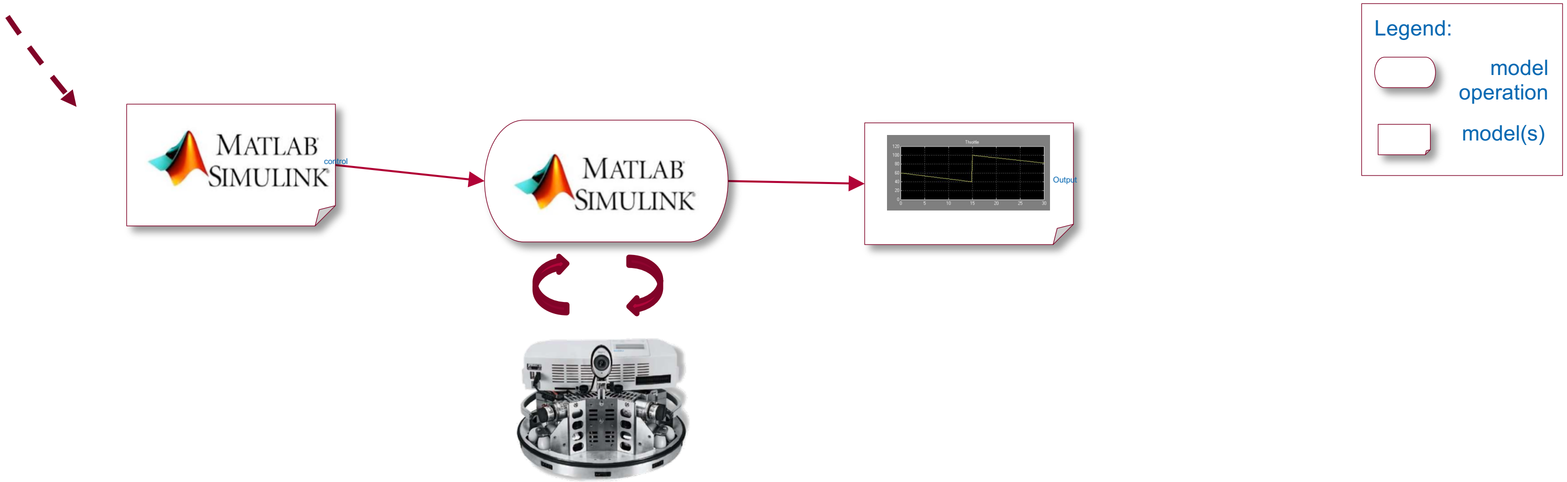
- Layer: Abstract Control Algorithm + Idealized Plant
- Domain: Control/Software + Physics
- Multi-Paradigm: Yes, if control is discrete
- Cyber-Physical system: Yes, as control is cyber world and plant is from the physical world
- Integration: Decomposition & Composition compostion-based

Rapid Prototyping (RP) vs. Robot Simulator



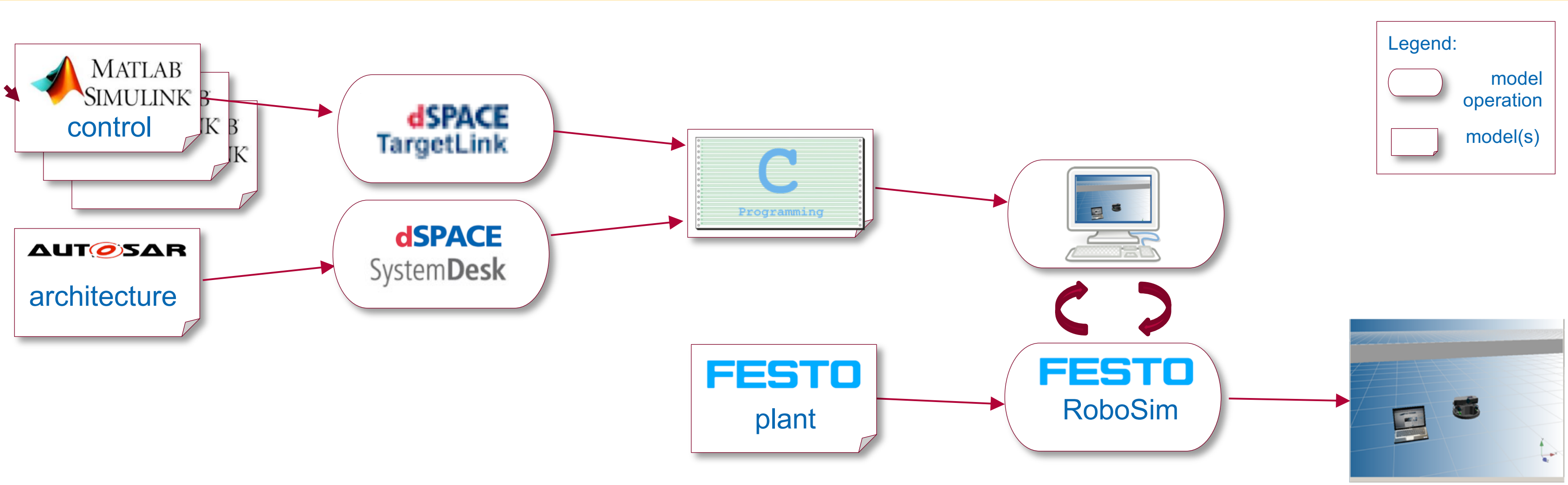
- Layer: Abstract Control Algorithm + Realistic Plant
- Domain: Control/Software + Physics
- Multi-Paradigm: Yes, if control is discrete
- Cyber-Physical system: Yes, as control is cyber world and plant is from the physical world
- Integration: Consistency via co-simulation (tool-based)

Rapid Prototyping (RP) vs. Robot



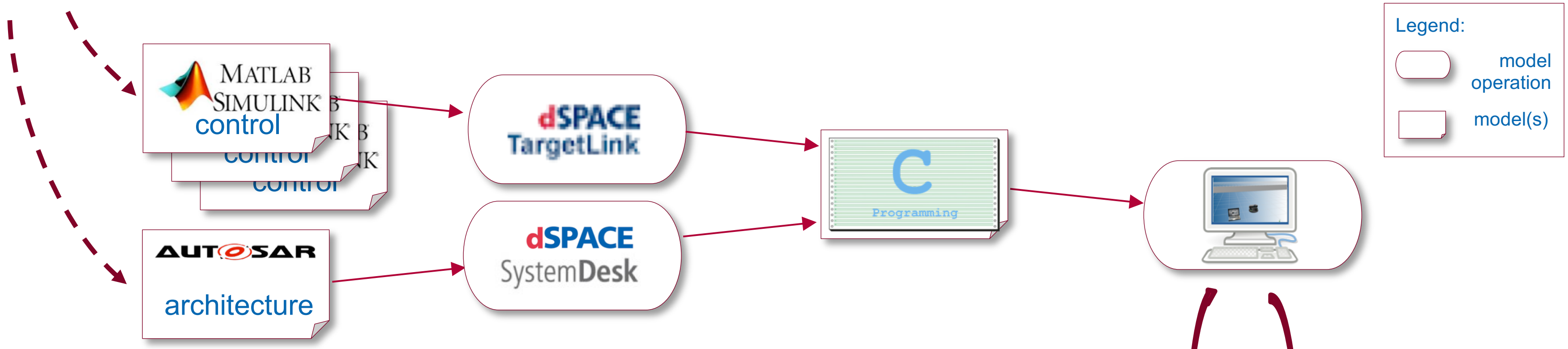
- Layer: Abstract Control Algorithm + Real Plant
- Domain: Control/Software + Real Physics
- Multi-Paradigm: Yes, if control is discrete
- Cyber-Physical system: Yes, as control is cyber world and plant is from the physical world
- Integration: Consistency via rapid protoyping (tool-based)

Software in the Loop (SiL) vs. Desktop + Sim

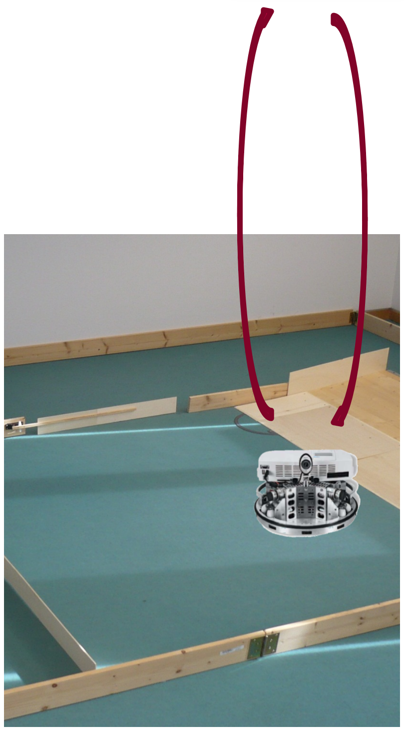


- Layer: Control Software + Architecture + Realistic Plant
- Domain: Control/Software + Scheduling + Realistic Physics
- Multi-Paradigm: 1) Yes, if control is discrete 2) Combine architecture and control
- Cyber-Physical system: Yes, as control is cyber world and plant is from the physical world (control and architecture are both cyber)
- Integration for 1): Consistency via co-simulation (tool-based)
- Integration for 2): Decomposition and synthesis composition-based

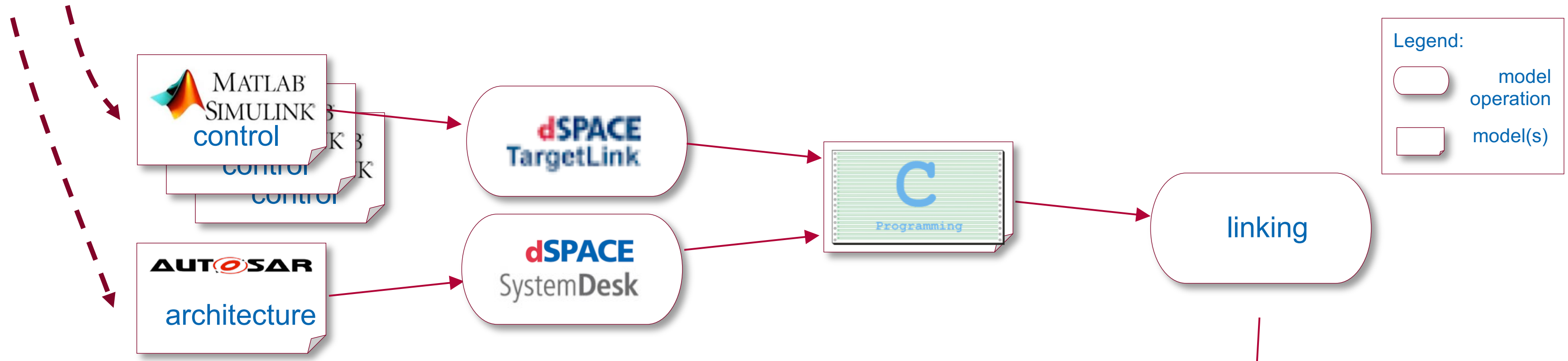
Software in the Loop (SiL) vs. Desktop + Robot



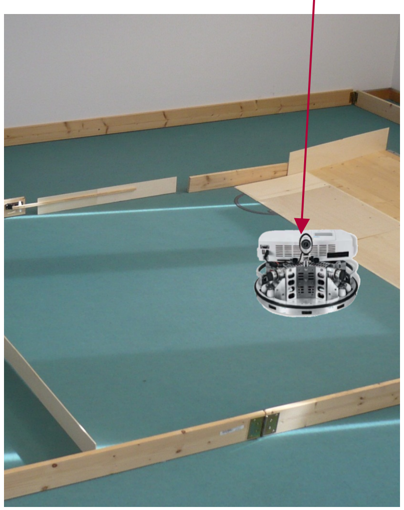
- Layer: Control Software + Architecture + idealized Hardware + Real Plant
- Domain: Control/Software +Architecture + Scheduling + WLAN + Real Physics
- Multi-Paradigm: 1) Yes, if control is discrete 2) Combine architecture and control
- Cyber-Physical system: Yes, as control is cyber world and plant is from the physical world (control and architecture are both cyber)
- Integration for 1): Consistency via rapid-protoyping (tool-based) via WLAN
- Integration for 2): Decomposition and synthesis composition-based

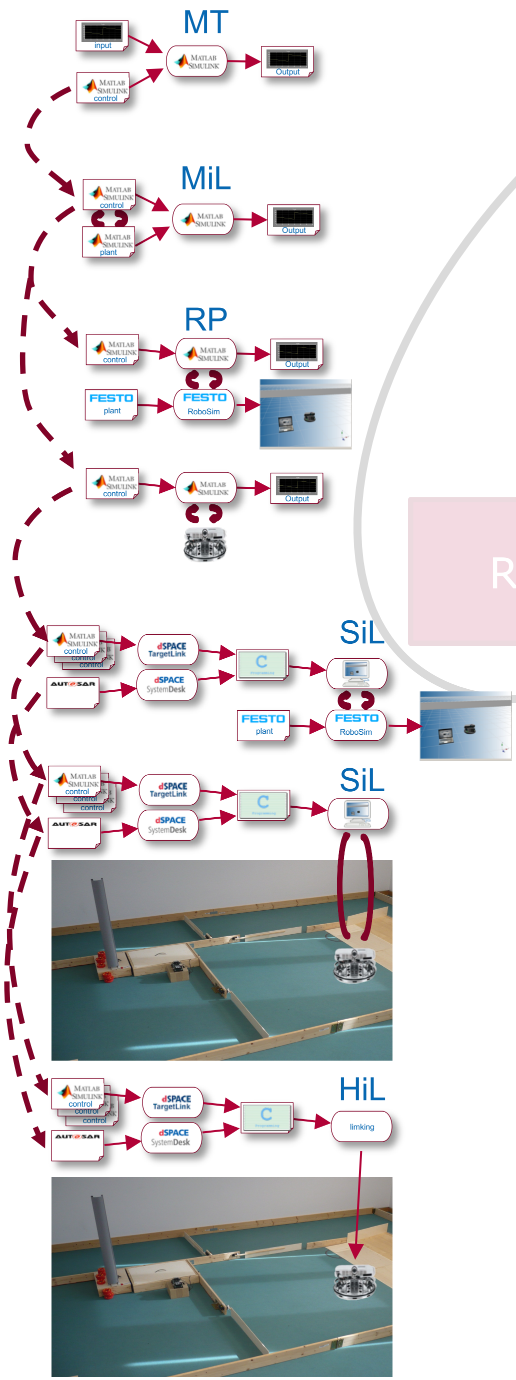


Hardware in the Loop (HiL)



- Layer: Control Software + Architecture + Real Hardware + Real Plant
- Domain: Control/Software +Architecture + Scheduling + Real Physics
- Multi-Paradigm: 1) Yes, if control is discrete 2) Combine architecture and control
- Cyber-Physical system: Yes, as control is cyber world and plant is from the physical world (control and architecture are both cyber)
- Integration for 1): Consistency via execution (tool-based)
- Integration for 2): Decomposition and synthesis composition-based



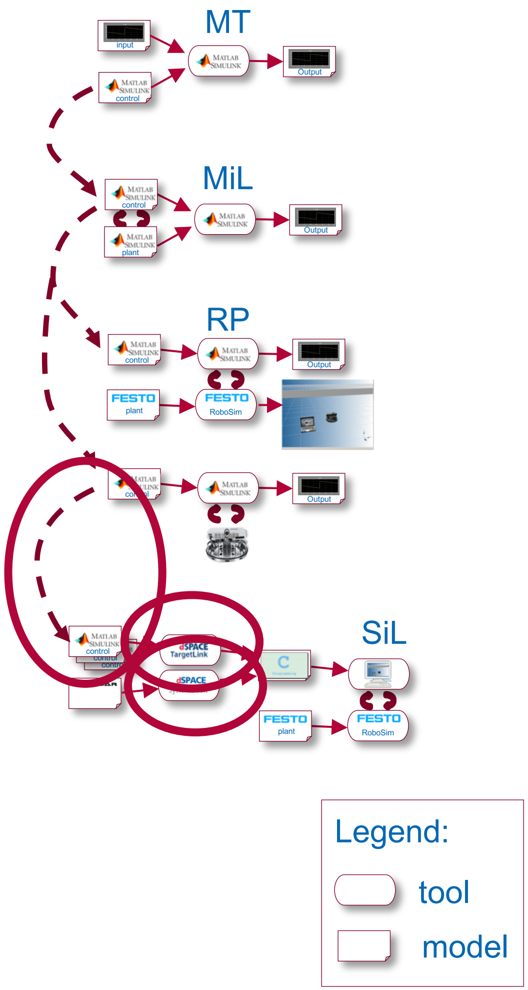


Legend:
- tool
- model

MT/MiL

- Vertical **refinement** of functional models (consistency manually)
- Horizontal **integration** of functional and plant models
- Horizontal **integration** of multiple functional models, an architecture model, and a plant model
- Vertical **refinement** of functional models (to realize functions while meeting resource constraints)

Vertical Enrichment & Transformation



- Vertical **enrichment** of functional models and architecture
- Floating-Point 2 Fix-Point to reduce resource demands models (consistency manually)
- Fix-Point data-flow model 2 C-code models (consistency automatically)
- Autosar 2 C-code models (consistency automatically)

Different paradigms

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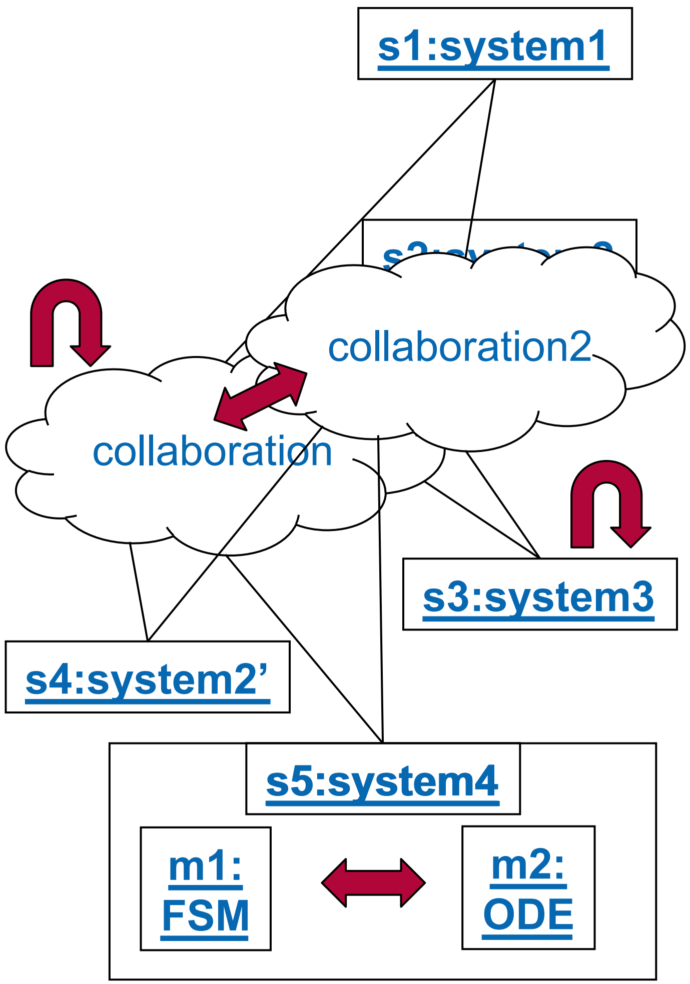
4. Future Needs for Integration



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  - operated independent from each other without global coordination
  - no centralized management decisions (possibly confliction decisions)
- **Dynamic architecture** and **openness**
  - must be able to dynamically adapt/absorb structural deviations
  - subsystems may join or leave over time in a not pre-planned manner
- **Advanced adaptation**
- **Resilience**
- **Cross-Domain Integration**
- **Integrate Models of Computation**

Bridging Paradigms & Formalism as Backbone

Tool-based integration of the models		
Requires an implicit notion of composition combining the formalisms of the models	Composition-based integration of the models	
Requires an implicit notion of formalism bridging the formalisms of the models	Requires an implicit notion of formalism bridging the formalisms of the models	Formalism-based integration of the models (formalism covers the formalisms of the models)

Overview over the Needs for Formalisms

Needs:

- **Operational** and **managerial independence**
- **Dynamic architecture** and **openness**
- **Scale** for local systems or networked resp. large-scale systems of systems
- **Integration** of the physical, cyber, (and social) dimension
- **Incremental adaptation** at the system and system of system level
- Independent **evolution** of the systems and joint **evolution** the system of system
- **Resilience** of the system of system

Model Characteristics:

- **Compositionality**
- **Dynamic structures**
- **Abstraction**
- **Hybrid behavior**
- **Non-deterministic**
- **Reflection for models**
- **Incremental extensions**
- **Probabilistic**

Coverage of the Needs for Formalisms

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Needs:

- **Operational** and **managerial independence**
- **Dynamic architecture** and **openness**
- **Scale** for local systems or networked resp. large-scale systems of systems
- **Integration** of the physical, cyber, (and social) dimension
- **Incremental adaptation** at the system and system of system level
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Model Characteristics:

- **Compositionality**
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- **Non-deterministic**
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- **Incremental extensions**
- **Probabilistic**

Our Work:

- **SMARTSOS (**employing Timed and Hybrid GTS [Giese+2015]**)**
- **Timed GTS ([**Becker&Giese2008]**)**
- **Hybrid GTS ([**Becker&Giese2012]**)**
- **Probabilistic GTS ([**Krause&Giese2012]**)**

Probabilistic timed GTS ([Maximova2018]**)**

?

BUT: We would need as foundation formalisms that supports all required characteristics at once!

Outline

1. Foundations
2. Cyber-Physical Systems
3. HPI CPSLab & Integration
4. Future Needs for Integration
5. **Conclusion & Outlook**

5. Conclusion & Outlook

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- **Multiple models** and their **integration** is the heart of the matter developing complex systems
- In case of **cyber-physical systems** it holds:
  - models employ **different paradigms** specific for their **layer** and/or **domain**
  - **Integration** of the models is of **paramount importance** during the development
- **Current challenges:**
  - Build cost-effectively the required **formalisms** / **compositions** / **tools** to integrate the models
  - Support analysis also for **emergent properties**

Conclusion & Outlook

- Future **cyber-physical systems** have many **additional needs** (compositionality, dynamic structures, reflection, ...) we have to address **at once** (via formalism, composition, or tool).
- **Future challenges:**
  - Setup the **foundation** for the required **formalisms** / **compositions** / **tools** to integrate the models covering the additional needs
  - Support analysis for **emergent properties** covering also the additional needs
  - Support integration **at runtime**

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