Hasso Plattner Institut

Digital Engineering · Universität Potsdam

CALCO2021

# Towards Engineering Smart Cyber-Physical Systems with Graph Transformation Systems

*Invited Talk at the 9th Conference on Algebra and Coalgebra in Computer Science (CALCO 2021), September 2 2021.*

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# Outline



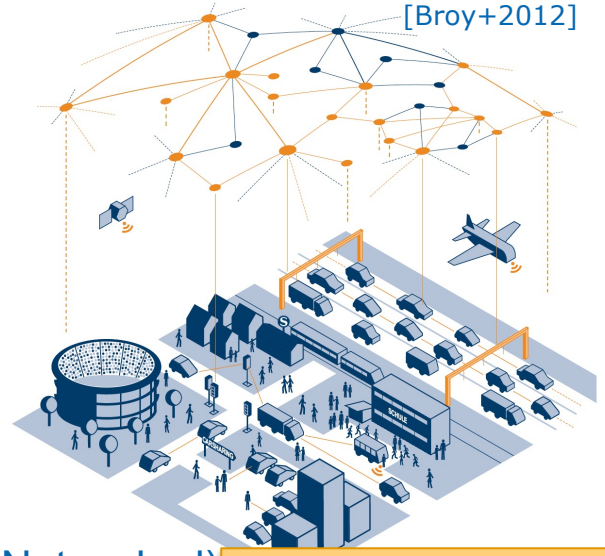
1. Motivation
2. Being Smart
3. Smart & Learning
4. Conclusions & Outlook

# Outline



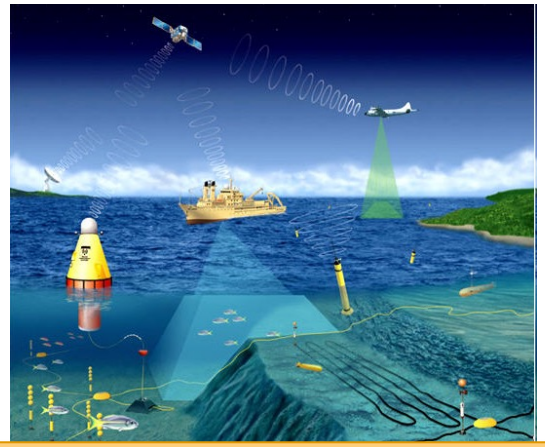
1. Motivation
2. Being Smart
3. Smart & Learning
4. Conclusions & Outlook

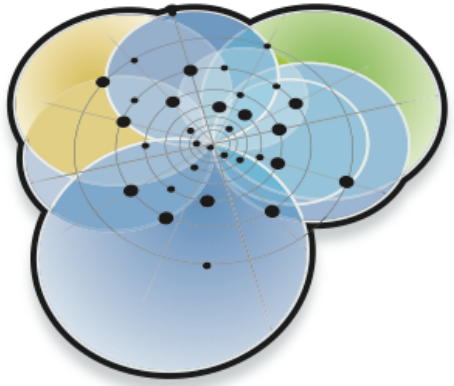
# 1. Motivation
# The Future: You name it …


[Broy+2012]

(Networked)
**Cyber-Phys**

Internet of Things




[Northrop+2006]

Ultra-Large-Scale Systems

**Smart Cyber-Physical Systems (of Systems)**

E-Health

Smart Fact
E.g. Industry 4.0

Smart Home

Smart Logistic

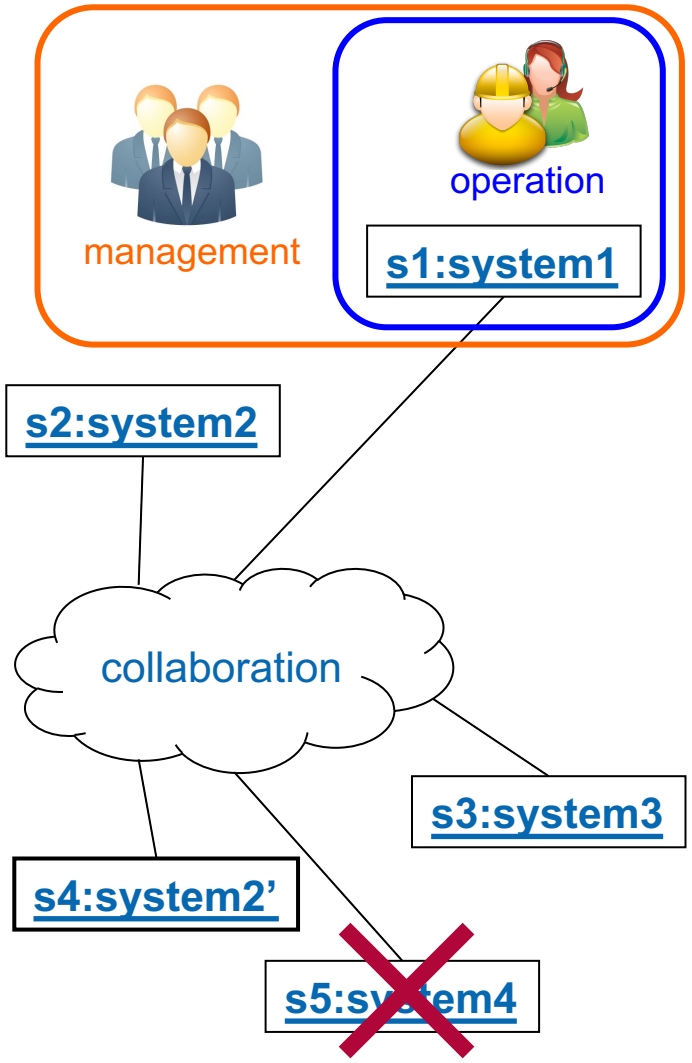
Ambient
Assisted Living

Micro Grids

Smart City

# A Selection of Critical Future Challenges (1/5)

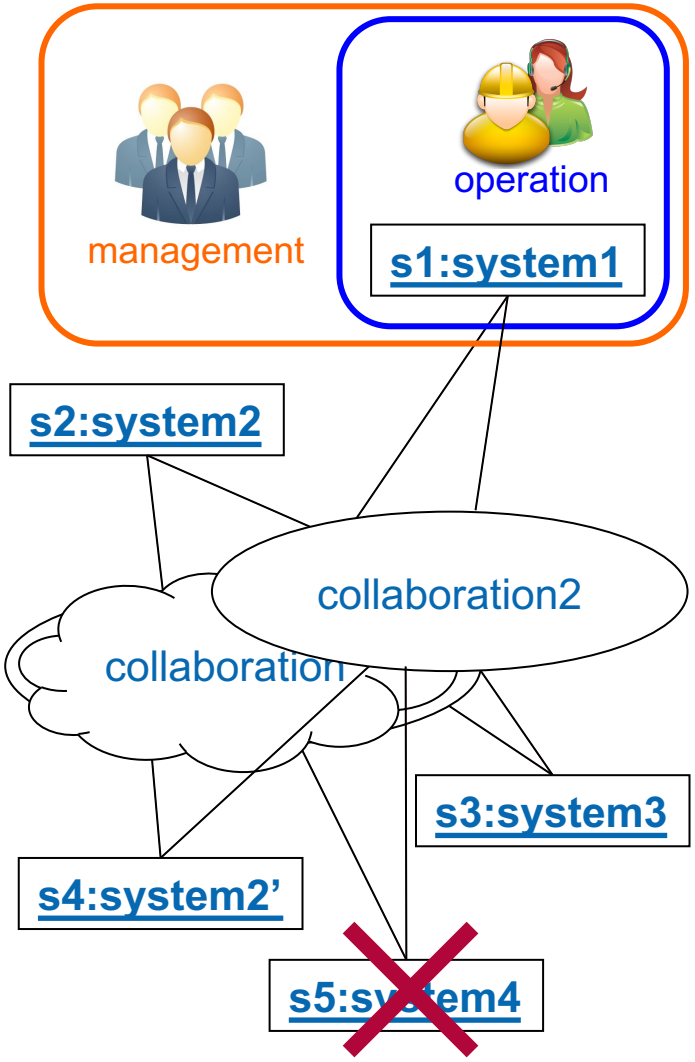





- **Operational** and **managerial independence**
  - operated independent from each other without global coordination
  - no centralized management decisions (possibly confliction decisions)
  - decoupled evolution and co-existence of different versions
- **Dynamic architecture** and **openness**
 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

# Challenge: Service-Oriented Architecture





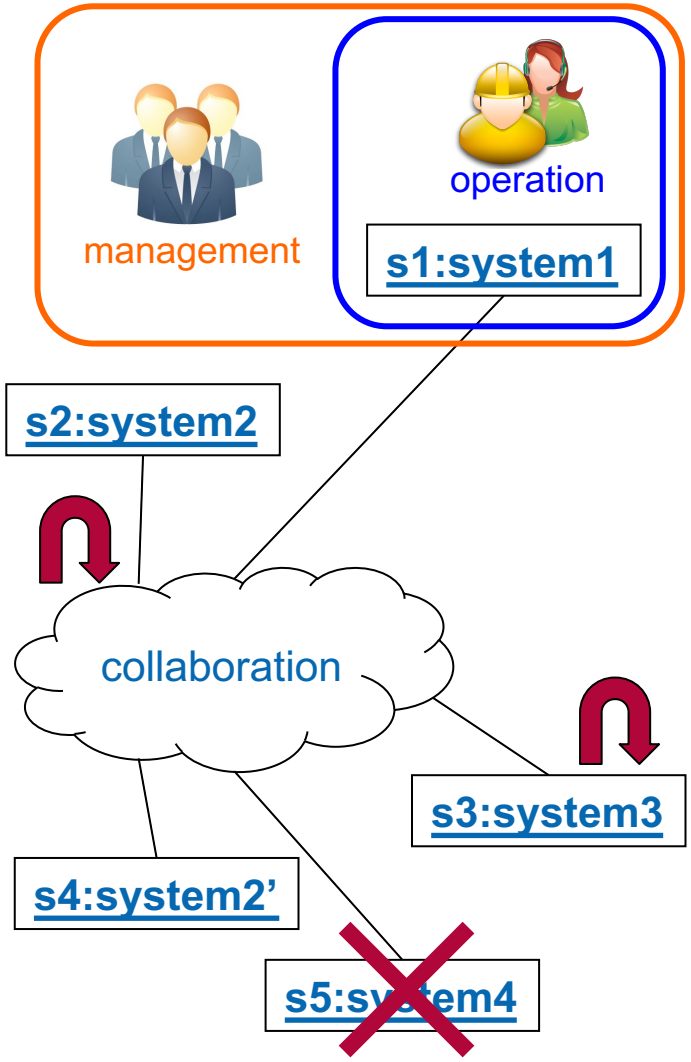

- **Service-Oriented Architecture (Service oriented architecture Modeling Language (SoaML)):**
  - Dedicated services are offered by systems via defined **service contracts** can be offered, looked up, and bound at run-time
  - Interoperability is provided by a **service bus**
  - a UML profile for modeling that supports **collaborations** as first class elements (service contracts) and links collaborations with **component-based models**

**Observations:**

- Service contracts permit to realize **operational** and **managerial independence**
- Offering, look up, and bind service and runtime supports **dynamic architectures** and **openness**
- **But: - dynamics not covered and**
  **- no support for real-time or physics**

# A Selection of Critical Future Challenges (2/5)



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  - subsystems may join or leave over time in a not pre-planned manner
- **Advanced adaptation**

# Challenge: Advanced Adaptation



"**Adaptation** is needed to compensate for changes in the mission requirements […] and operating environments […]" [Northrop+2006]

"The vision of Cyber-Physical System (CPS) is that of open, ubiquitous systems of coordinated computing and physical elements which interactively **adapt to their context, are capable of learning, dynamically and automatically reconfigure themselves …**" [Broy+2012]

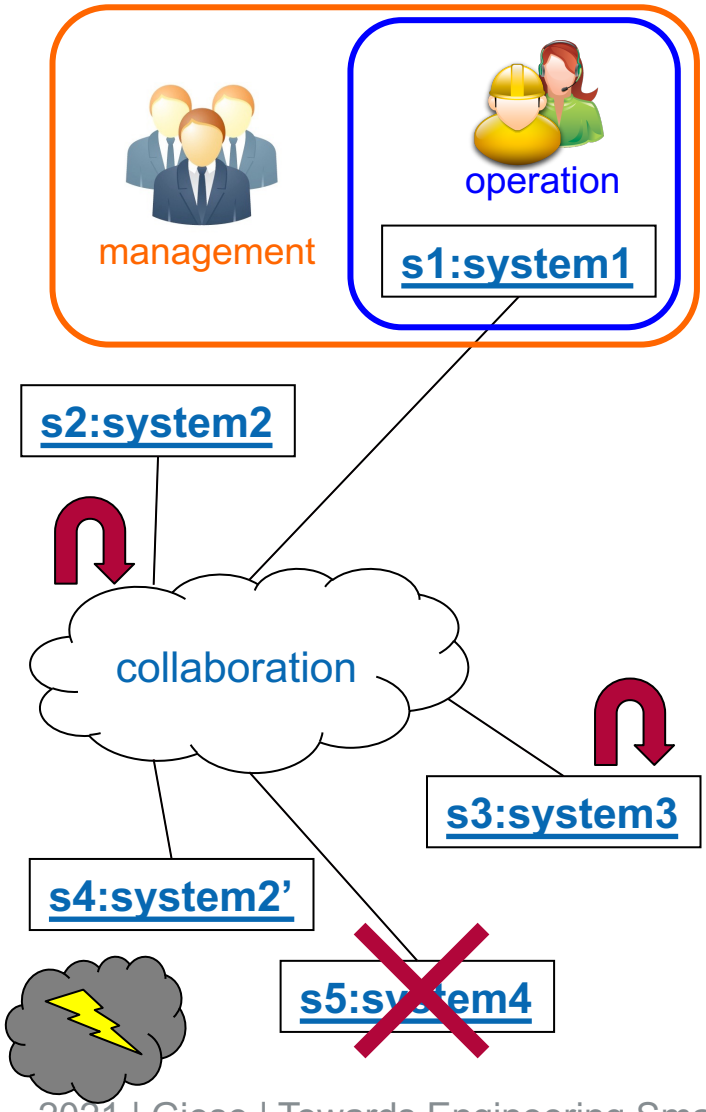
"Incrementality comes into play because often changes are local to restricted parts. […] **Incrementality** becomes even more necessary when changes occur at runtime and the software itself is responsible for reacting in a **self-managed manner**. In this setting, the processing that needs to be performed after each change is subject to severe time constraints." [Ghezzi2012|

**Required kind of self-adaptation:**

- System level adaptation
- System-of-systems level self-adaptation
- Incremental self-adaptation

# A Selection of Critical Future Challenges (3/5)



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- **Advanced adaptation**
- **Resilience**

# Challenge: Resilience



"The vision of Cyber-Physical System (CPS) is that of open, ubiquitous systems […] which […] and **fulfill stringent safety, security and private data protection regulations**." [Broy+2012]

"Resilience[:] This area is the attribute of a system, in this case a SoS that makes it less likely to experience failure and more likely to recover from a major disruption." [Valerdi+2008]

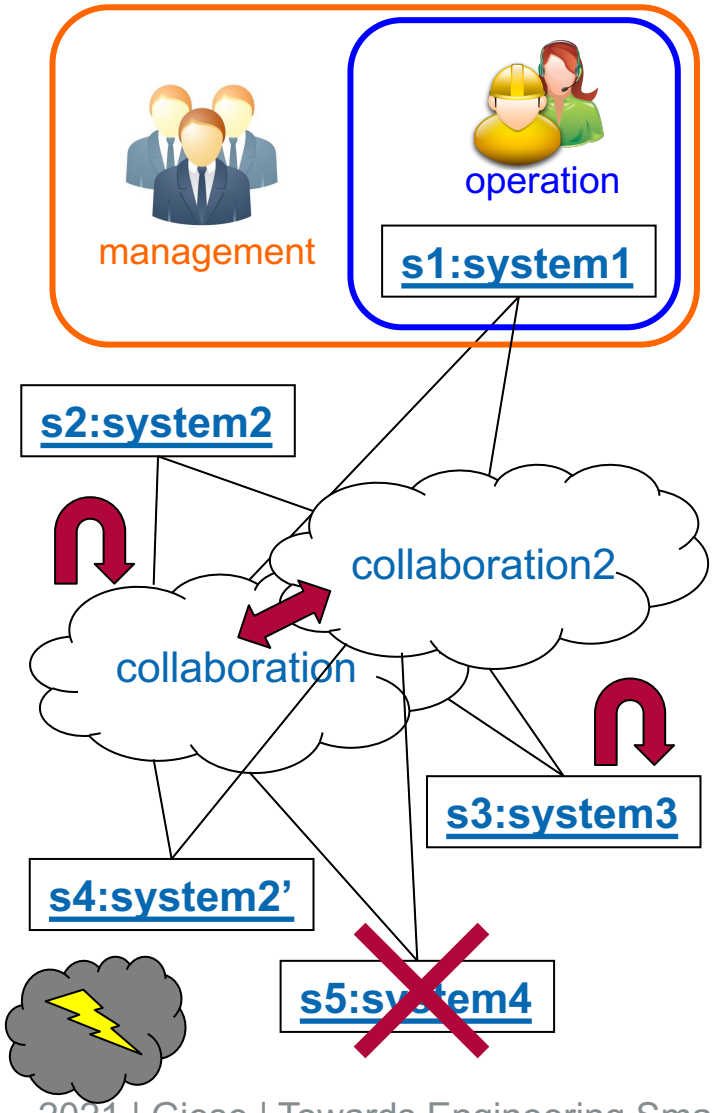
"Resilience is the capability of a system with specific characteristics before, during and after a disruption to absorb the disruption, recover to an acceptable level of performance, and sustain that level for an acceptable period of time." Resilient Systems Working Group, INCOSE

**Required coverage of resilience:**

- Physical and control elements (via layers of idealization)
- Software elements (via layers of abstraction)
- Horizontal and vertical composition of layers

# A Selection of Critical Future Challenges (4/5)



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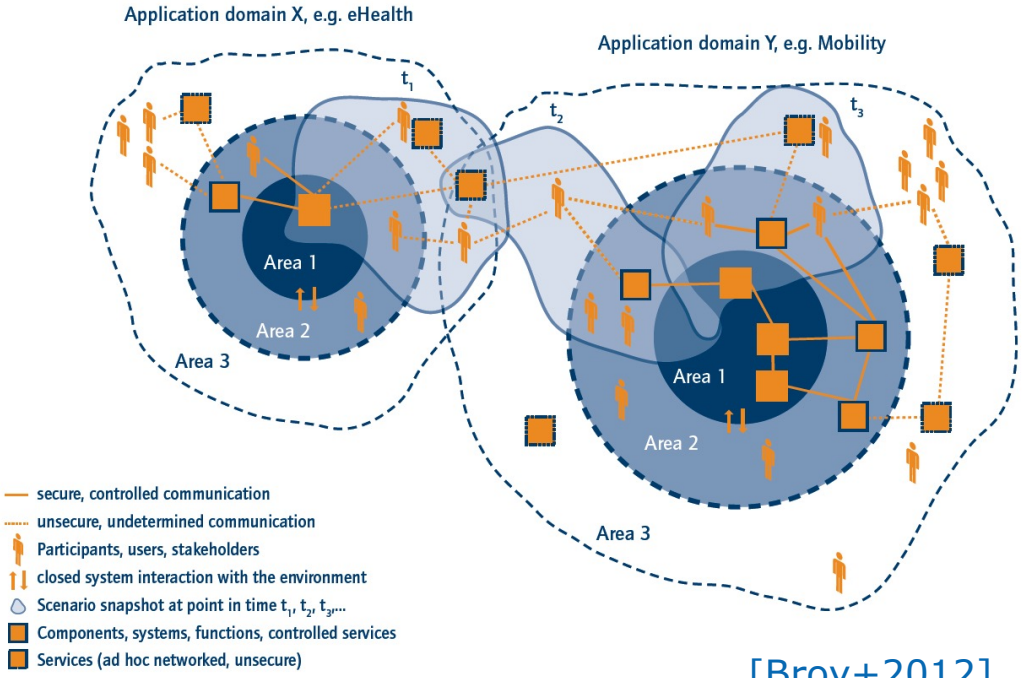
- **Advanced adaptation**
- **Resilience**
- **Cross-Domain Integration**

# 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]

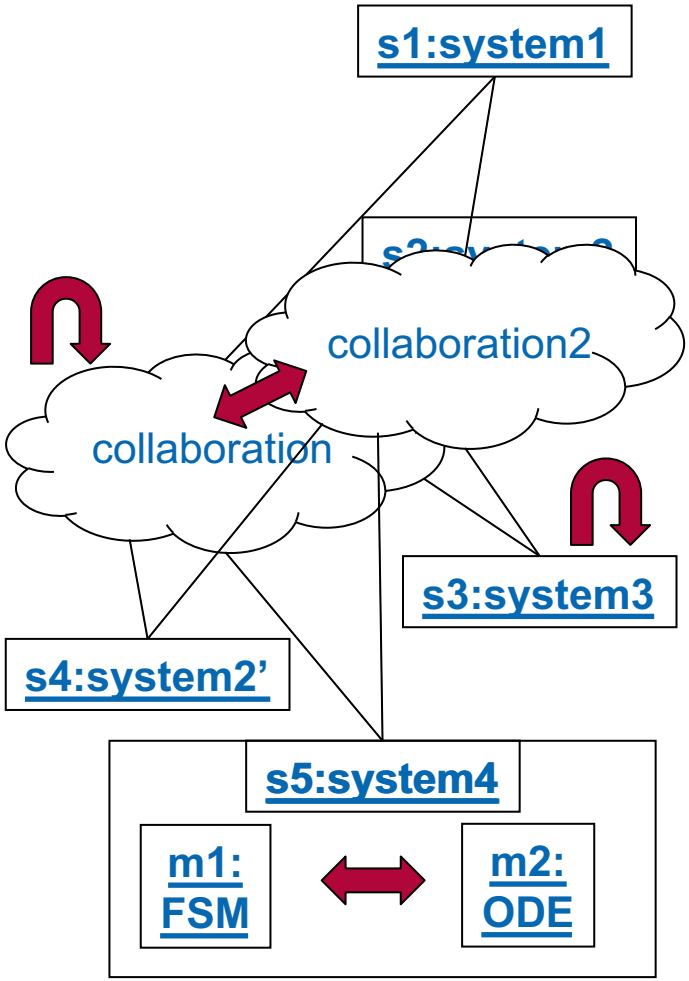
CPS of different domains have to be connected:

- 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**

# A Selection of Critical Future Challenges (5/5)



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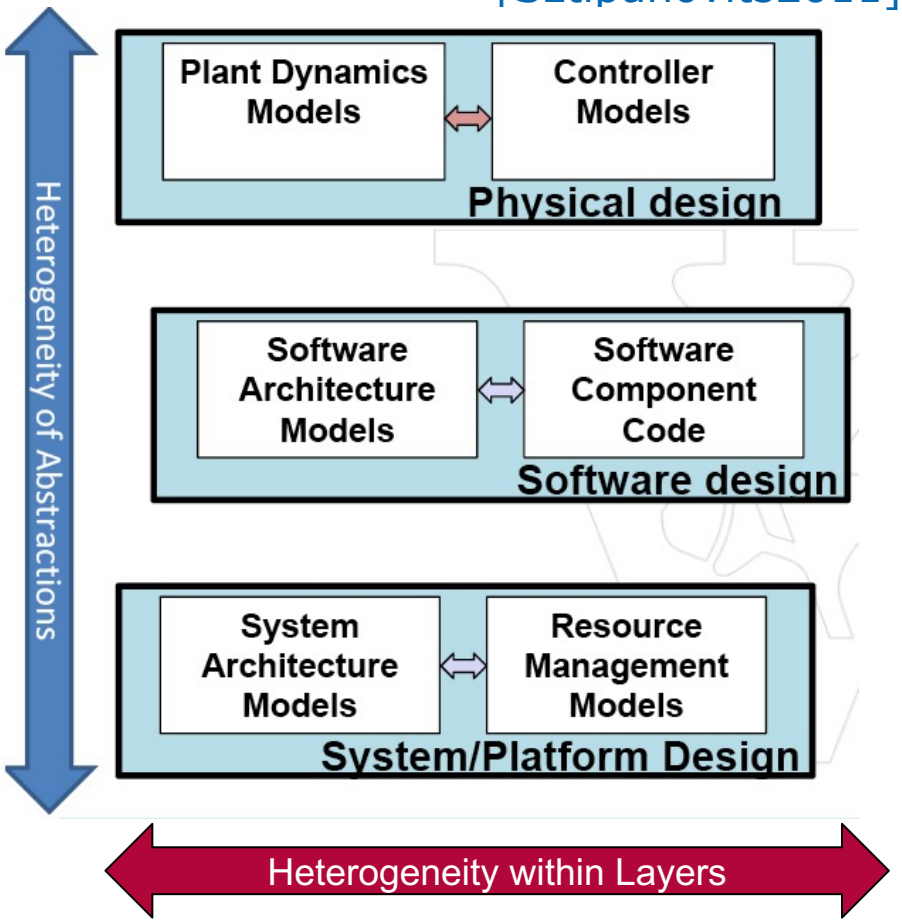
- **Advanced adaptation**
- **Resilience**
- **Cross-Domain Integration**
- **Integrate Models of Computation**

# 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**

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# 2. Being Smart: Adaptation Feedback Loop (MAPE-K)



**Plan**: what adaptation is "good" resp. "best"" for the made perceptions

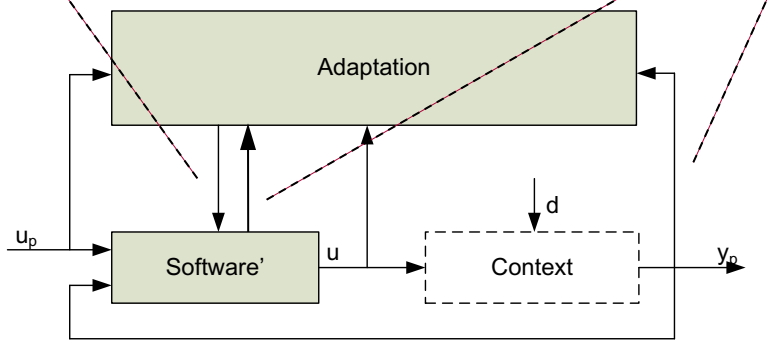
**Analysis**: is an adaptation "required"/beneficial for the made perceptions

**Knowledge** guiding the adaptation

- Simple: implicit
- Complex: partially explicit

**Execute/Adapt**: enact planned adaptation

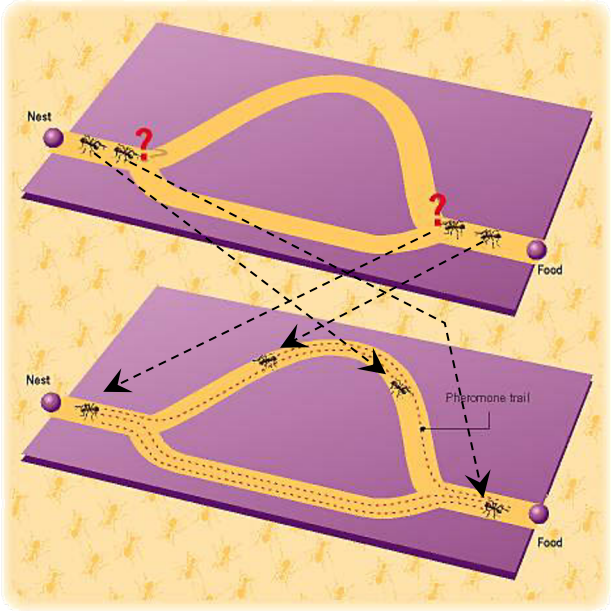
**Monitor/Observe**: how to interpret observations (**perception**)




**Is Simple Self-Awareness Enough?**

# Simple Self-Awareness :
## Let's have a look at Nature ...

**Ant colonies** operate as a **superorganism** that combines information processing of many ants and their interaction with the environment at the physical level (using stigmergy as coordination mechanism).




**Example:**

- Asymmetric binary bridge experiment

**Observations:**

- Initially both options will be taken with the same probability.
- The concentration of the pheromones will increase faster on the shorter path.
- The higher concentration of pheromones on the shorter path will make it more likely that an ant choses this shorter one.
- Positive feedback will amplify this effect and thus finally the longer path will only be used seldom.

➜ Can our problems be solved by borrow ideas from nature?

# Simple Self-Awareness : Let's have a look at Nature ...



**Another Example:**

- "Ant Mill"

**Observations:**

- Such a behavior would be not acceptable for an engineered system even for **unexpected circumstances (rare events)**.
- If even "Nature" come up with designed solutions that fail (even evolution selected for ages), how could we envision to be more successful?
- But there is also a solution in nature:

**reflect** on itself (**None Simple Self-Awareness**)

# Complex Aware-ness: Runtime Models

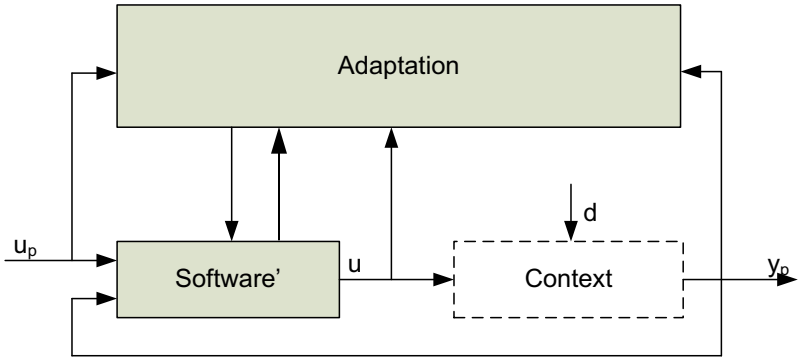


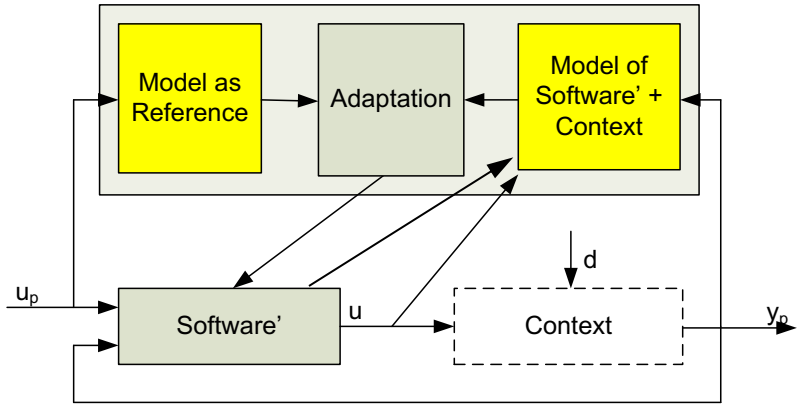
**Simple Awareness "without" models:**

- Still explicit or implicit **design-time models** are used guide adaptation processes

**Complex Awareness with runtime models:**

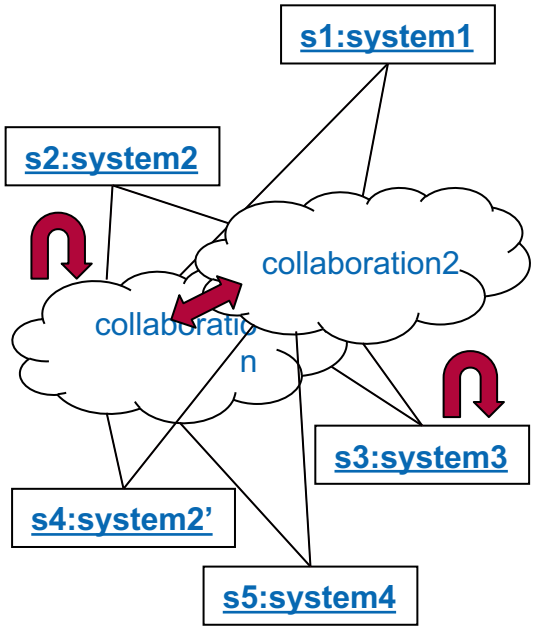
- Explicit **runtime models** are **learned** to guide adaptation processes and allow **reasoning**
- Model as reference can include goals
- Model of software + context capture changes
- **Limitation:** covers only changes captured by the runtime models (possibly **multiple**!); requires correct adjustment from observations
- **Option:** adaptation can also reason with these models (e.g., predict outcome of changes)



# Self-Awareness & System of Systems



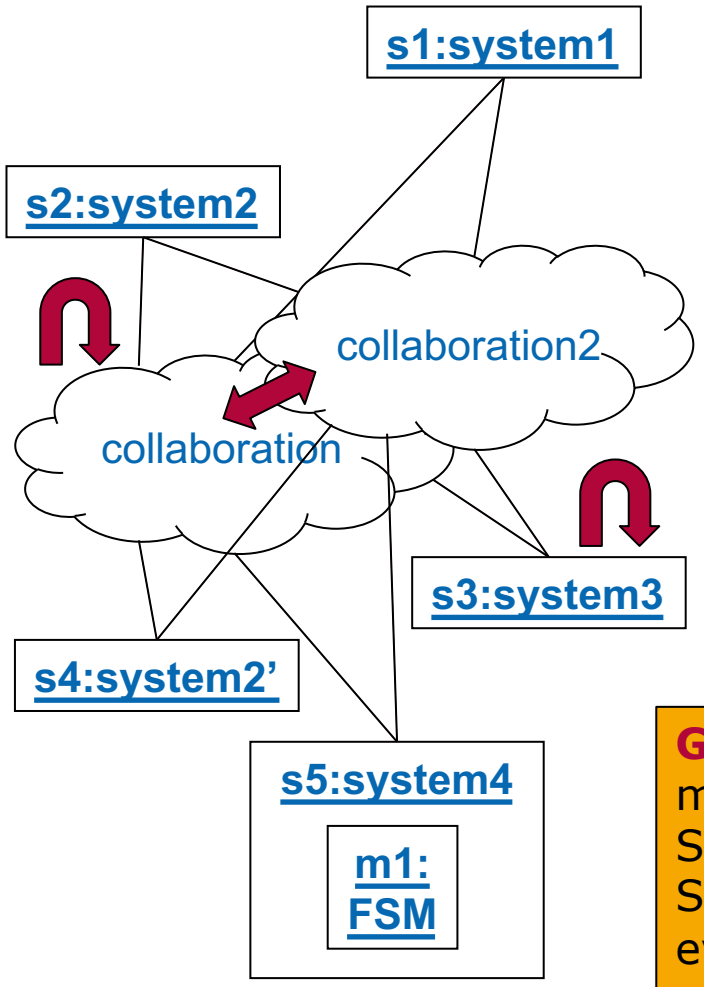



- **Self-Adaptive Systems:**
  - Make systems **self-aware**, context-aware, and requirements-aware using some form of **reflection**
  - Enable systems to adjust their structure/behavior accordingly
- **Self-Organization:**
  - The capability of a system of systems to organize their structure/behavior without a central control (emergent behavior)

- **Observations:**
  - a spectrum from centralized top-down self-adaptation to decentralized bottom-up self-organization with many intermediate forms exists
  - existing (formal) models and analysis approaches for CPS are no longer applicable as they do not cover reflection/adaptation (design, verification, ...)

# Some Related Observations …






[Giese+2015]

- **Service-Oriented Architecture** can be described by a **graph** of links between the systems that evolve
- **Self-Adaptive** and **Self-Organization** can be described by a **graph** of links between the components resp. systems that evolve/reconfigure and in case of **reflection** most models can be described by such a **graph** as well
- **Runtime Models** can be described by a dynamic **graph** of models and links between them

**Graph transformation systems** encoding models and their linking would allow to combine Service-Oriented Architecture, Self-Adaptive / Self-Organization, and Runtime Models with evolving structures and **could be** the basis for a **solid foundation …**

# Complex Self-Awareness:
## A look at a complex example...



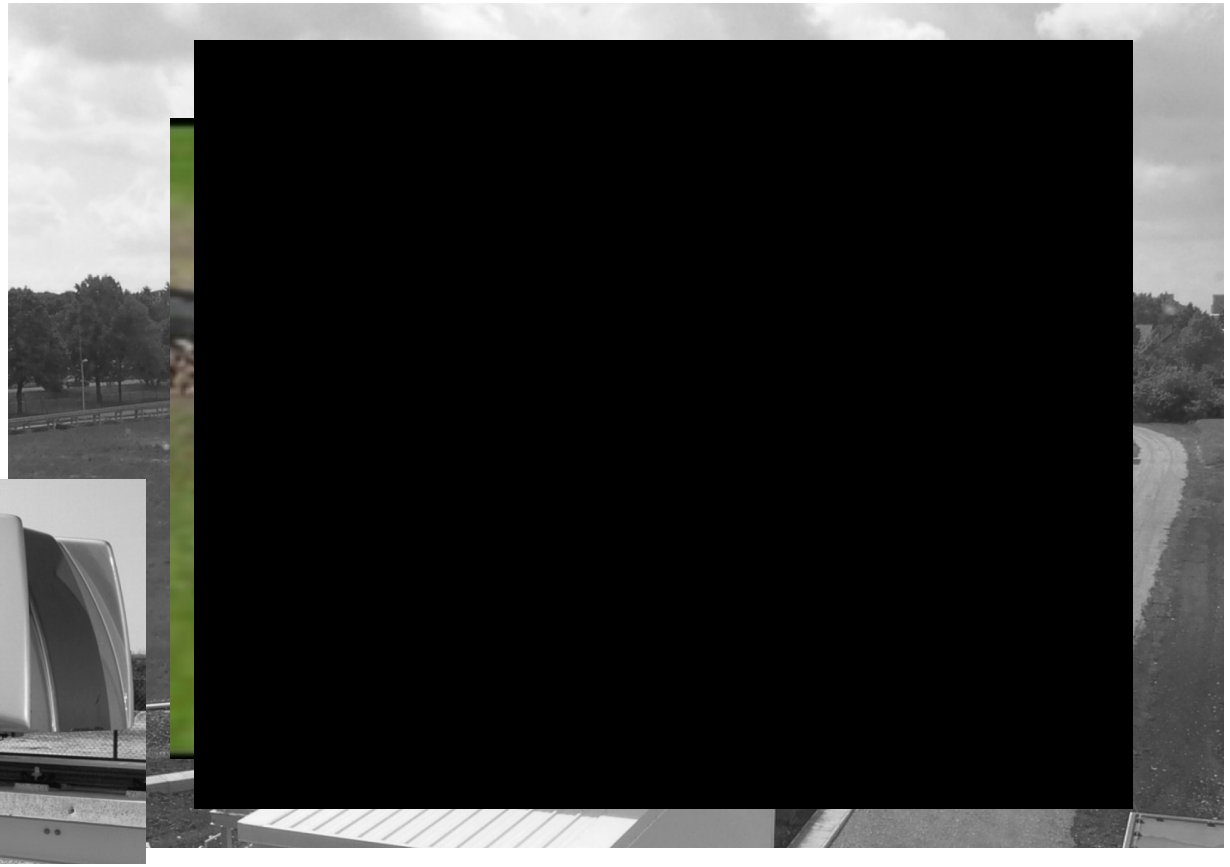
A system of **autonomous shuttles** that operate on demand and in a decentralized manner using a **wireless network**.

**Smart CPS:**

- Hard real-time
- Safety-critical
- Self-Optimization

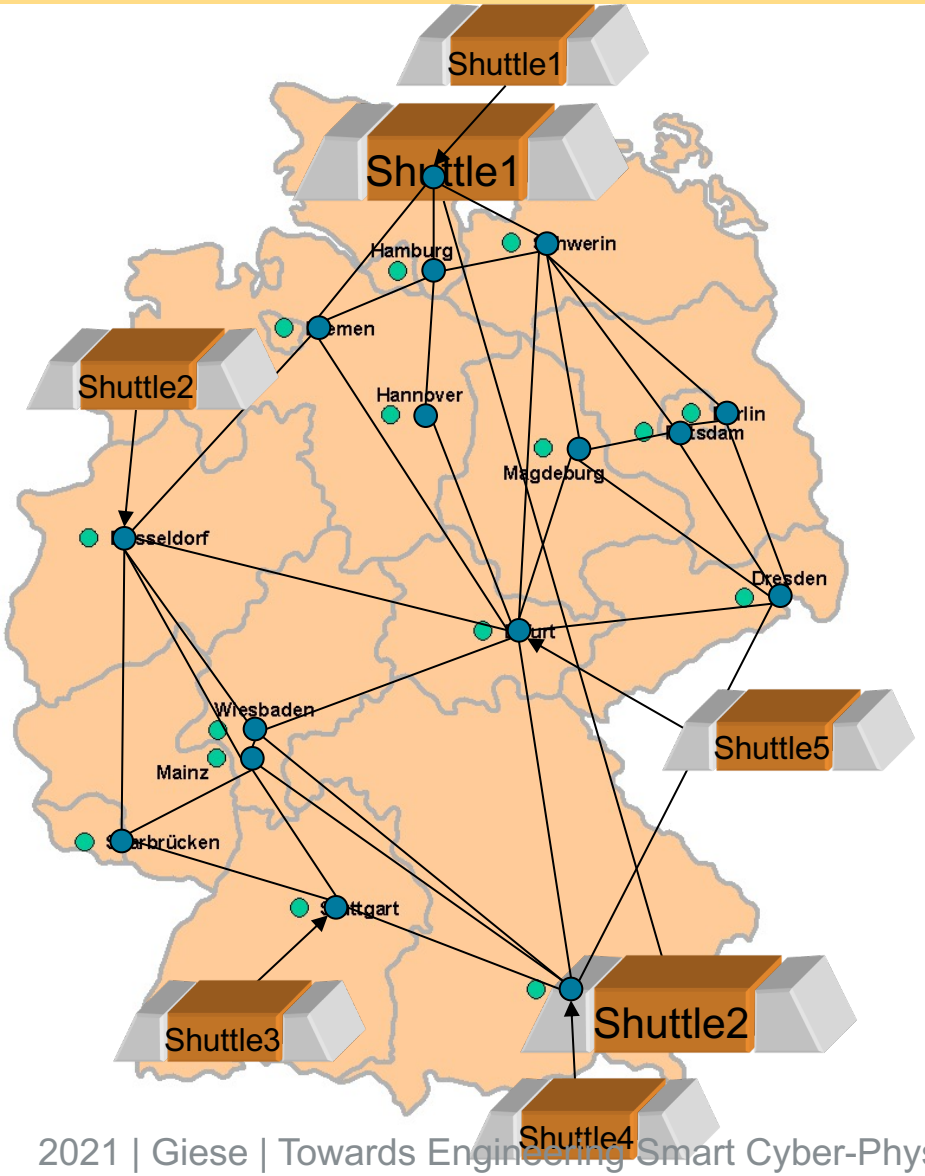
**Needs:**

- Optimized maneuvers, operation, and resource utilization (e.g., convoy)



# Related Observation Concerning the Example






**Modeling Problems:**

- Shuttles move on a topology of tracks
- Arbitrary large topologies

**Solution:**

- State = Graph
- Reconfiguration rules = graph transformation rules
- Safety properties = forbidden graphs
- ⇨ Formal Verification possible

**Very strong reduction:** not all properties are represented

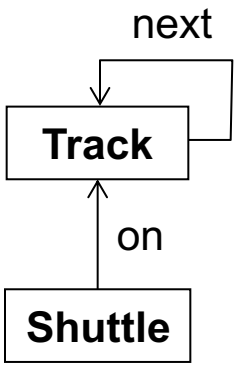
- Dynamic convoy structures and movement of the shuttles on the topology of tracks
- Real-Time movement of the shuttles on the topology of tracks
- Real-Time protocols for convoy coordination
- Continuous driving behavior
- Random communication errors
- ...

non-functional

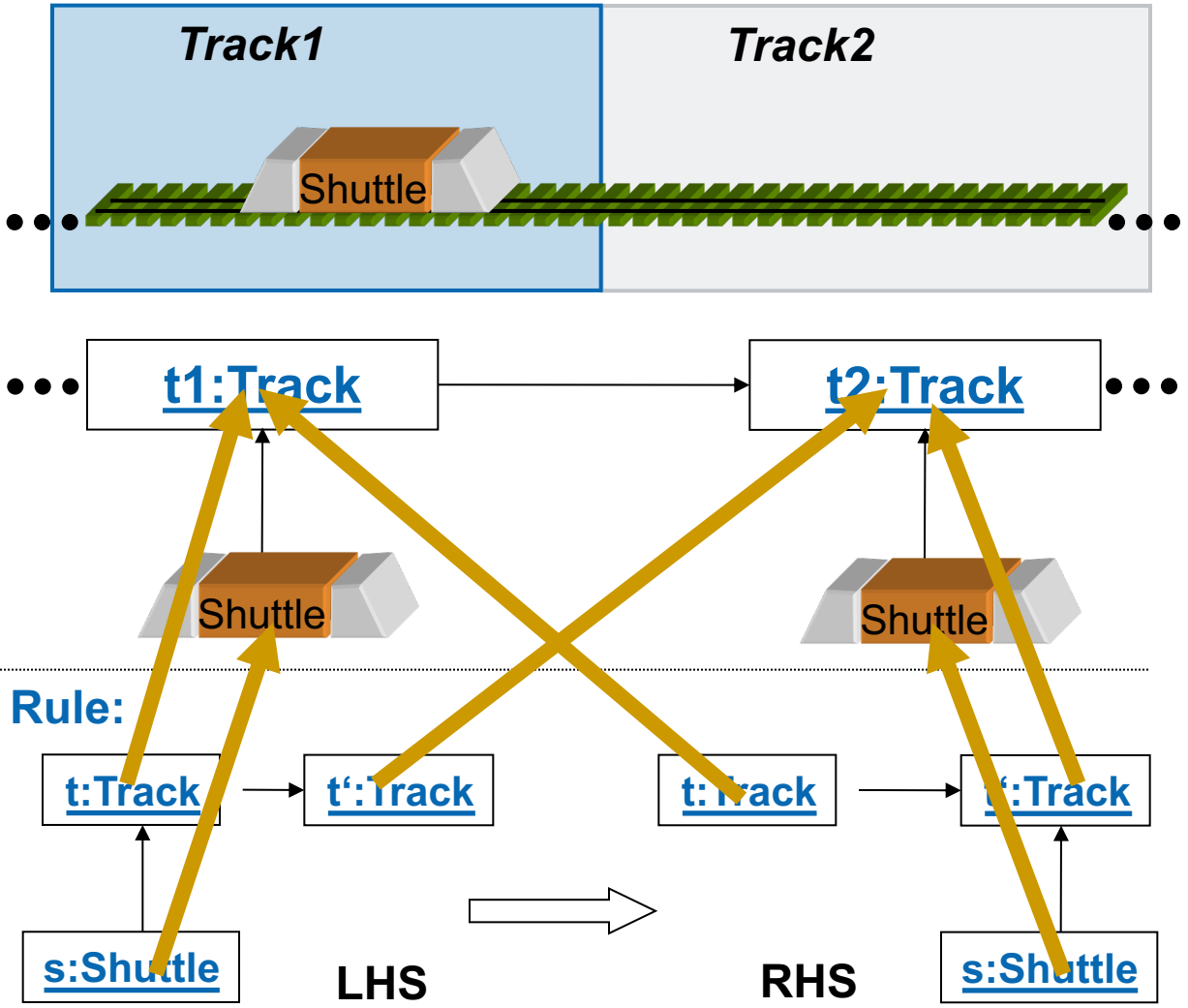
# Graph Transformation Systems: Naïve Example



- Map the tracks
- Map the shuttles



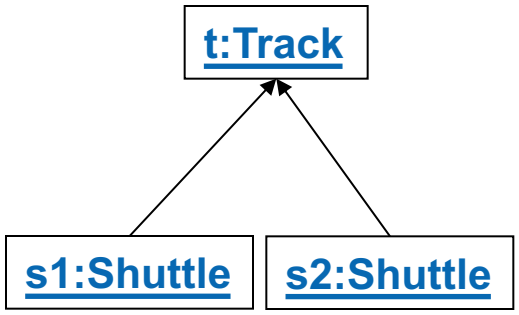

- Map the movement to rules (movement equals dynamic structural adaptation on the abstract level)

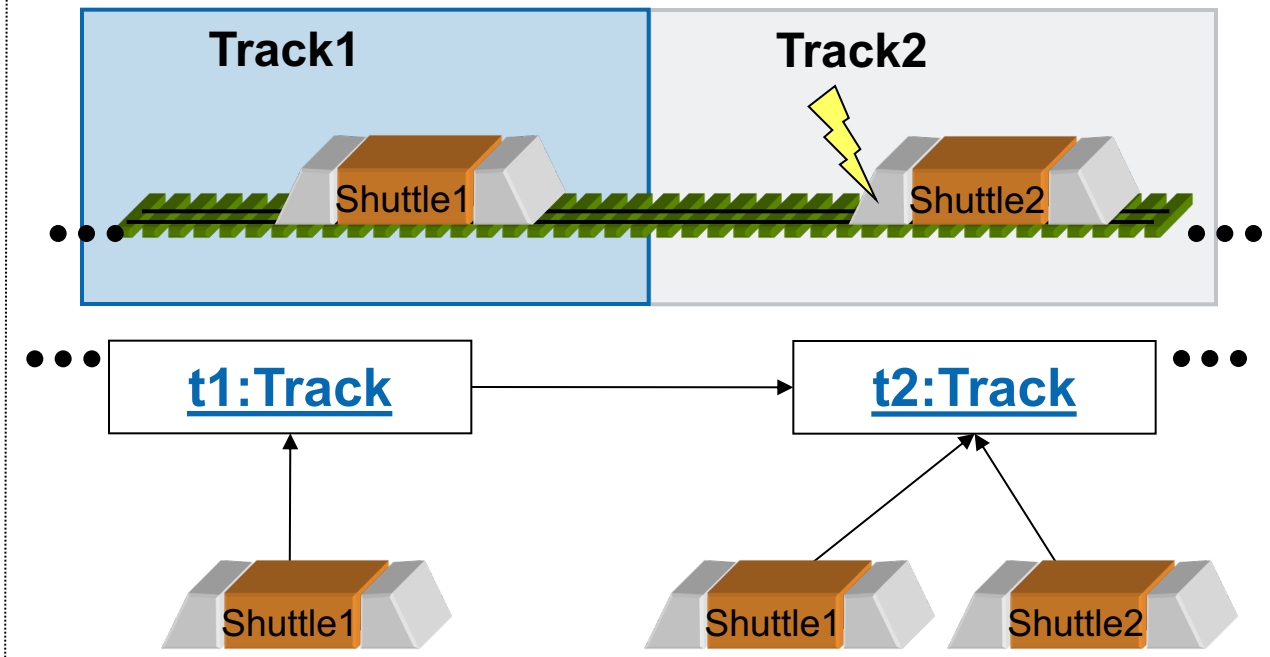


# Graph Transformation Systems: Naïve Example

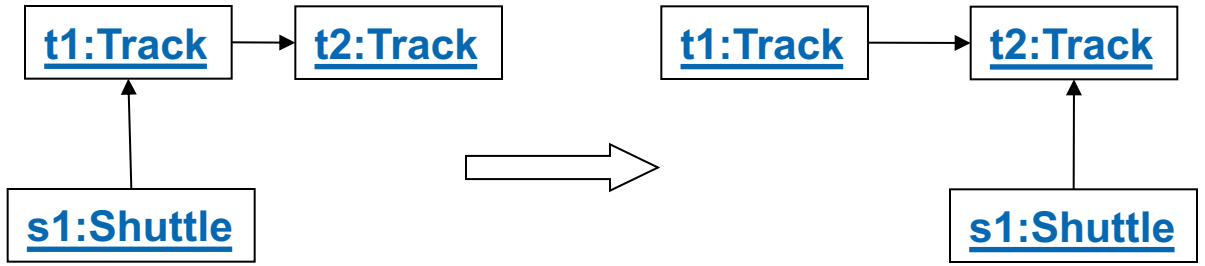


***Forbidden Graph***



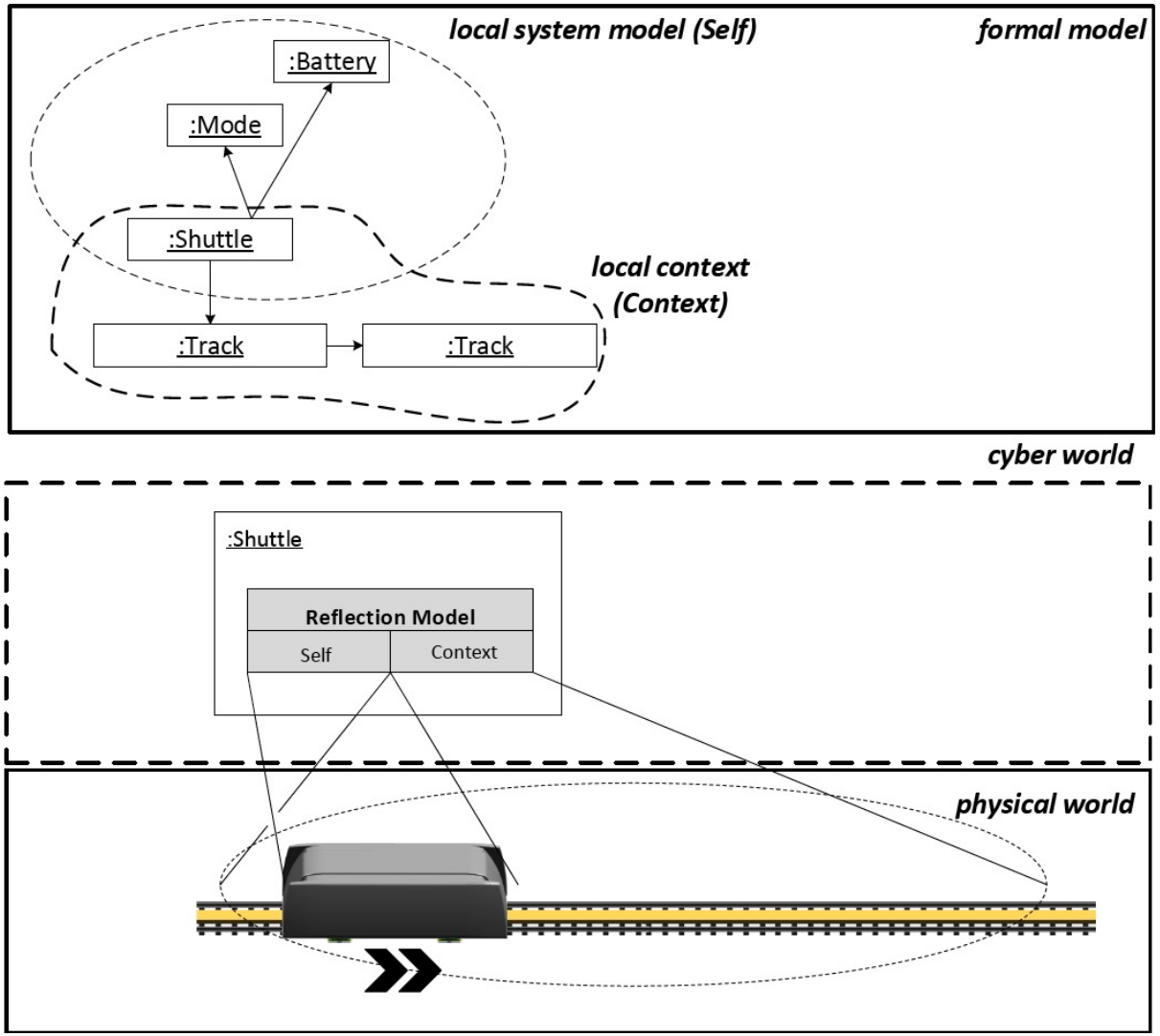




**Rule:**



# Runtime Models & Idealized Perception






[Giese+2015]

**SMARTSOS** suggests:

- use a **graph** of links between the systems, components, and internal represented data as well as
- use **graph transformations** to capture possible changes

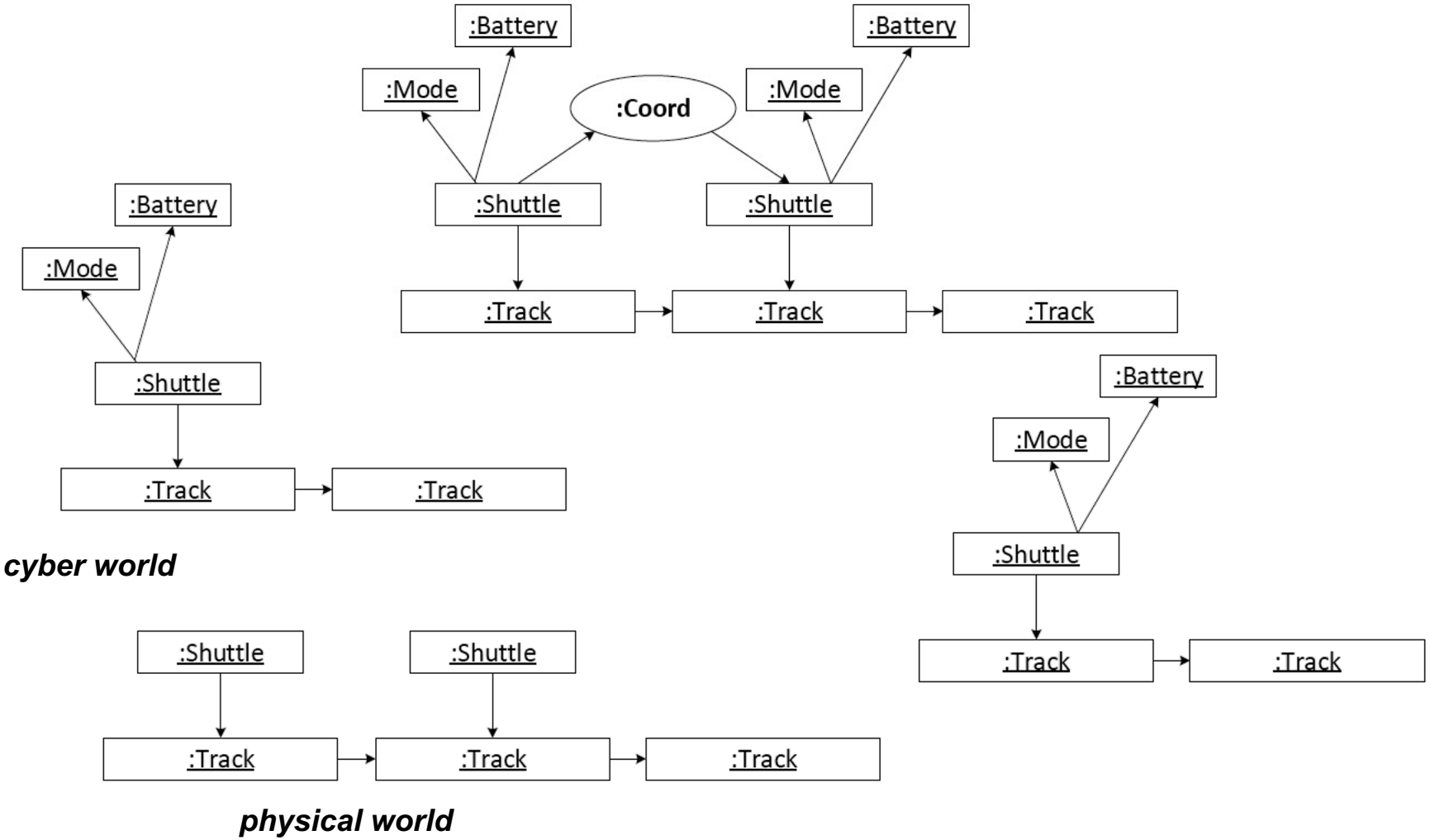
to model

- **Service-Oriented Architecture**,
- **Self-Adaptive** and **Self-Organization**, and
- **Runtime Models**

# Idealized Consistent Cyber & Physical World

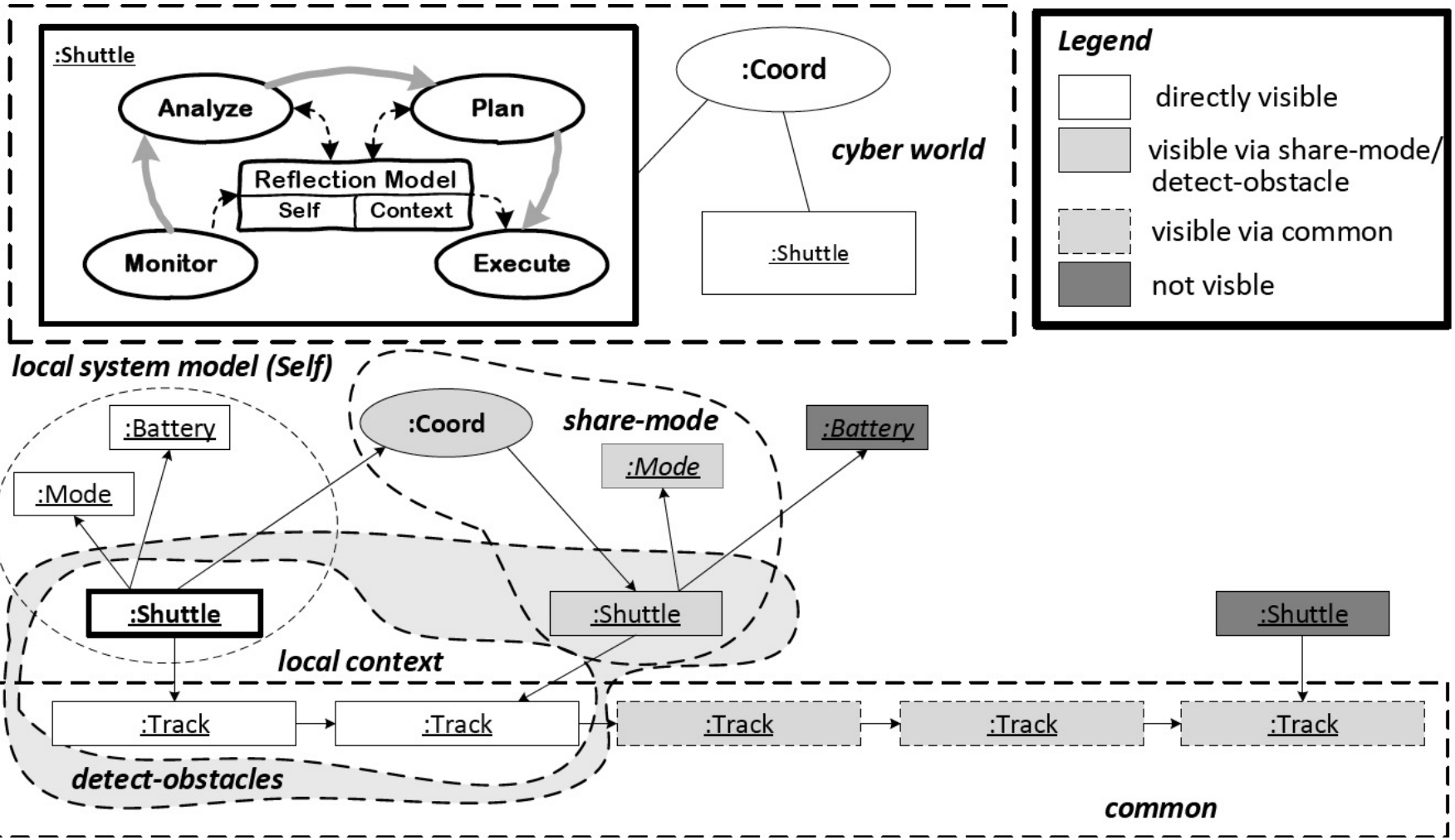


[Giese+2015]



# Runtime Models & Exchanging Perceptions



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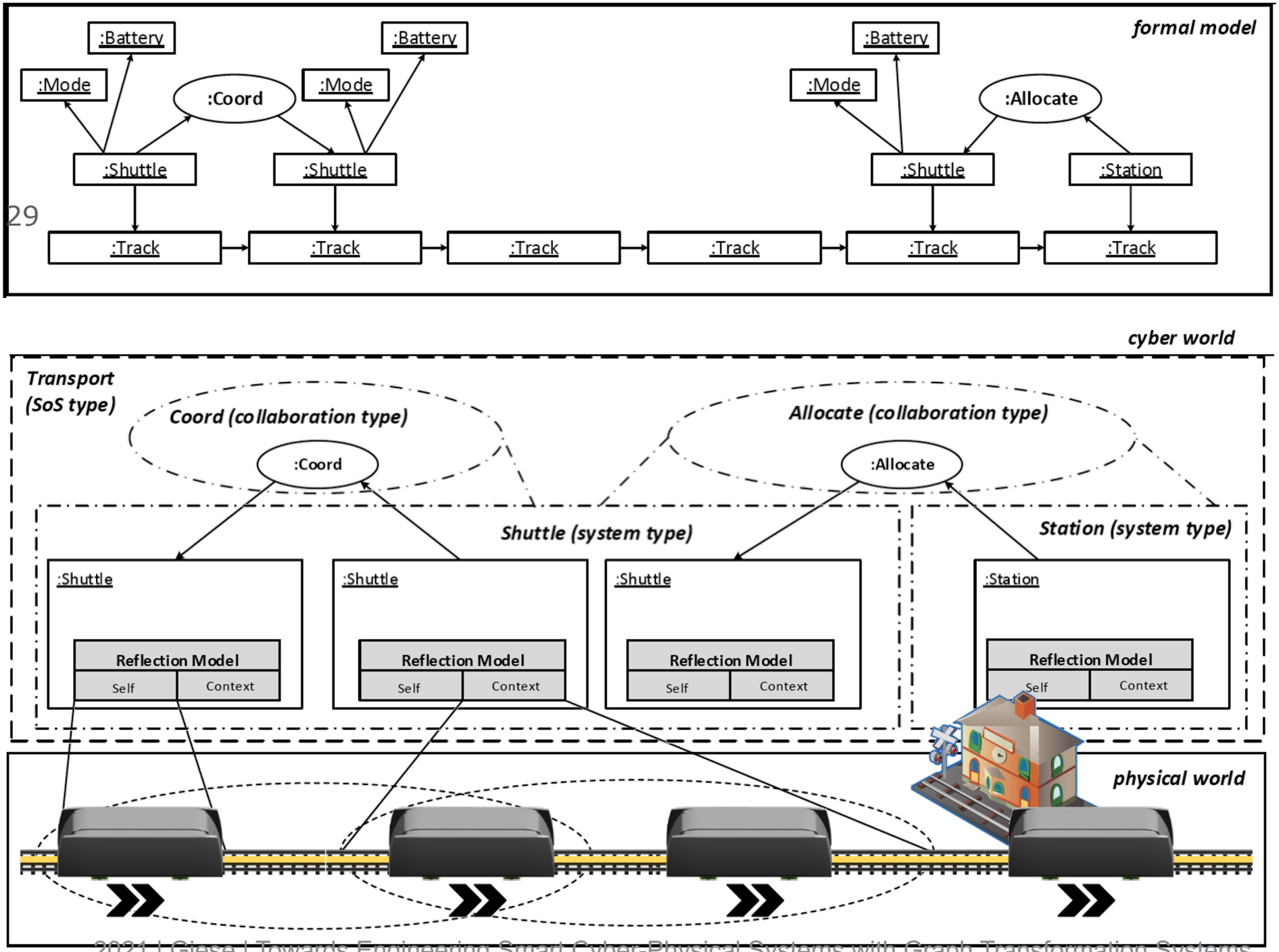
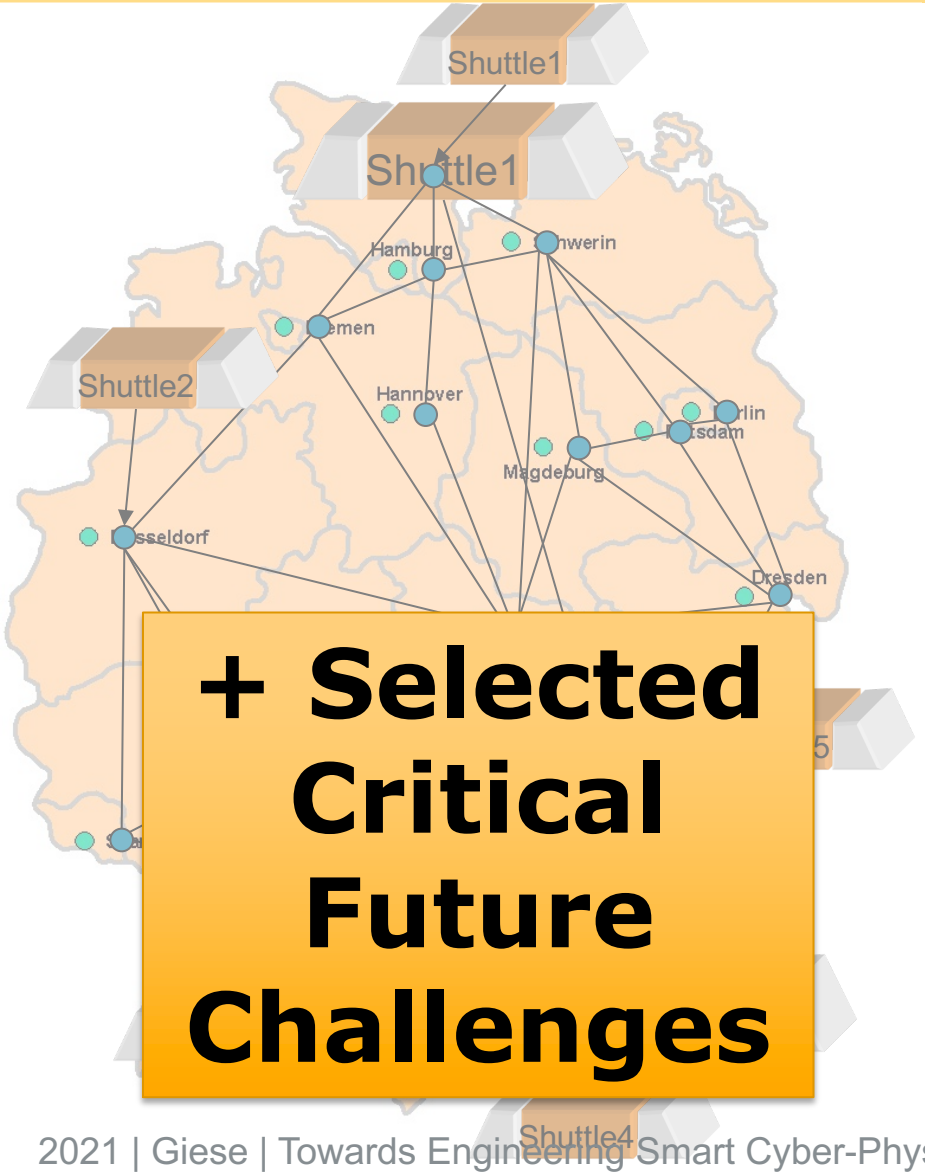

formal model
:Battery
:Mode
:Coord
:Shuttle
:Track
:Allocate
:Station
cyber world
Transport
(SoS type)
Coord (collaboration type)
Allocate (collaboration type)
Shuttle (system type)
Station (system type)
Reflection Model
Self
Context
physical world

# Related Observation Concerning the Example






**+ Selected Critical Future Challenges**

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# Coverage of the Challenges for Models



**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
- **Adaptation** at the system and system of system level
- **Decoupled evolution** and **co-existence of different versions**
- **Resilience** of the system of system

**Model Characteristics:**

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

**Our Work:**

- **SMARTSOS (**employing Timed and Hybrid GTS [Giese+2015]**)**
- **Timed GTS ([**Becker&Giese2008]**)**
- **Hybrid GTS ([**Becker&Giese2012]**)**
- **Probabilistic timed GTS ([**Maximova2018]**)**
- **Probabilistic GTS ([**Krause&Giese2012]**)**

# Coverage of the Challenges for Analysis



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**Our Work:**

SMARTSOS

- **Checking Inductive Invariants for GTS (**[Becker+2006]**), Timed GTS (**[Becker&Giese2008]**), and Hybrid GTS (**[Becker&Giese2012]**) and Checking k-Inductive Invariants for GTS (**[Dyck&Giese2017]**) resp. Attributed GTS (**[Schneider+2020]**)**

- **Model Checking Probabilistic GTS (**[Krause&Giese2012]**)**
- **Probabilistic timed GTS: Model Checking (**[Maximova+2018]**), Compositional Model Checking (**[Maximova+2021]**)**

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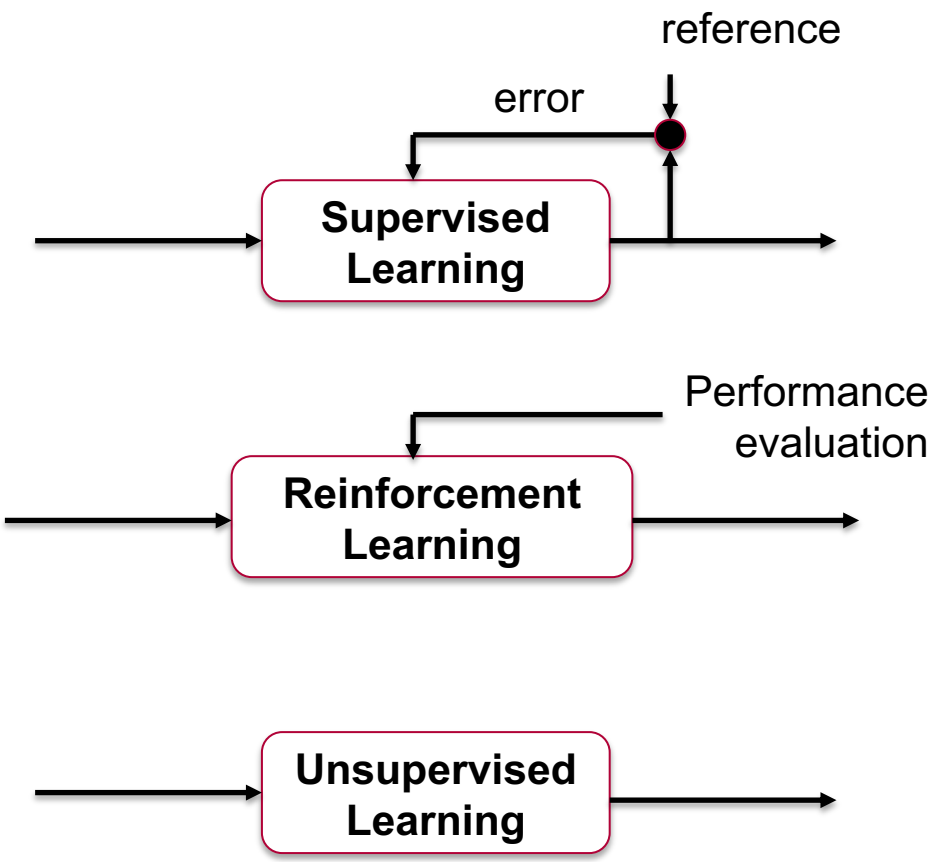
# 3. Smart & Learning: Learning vs. Training






**Learning** allows to adjust the behavior of systems:

- **Trained systems**:
  - learning only **offline**
  - **BUT:** additional surveillance must be **online**
- **Learning systems**:
  - Often initially **trained**
  - Steady improvement by learning **online**
  - additional surveillance needed?

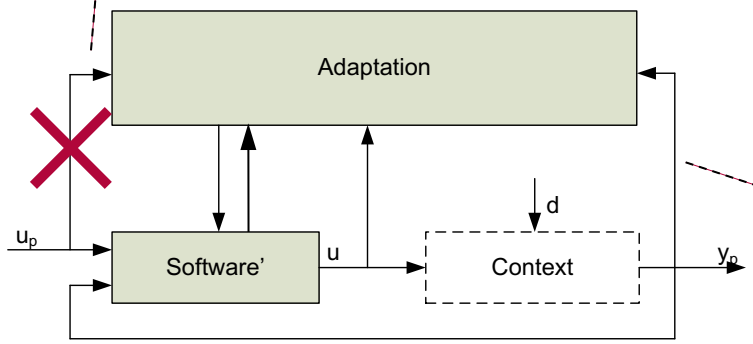
# Simple Awareness & Learning



**Train goals**: adjust goals according to success w.r.t. higher level goals

**Variable goals**: react to changes of the goals

**Static goals**: no variation




**No learning**: react to perceptions directly; avoid explicit model at run-time

**Training/Learn perception**: how to interpret observations

# Complex Self-Awareness & Learning

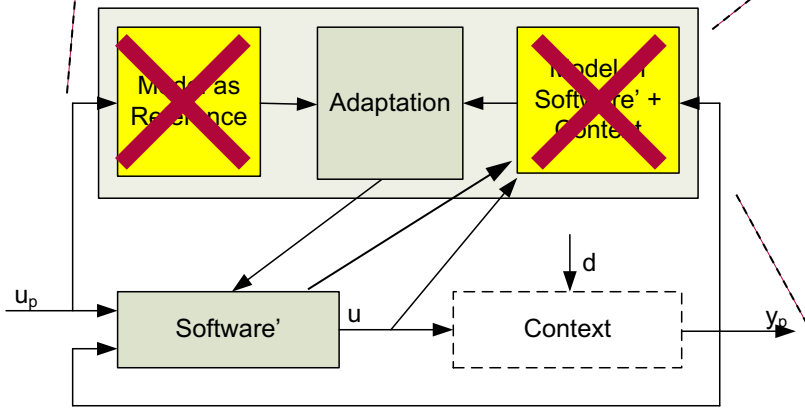


**Train/Learn goals**: adjust goals according to success w.r.t. higher level goals

**Train/Learn adaptation**: …

**Variable goals**: react to changes of the goals

**Static goals**: no variation




**Learn also runtime model concepts** (unknown unknowns); runtime models evolve according to the perception of useful differences

**Learn runtime models** (known unknowns); parameters, elements, and relations of runtime models are **learned** according to the perception

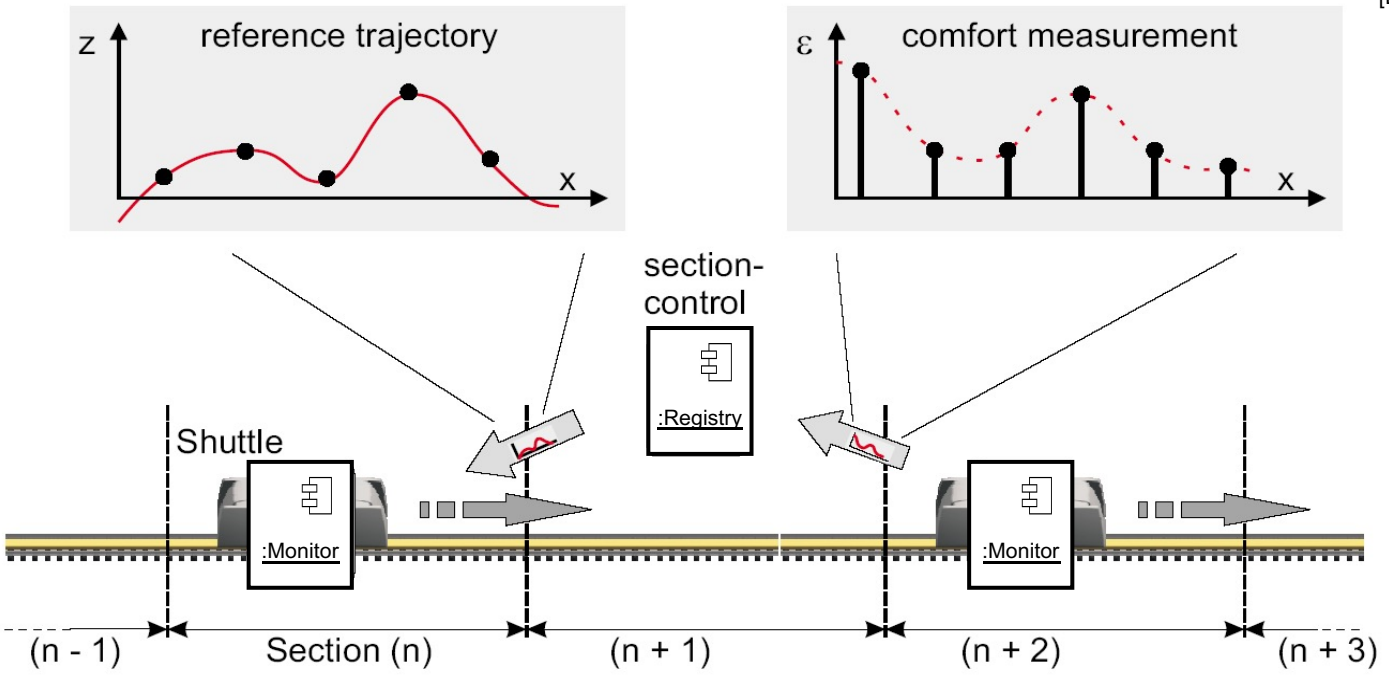
**No learning**: react to perceptions directly; avoid explicit model at run-time

**Train/Learn perception**: how to interpret observations

# Complex Self-Awareness & Learn Context (1/3)



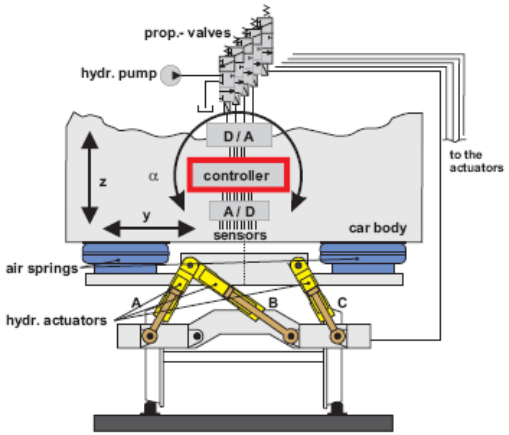
[Burmester+2008]



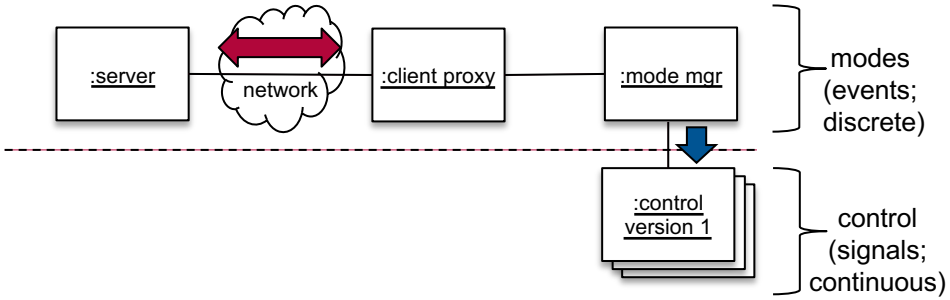

- **Server (Registry of the section control; not global!):**
  - Offers track profile (distributed learning of a runtime model of the track)
- **Client (Monitor of the shuttle):**
  - Applies track profile (local learning of a runtime model of the shuttle and planning an adaptation in form of an optimal trajectory)
  - Must handle cases where the service is available or not

# Complex Self-Awareness & Learn Context (2/3)






**Scheme:**




**Suspension/tilt module**

- air springs (filter for higher frequencies)
- active suspension system (lower frequencies)

**We consider three different control strategies:**

**(1)** **robust controller:** track as reference point; damping the relative movement
⇨ only achieves moderate damping.

**(2)** **absolute controller** uses a virtual skyhook in order to ensure the absolute acceleration of the shuttle body is minimized
⇨ comfort usually maximized; problematic on inclines

**(3)** **reference controller**: Instead of virtual skyhook, the real track is used as reference
⇨ highest comfort; requires data about the track

[Burmester+2008]

**Client proxy:**

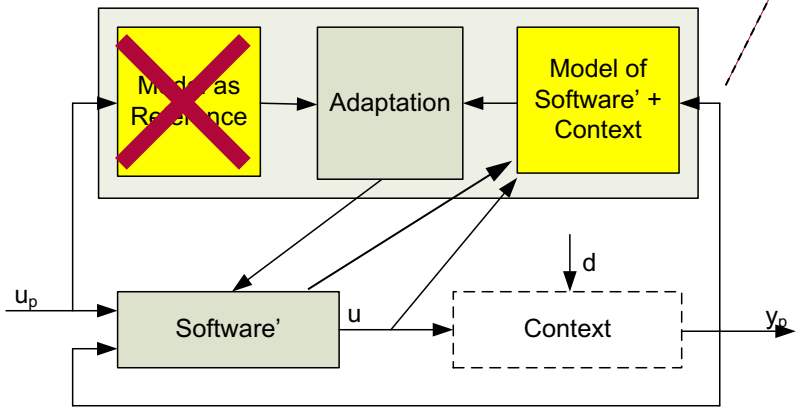
- Find local responsible registry
- register at the local registry (requestInfo)
- Receive data from the registry (sendInfo)
- Manage cases where the data is available or not (outside the proxy)
- Send data to the registry (experience)
- **PLUS:** detect invalid runtime model!

# Complex Self-Awareness & Learn Context (3/3)



**Distributed learning runtime models** (known unknowns); parameters, ~~elements, and relations~~ of runtime models are **learned** according to the perception of other agents

**Static goals**: no variation




**Learning runtime models** (known unknowns); parameters, ~~elements, and relations~~ of runtime models are **learned** according to the perception

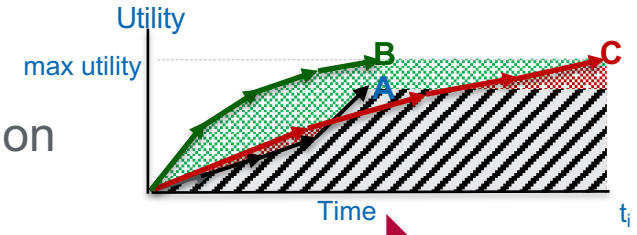
**OBSERVATION:** There is no guarantee that the runtime models are not invalid due to fact that they always rely on potentially erroneous or outdated measurements/ perceptions → **detection + backup strategy always necessary**

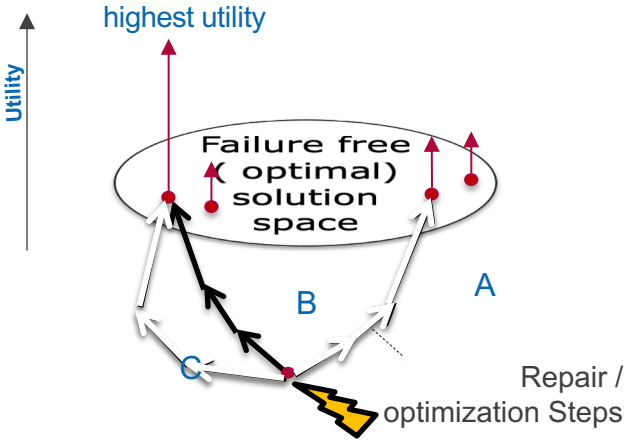
# Complex Self-Awareness & Train Goals (1/4)



[Ghahremani+2017]
[Ghahremani+2018]

Self-adaptive systems that are rule-based
Architecture-based self-healing and self-optimization




| | Optimization -based (C) | Rule -based (A) | Utility -driven (B) |
|---|---|---|---|
| Optimal order of repairs | ✓ | ✗ | ✓ |
| Scalable | ✗ | ✓ | ✓ |
| Maximum Utility | ✓ | ✗ | ✓ |
| Expressiveness | + | – | +/– |

**Required:** Function computing the impact on the utility for each possible rule application

**Open Question:** Can we learn these functions offline (training)?

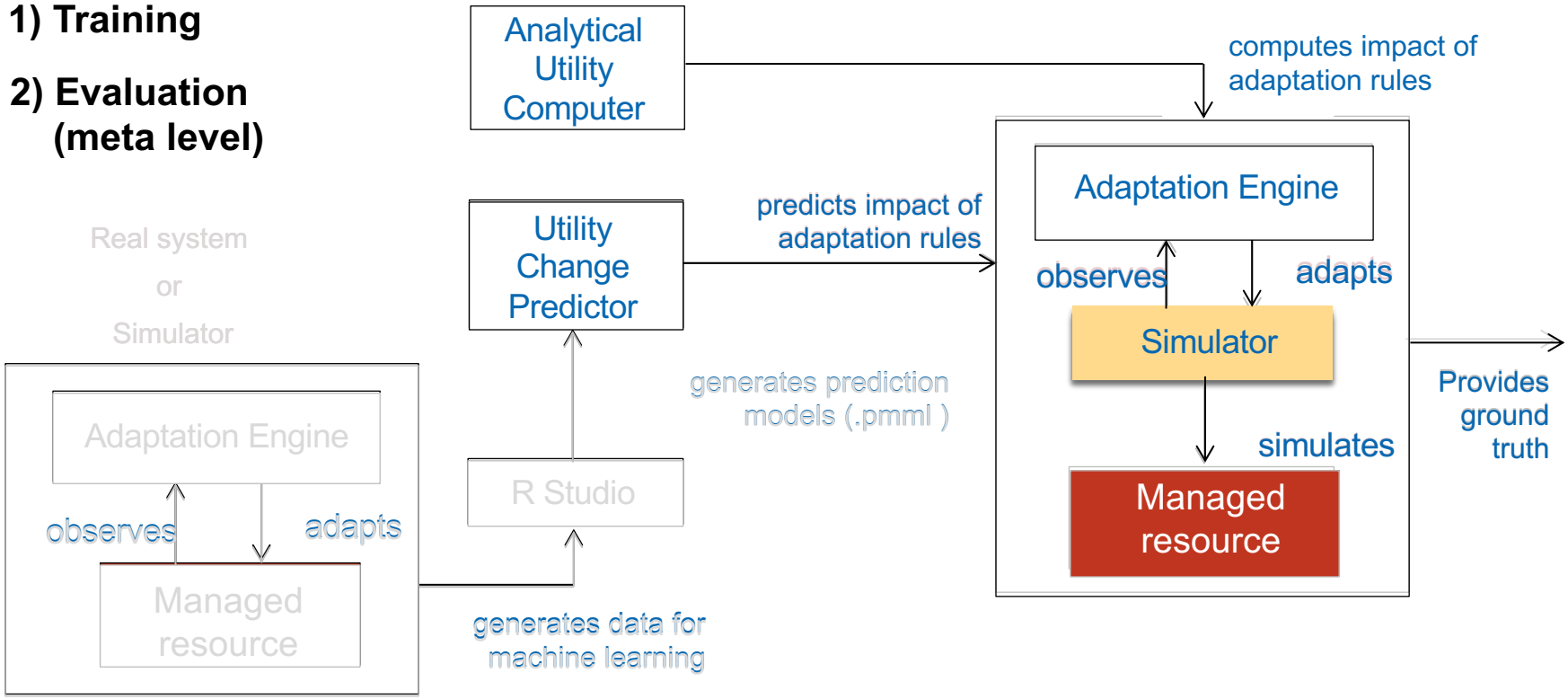
# Complex Self-Awareness & Train Goals (2/4)

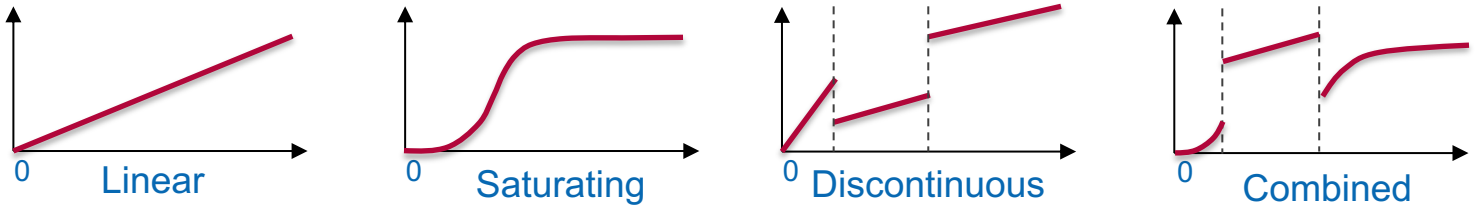


[Ghahremani+2018]

**1) Training**

**2) Evaluation (meta level)**



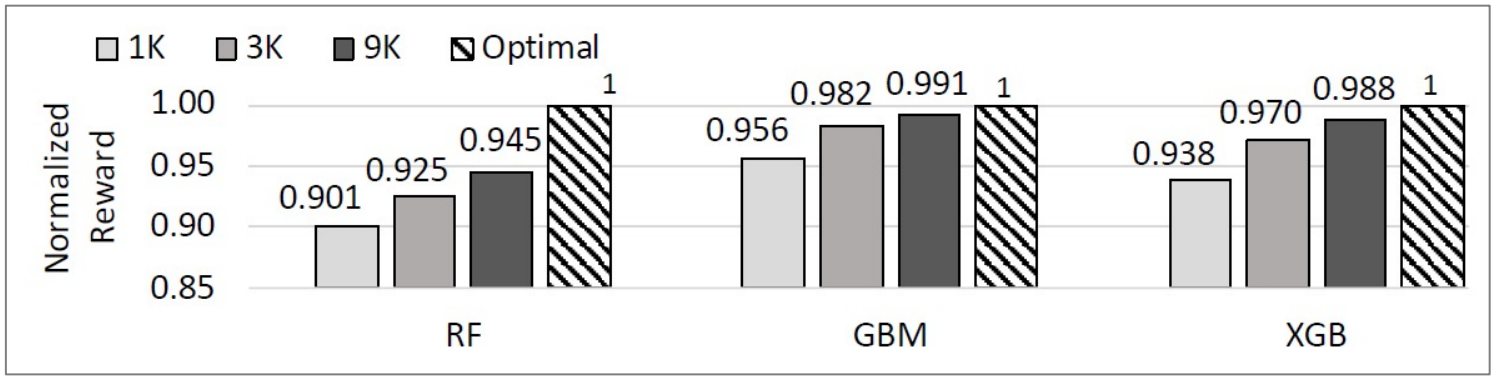
# Complex Self-Awareness & Train Goals (3/4)



[Ghahremani+2018]

**RQ:** Does the performance approximate the analytic-defined optimum?

**YES**




Normalized rewards across prediction models for the **combined** variant

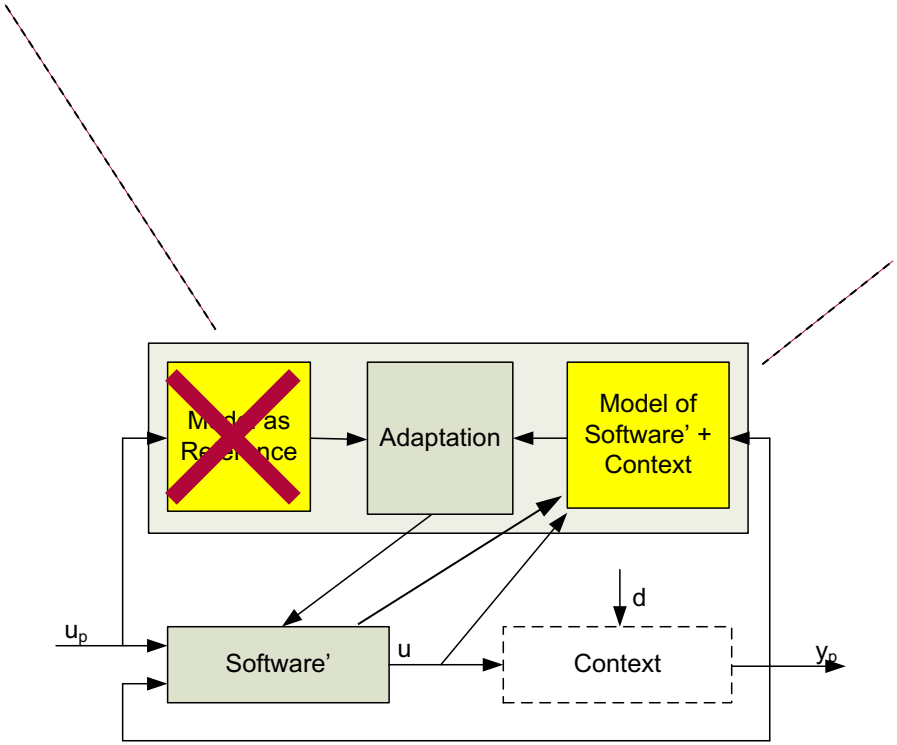
$$\text{Normalized Reward (mod)} = \frac{Reward\ (mod) - Reward(Baseline)}{Reward\ (Optimal) - Reward(Baseline)}$$

# Complex Self-Awareness & Train Goals (4/4)



**Train goals**: adjust goals according to success w.r.t. higher level goals

**PROBLEM:** There is no guarantee that the trained goals are valid due to fact that they always rely on potentially erroneous or outdated measurements/perceptions
→ **optimality is not guaranteed**




**Learn runtime models** (known unknowns); parameters, elements, and relations of runtime models are **learned** according to the perception

# Outline



1. Motivation
2. Being Smart
3. Smart & Learning
4. Conclusions & Outlook

# 4. Conclusions & Outlook



**Graph transformation systems** encoding models and their linking allow to combine Service-Oriented Architecture, Self-Adaptive / Self-Organization, and Runtime Models with evolving structures and are a suitable basis for a **solid foundation.**

- Runtime models and via collaborations shared runtime models enabled **Self-Adaptation** and **Self-Organization** of the systems and system of system
- **Limitations:**
  - Model is a rather strong **idealization**
  - Analysis relies on the **validity/trustworthiness** of the models
    - Development-time models may become invalid over time
    - Runtime models for self-awareness may become invalid

# Outlook (1/5)
## Modeling



**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
- **Adaptation** at the system and system of system level
- **Decoupled evolution** and **co-existence of different versions**
- **Resilience** of the system of system

**Model Characteristics:**

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

**Our Work:**

- **SMARTSOS (**employing Timed and Hybrid GTS [Giese+2015]**)**

**AND:** support more advanced run-time models (history, behavior, …)

- **Timed GTS ([**Becker&Giese2008]**)**
- **Hybrid GTS ([**Becker&Giese2012]**)**

?

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

- **Probabilistic GTS ([**Krause&Giese2012]**)**

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

# Outlook (2/5)
## Analysis



**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
- **Adaptation** at the system and system of system level
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**Model Characteristics:**

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

**AND:** cover the learning …

**State-of-the-Art & our Work:**

SMARTSOS

- **Checking Inductive Invariants for GTS ([Becker+2006]), Timed GTS ([Becker&Giese2008]), and Hybrid GTS ([Becker&Giese2012]) and Checking k-Inductive Invariants for GTS ([Dyck&Giese2017]) resp. Attributed GTS ([Schneider+2020])**

  Only state properties!

- **Model Checking Hybrid Systems**

  Only sequence properties for finite discrete state systems with rather bad scalability!

- **Model Checking Probabilistic GTS ([Krause&Giese2012])**
- **Probabilistic timed GTS: Model Checking ([Maximova+2018), Compositional Model Checking ([Maximova+2021])**

Only very restricted probabilistic sequence properties …

**BUT:** We have to assure resilience for complex sequence properties (even ensemble properties) of **hybrid probabilistic infinite state systems**.

# Outlook (3/5)



**Any approaches** supporting Service-Oriented Architecture, Self-Adaptive / Self-Organization, and Runtime Models with evolving structures and Training/Learning will face tough challenges:

- **Challenges:**
  - Models have to capture many characteristics (e.g., dynamic structure, hybrid) usually tackled using different paradigms
  - Even in case of strong **idealization** often relevant properties can not be analyzed
  - Analysis relies on the **validity/trustworthiness** of the models
    - Development-time models may become invalid over time
    - Runtime models for self-awareness may become invalid

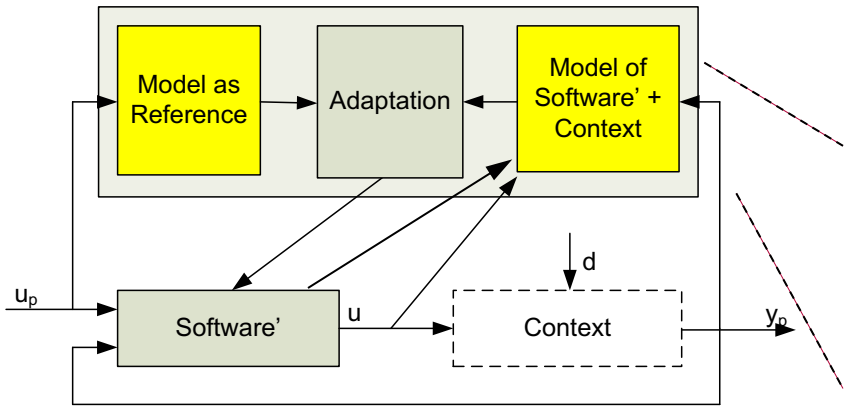
# Outlook (4/5)



Runtime models for self-awareness **may** become invalid

**Train/Learn goals**: adjust goals according to success w.r.t. higher level goals

**Train/Learn adaptation**: ...




**Learn also runtime model concepts** (unknown unknowns); runtime models evolve according to the perception of useful differences

**Learn runtime models** (known unknowns); parameters, elements, and relations of runtime models are **learned** according to the perception

**Train/Learn perception**: how to interpret observations

Correctness of the training/learning, is crucial if we have no **robust backup** and guarantees are required

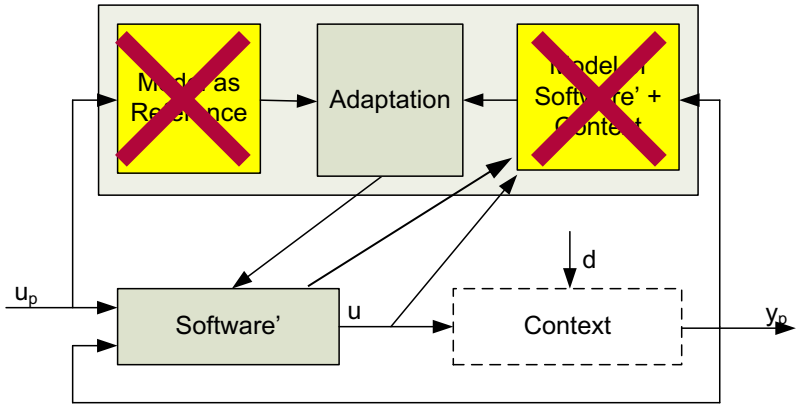
# Outlook (5/5)



Runtime models for self-awareness **may** become invalid

**BUT:** Development-time models **will** become invalid over time

**Static goals**:
no variation

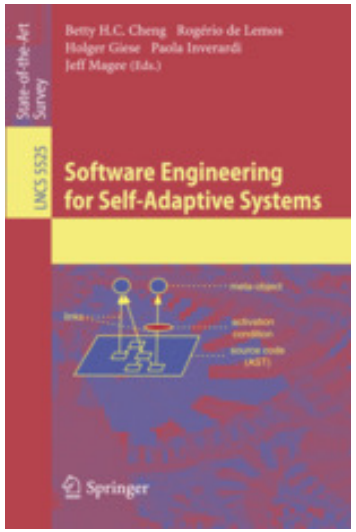


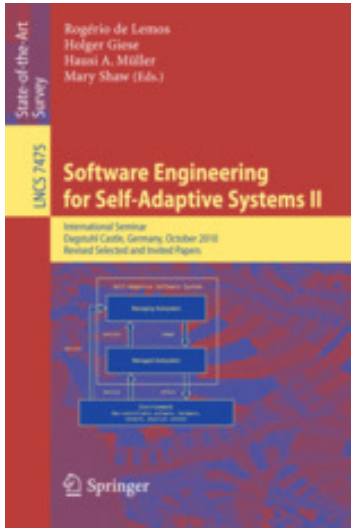

**No learning**: react to perceptions directly; avoid explicit model at run-time

Avoiding training/learning is also not safe (in the long run) if we do not have a **robust solution**!

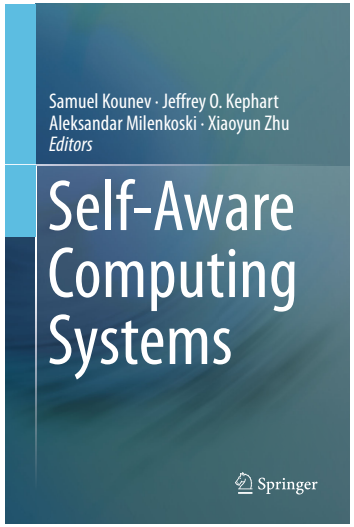
# Some Literature










**Books:**

- **Software Engineering for Self-Adaptive Systems**
- **Software Engineering for Self-Adaptive Systems II**
- **Software Engineering for Self-Adaptive Systems III. Assurances**
- **Self-Aware Computing Systems**

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