Interfaces in Evolving Cyber-Physical Systems of Systems (CPSoSs)

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Outline

- **Introduction and Objectives**
- Interface Layers
- Relied Upon Interface (RUI)
- Handling Evolution at RUIs
- Conclusion

Interfaces in CPSoSs

- Interfaces are points of interaction of CSs with
  - each other → direct interactions of CSs
  - with their common environment → indirect interactions of CSs
- Tackle CPSoS key challenges related to emergence, dynamicity, evolution, and dependability by
  - Identification of relevant interfaces
  - Proper specification and standardization of interfaces
  - Managed modification of interface specifications
- Interactions over interfaces time-sensitive in nature
  - Time plays an important role, also for appearance of desired or avoidance of undesired emergence
  - Availability of a sparse global timebase [see later in the course] to temporally coordinate interactions → time-aware SoS

Constituent System processing

- Computer system of CS processes Itoms
  - According to interface specification that determines all possible behaviors of CS
    - Internals of CS must deliver service defined in *interface specification*
    - Exact details of service implementation hidden/irrelevant
  - Itoms received
    - by sensors observing property of *physical state* in *entourage* of CS, or
    - Received by messages from cyber space
  - Itoms produced
    - Implemented as influences on properties of things in *entourage* of CS, or
    - Sent as *messages* to *cyber space*

CS implements time-aware computational element operating on Itoms that are exchanged with CS environment

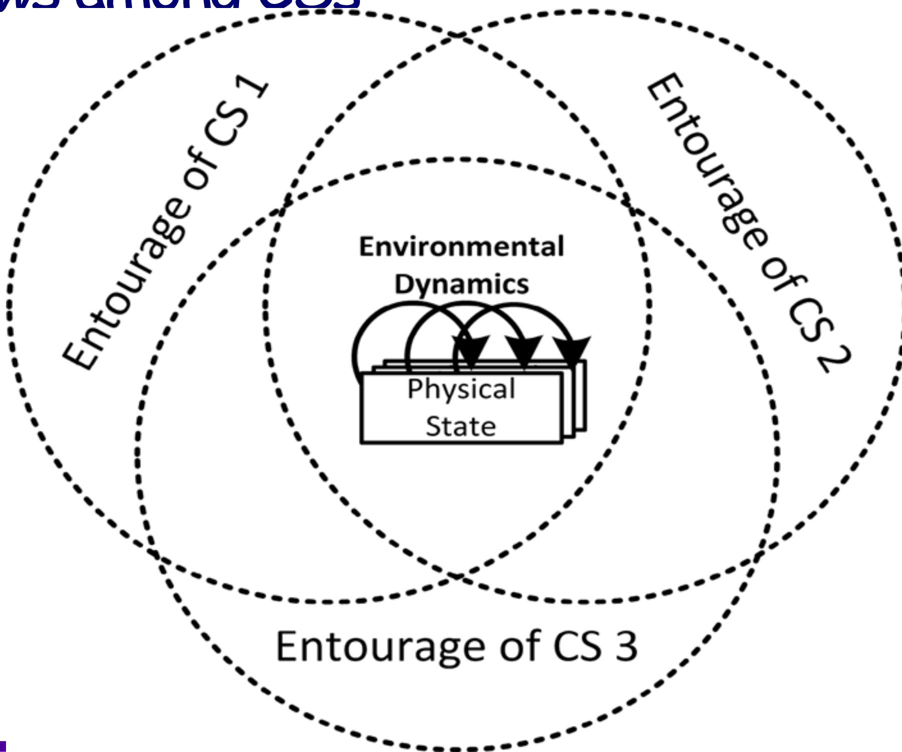
Environment
Physical Environment

- Physical environment consists of things and physical fields (energy)
- Properties of physical environment can be modeled as **dynamic network of physical state variables** described by **environmental model**
  - Captures interrelationships (e.g., transfer delays, functional dependencies, location) of *state variables*
  - Networked view allows for
    - Simple composition of *environmental models*
    - Consideration of different levels of modeling detail
    - Taking interfacing effects of CS actuators and sensors into account
  - Example: Ontology-based environmental model [Höf13]

- Environmental dynamics (time-sensitive autonomous processes) act on *physical state variables*
- Actuators allow CS to act on *physical state variables*
- Sensors allow CS to (partially) observe *physical state variables*

Concept of Overlapping Entourages of CSs

- In *physical environment* the concept of location/proximity essential, physical interactions often depend on distance → force fields
- *CS entourage* helps to limit size of involved *environmental models*
- Overlapping *entourages* of CSs allow for considering *stigmergic information flows* among CSs



Objectives

- Conceptualize time-sensitive interactions in CPSoSs
  - Introduce *interface layers* in order to manage *complexity* of cyber-physical interactions
  - Propose CS interface design to discuss relevant interaction properties
- Discuss *managed evolution* of CPSoSs
  - By applying proposed interface design

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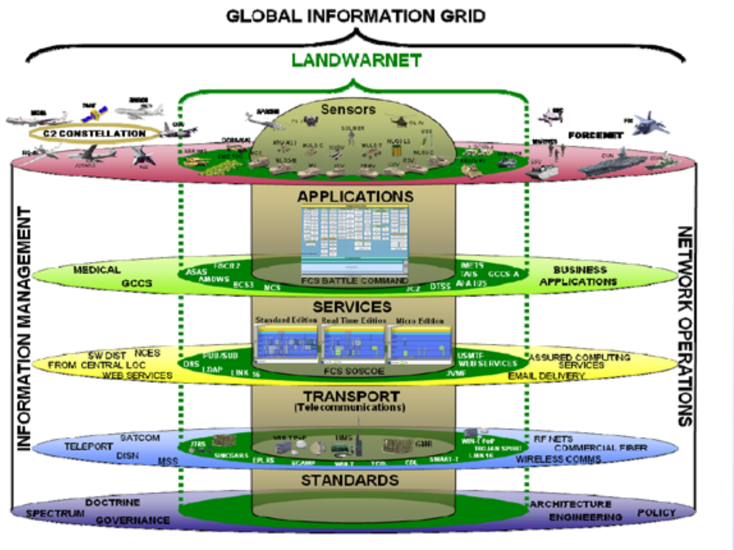
Interface Layers

- *Interface layers* enable discussion of *interface properties* and their definition in *interface specifications*
  - At different abstraction levels/modeling viewpoints
  - Example: Future Combat System Network, see figure on the right, https://en.wikipedia.org/wiki/FCS_Network



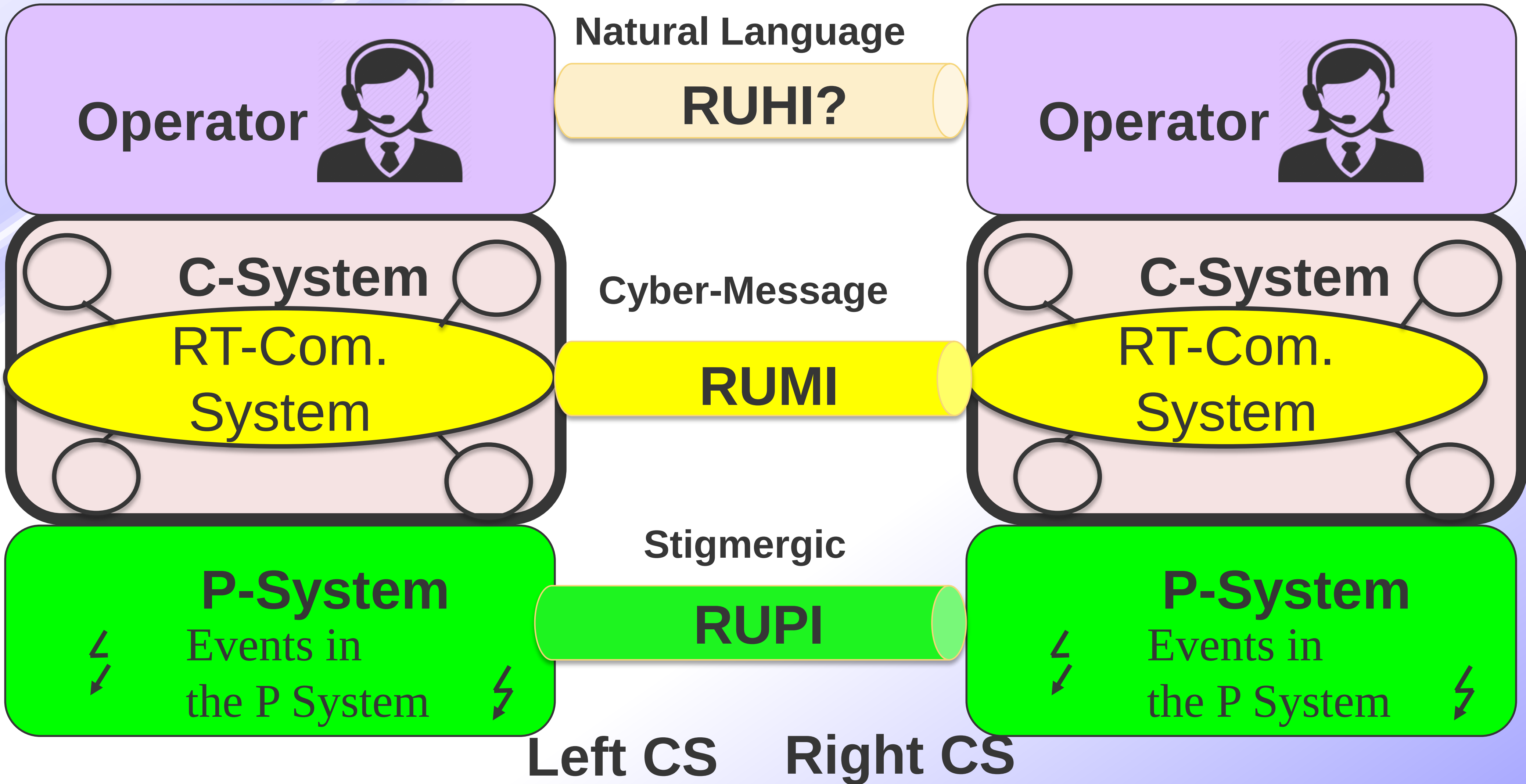
- Cyber-physical Interface Layer
  - Level of messages and things/energy
  - Interactions realized by concrete technology, and sensors/actuators
- Informational Interface Layer
  - Level of Itoms
  - Abstraction over cyber-physical interactions and associated context dependencies
  - Focus on *direct* and *indirect information flows*
- Service Interface Layer
  - Level of services, motivated by benefits of Service-oriented Architecture (SoA)
  - Abstraction over individual information channels
  - Useful for discussing and managing CPSoS dynamicity and evolution

Cyber-Physical Interface Layer

- Information represented by data items
  - Cyber space: a bit pattern
  - Physical environment: properties of things/energy
  - Too detailed for studying many interesting CPSoS properties (e.g., emergence, evolution, dynamicity)
- Data items are transferred among interacting CSs during Interval of Discourse (IoD) over time
  - All cyber interactions at lowest level realized by physical interactions

  → Time is elemental property of all interactions
- Interface properties at cyber-physical layer defined in Cyber-Physical Interface Specification (CP-Spec)
  - Interface Physical Specification (P-Spec)
  - Interface Message Specification (M-Spec)

Different Communication Channels



Physical Interfaces

- Realized by energy transforming interface devices
  - Sensor: take observations (time-stamped) from physical environment and produces bit pattern
  - Actuator: takes a bit pattern and timely s
    actions initiated from computer system in
    physical environment
  - Delay and jitter affects temporal accurac

- Formation of *basic Itoms*
  - Representation: bit pattern
  - Explanation: Design + placement of sensors/actuators determine semantics of in-/output bit pattern
- Physical Specification (P-Spec) describes properties of sensors/actuators
  - For example: sample rates, value/time uncertainties, observation granularity, …
  - P-Spec + environmental model allows description/simulation of *stigmergic channels*
    - Input side: formation of basic Itoms from sensor observations
    - Output side: how basic Itoms are implemented as influences on properties of things/energy by actuators

From Basic Itoms to Higher-level Itoms

- Raw data versus refined data
  - Often property of a thing (e.g., voltage level) encodes additional meaning (e.g., digital zero and one) to receivers
  - After *raw data* (measured value) has been properly abstracted to *refined data* the *raw data* becomes irrelevant
  - Refinement process takes place according to sender/receivers shared *conceptual context*
  - Multiple refinement levels possible
- Formation of Higher-level Itoms
  - Lower-level Itom (e.g., a basic Itom) transformed to Higher-level Itom by
    - Adding meta data from sender/receivers shared conceptual context
    - Removing unnecessary information (raw object
  - Example: speed limit sign at roadside which should be interpreted by an autonomous car
    - Camera sensor obtains large array of pixels (basic bitmap Itom)
    - Image classification
    - Contextualization
    - Speed limit Itom

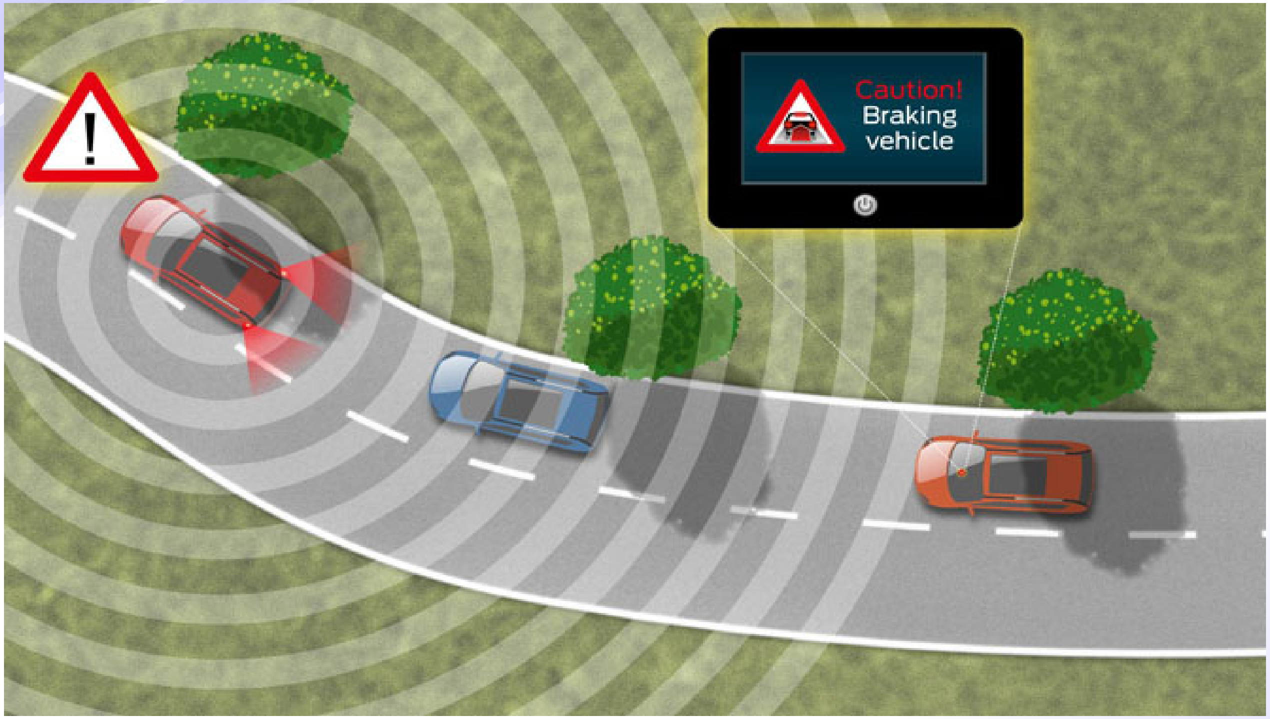
Message/Cyber Interfaces

- Cyber interfaces produce/consume messages according to M-Spec consisting of three parts
- Transport specification: all properties of message needed by involved communication system (cyber space)
  - Syntactic specification: defines named syntactic units called message variables
  - Semantic specification: links name of message variables to their explanation
- Cyber interface can be structured as ports (channel endpoints) where messages are placed for sending, or received messages read from
  - Port properties: direction, size, type, temporal properties, dependability properties
- Syntactic+Semantic specifications define Itom contained in message
- Different types of compatibility between cyber interfaces
  - Context compatibility: same data (bit pattern) is explained in same way at sender and receivers
  - Context Incompatibility: same data (bit pattern) is explained differently at sender and receivers
  - Syntactic Compatibility: syntactic chunks sent by sender re received by receivers without modification
  - Full Compatibility (Itom): Itom sent by sender is received by receivers without modification

Informational Interface Layer

- Informational layer concerns timely exchange of Itoms
- Valid abstraction over cyber-physical channels
  - Removal of details concerning concrete technology (protocols, sensors, actuators, …) that are irrelevant for describing information processing CSs
  - Context-independent information flows
  - Itoms explicitly specified and maximally refined
  - Valid abstraction demands that underlying cyber-physical channels must adhere to all constraints specified at informational layer (otherwise risk of *property mismatch* and *hidden channels*)
- Focus on direct and indirect information flows
  - Indirect information flows allow for
    - consolidated description of anonymous CSs
    - decentralized coordination [Val04]
    - description of cascading effects [Fis06]
- Itom channels specified in Interface Itom Specification (I-Spec) and characterized by
  - What kind of Itoms transported
  - Sender and receivers
  - Temporal and dependability properties

Example: Emergency Braking



- At informational layer: CS car notifies other cars about its sudden change of velocity to immediate stop by Itoms related to 'emergency brake'
- Possible implementations at cyber-physical layer
  - Stigmergic channel among braking car and cars behind
  - Stigmergic channel realized by brake light at sender and human operators of cars behind
  - Wireless car2car cyber channel

Direct vs. Indirect Communication

- Direct communication
  - Itoms transferred unidirectionally from one sender to one or more receiver CSs
  - Simple channel model (input, delay/jitter, output)
  - Behavior of interaction within interacting CSs
- Indirect communication
  - Itoms of sending CS affect state of common environment of interacting CSs
  - *Environmental dynamics* influence state as well
  - Receiving CSs can (partially) read state of common environment
  - Received Itoms reflect totality of all influences carried out on state in common environment
  - Senders and receivers need to share conceptual context such that receivers can form higher-level Itoms, i.e., access purpose/intention of senders
  - Indirect channel can be modeled by an Environmental Constituent System (ECS) that realizes common environment of interacting CSs

→ Not all systems involved in an interaction need to be modeled explicitly as long as their effects are considered as environmental dynamics

→ Indirect communication often closes causal feedback loops

Service Interface Layer

- System behavior structured as capabilities
  - Groups (sub)service/capability related Itom channels
  - Describes common characteristics and interrelationships of grouped Itom channels, i.e., interaction patterns
    Example: database service consisting of a request and a response Itom channel
  - CS in need of a service is matched to a service providing CS
- Service-oriented Architecture (SoA) principles
  - CS in need of capabilities (service consumers) + CS offering that capabilities (service providers) brought together by means of
    - Service registry: repository of interface service specifications (S-Specs)
    - Service discovery: process where service consumers match their requirements with service registry
    - Service composition: integration of multiple services into a new service
  - Immediate reduction of cognitive complexity
    - Necessary Itom channels can be (offline) instantiated by a scheduler/composition mechanism
    - Service composition/hierarchy of lower-level service to a higher-level service
      Example: service that provides humanoid robot capability to open doors consisting of several lower-level services
  - Loose coupling of CSs
    - Actual constituents of a service unimportant background details
    - Allows for self-organized SoS reconfiguration towards optimal usage of available resources

Service Interface Layer
Interface Service Specification (S-Spec)

- Set of quality metrics available to an independent observer to determine quality of provided service
- Service provider offers its capabilities under a Service Level Agreement (SLA)
- SLA is based on
  - Constraints of quality metrics codified in Service Level Objectives (SLOs)
  - Compensation actions in case SLOs are violated despite a committed service
- Service providers publish their SLA with reference to S-Spec of an offered service at service registry

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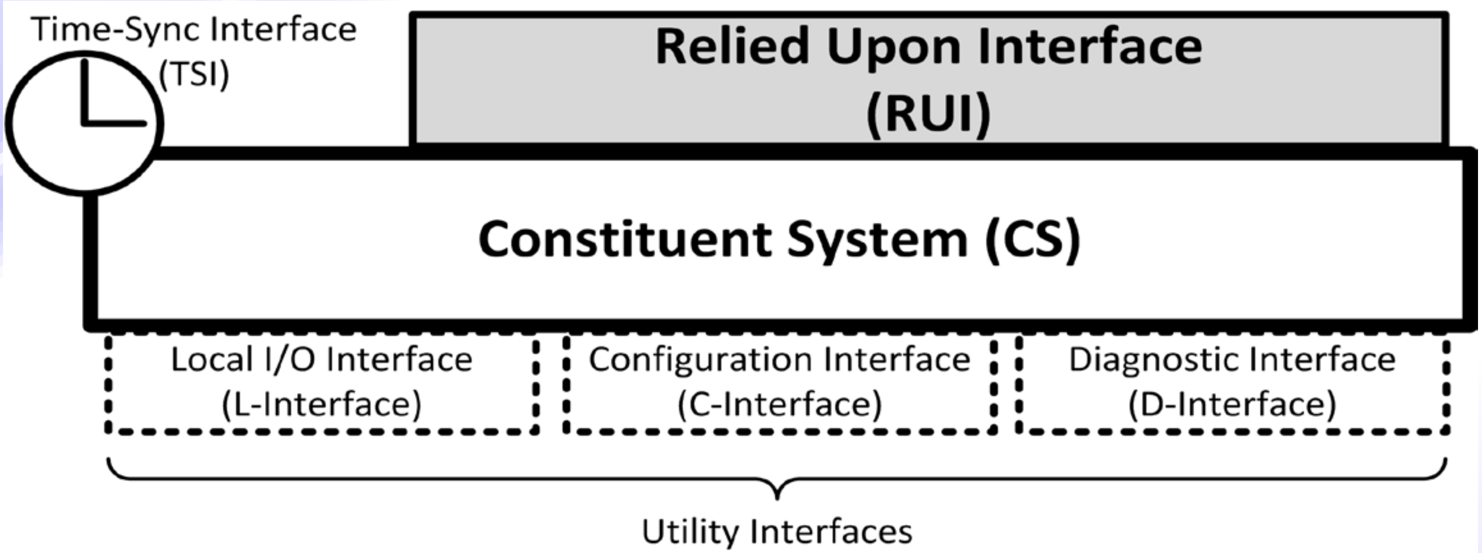
Interfaces of a Constituent System



- Time-Sync Interface: External sync. to realize sparse global timebase
- RUI: CPSoS as a whole relies on this interface of its CSs to provide emergent CPSoS service
- Utility Interfaces
  - Local I/O Interface for interaction with local environment of CS irrelevant to SoS service, e.g., Human Machine Interface (HMI)
  - Configuration Interface to update RUI specification (hardware, software upgrade) → management of CPSoS evolution
  - Diagnosis Interface for monitoring → management of CPSoS dynamicity

RUI Connecting Strategy

"RUI Connecting Strategy: Part of the interface specification of RUIs is the RUI connecting strategy which searches for desired, w.r.t. connections available, and compatible RUIs of other CSs and connects them until they either become undesirable, unavailable, or incompatible." [Ama16]

Example: In the Global Automated Teller Machine (ATM) network a cardholder together with smartcard-based payment card form a CS that is most of the time disconnected from other CSs. The RUI connecting strategy of the payment card CS is influenced by cardholder's need for cash (desire), nearby located and operational ATM terminals (availability), and whether the ATM terminal accepts the payment card (compatibility).

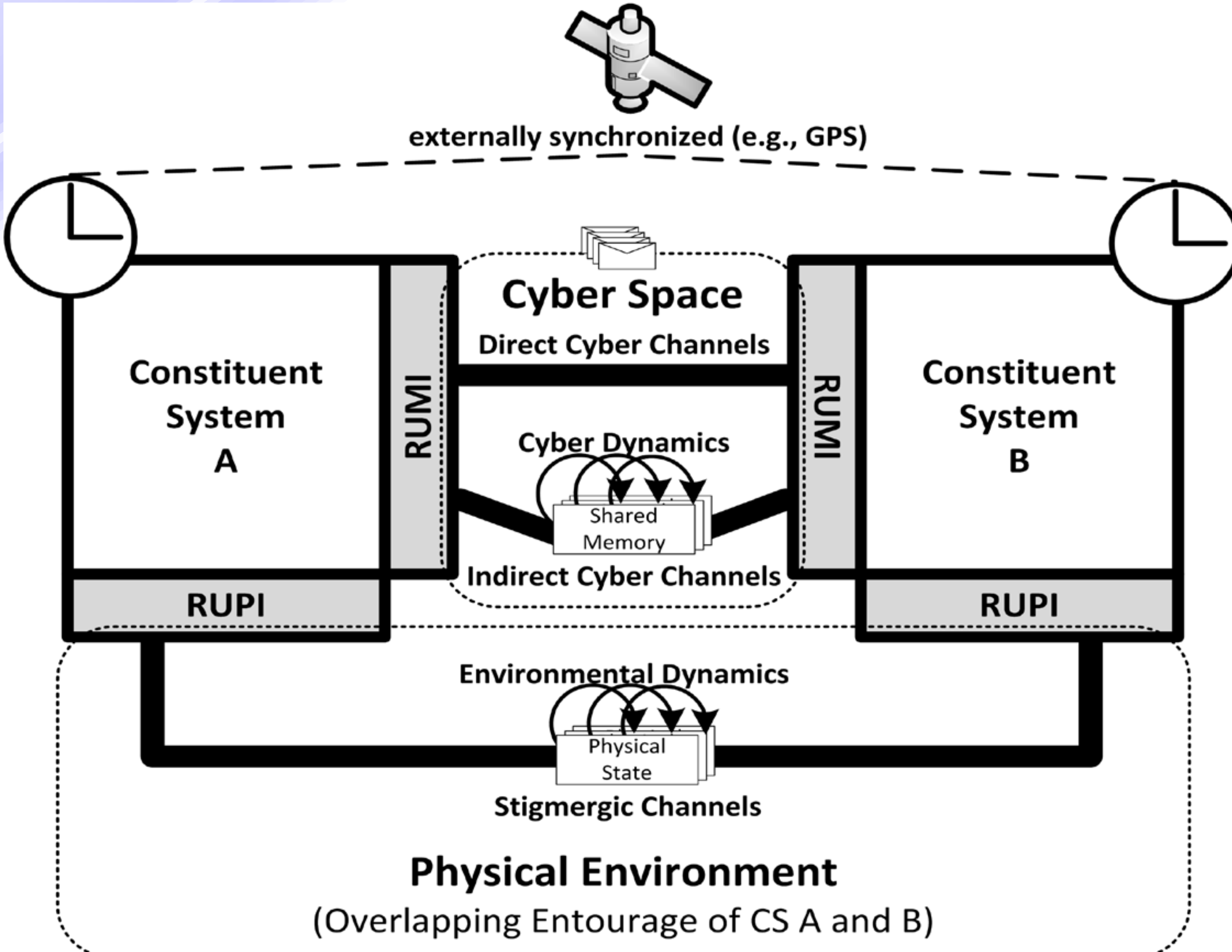
Roles of the Relied Upon Interface (RUI)

- System boundary: Structural decomposition of CPSoS into Constituent Systems (CSs) at RUIs
- Complexity firewall: RUI specification hides possibly complex behavior of CS from CPSoS and vice versa
- Information transfer: All for the entire CPSoS operation relevant interactions occur at RUIs
- Emergence: Identified purpose of CPSoSs is to realize emergent services which are located in CSs interactions at RUIs
- Dynamicity: Short-term changes (e.g., number of CSs varies, faults) need to be considered in RUI specification
- Evolution: Long-term changes (e.g., new emergent CPSoS services) affect how RUI specifications are updated

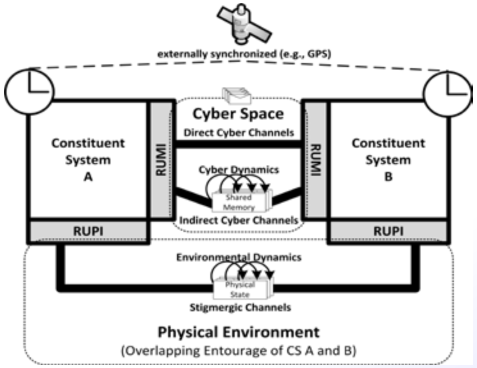
Interface Layers of RUIs

- Examination of RUIs at the introduced interface layers
  - Present RUI model at the different layers
  - Show how RUI interface layers are connected
- Focus on informational interface layer
  - Most suitable interface layer to study CPSoS properties concerning emergence, dynamicity and evolution
  - Propose a time-aware execution semantics of RUI model to study CPSoS properties

RUI at the Cyber-Physical Layer



RUI at the Cyber-Physical Layer



- Two CSs shown that have access to global timebase
  - Externally time-synchronized by e.g., GPS
- Introduce two RUI subinterfaces
  - Relied Upon Message Interface (RUMI)
    - Unidirectional transport of state & event messages by means of conventional direct cyber channels
      - State message only contains state observations (e.g., temperature of a room)
    - Indirect coordination with other CSs by means of indirect cyber channels
  - Relied Upon Physical Interface (RUPI)
    - Consists of interface devices: sensors and actuators
    - Interface devices act and observe entourage of CS
    - Overlapping entourage of CSs allow stigmergic channels/information flows
    - All interactions are indirect and over the common environment

RUI at the Informational Layer

- Unifies all physical and cyber interactions of cyber-physical layer by abstracting over
  - Concrete implementation technology (e.g., used sensors, actuators, message transport)
  - Informational context-sensitivity by using explicitly defined Itoms (object + meta data)
- Focus on direct and indirect information flows among CSs
  - Indirect channels modeled by instantiation of an additional Environmental CS (ECS)
- Informational layer useful for study of CPSoS properties during design and evolution
  - Emergence: informational layer captures all causal relations among CS interactions, allowing the analysis of emergence
    - Requires RUI specifications and associated interface models, and environmental model
    - In case of observed differences to cyber-physical layer (monitored actual interactions and actual occurrence of unpredicted emergence): possible presence of hidden channels
    - Hidden channel is latent information flow among CSs not considered in the models
  - Managed dynamicity: Investigate prompt CPSoS reactions to changes in environment
  - Managed evolution: Investigate how to steer CPSoS towards a desired evolutionary

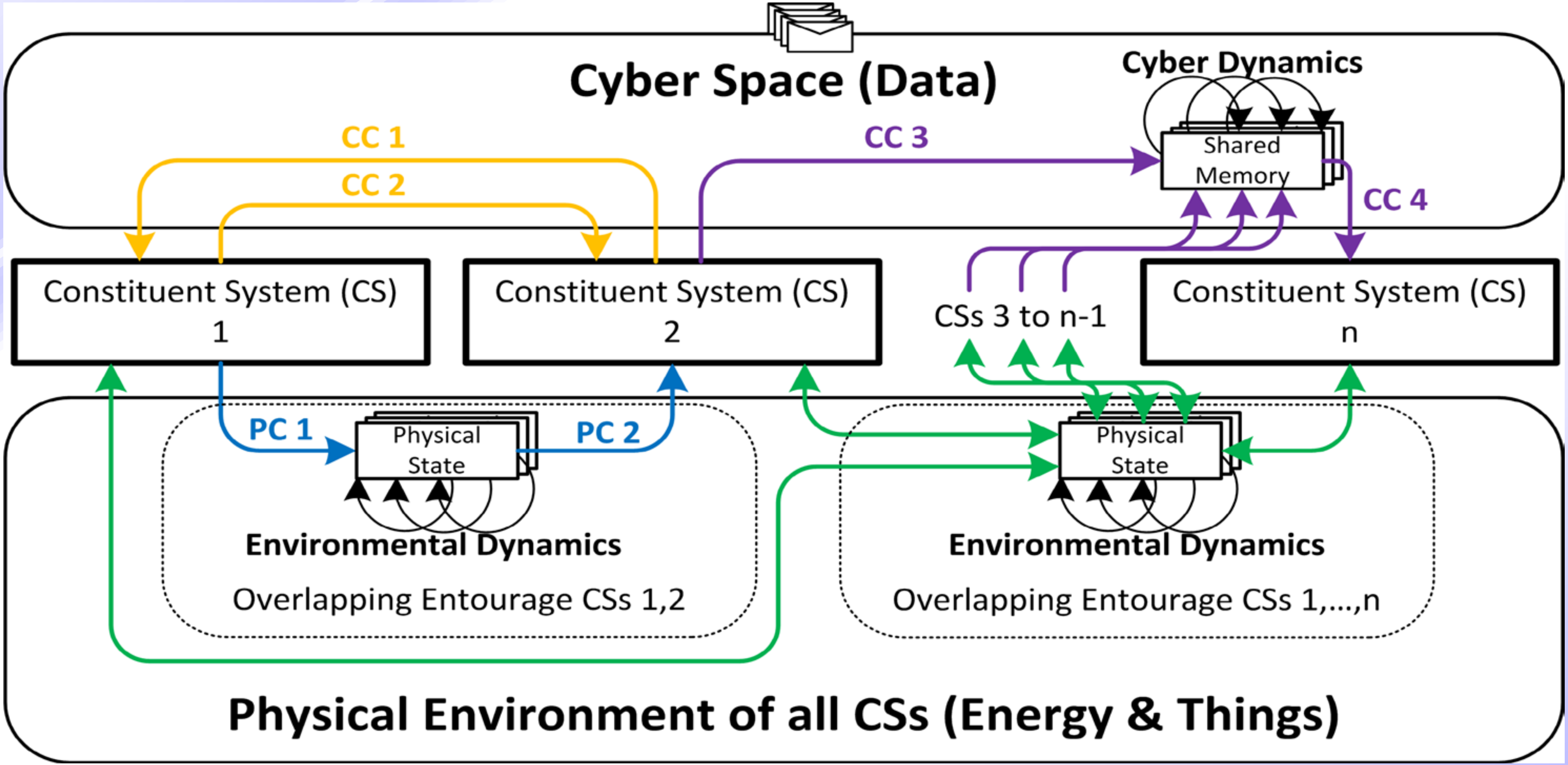
RUI at Service Layer

- Introduction of Relied Upon Service (RUS)
  - Provided at RUI of a CS
  - Described in service interface specification (S-Spec) as set of RUS-related operations
  - RUS operation is behavioral abstraction over one or more unidirectional Itom channels
    - Groups Itom channels together
    - Specifies interaction pattern, i.e., sequence of operation-related Itoms over all channel endpoints from perspective of RUS provider
      - Examples for interaction patterns: request-response, notify, solicit, …
- S-Spec + associated SLA published by RUS provider at service registry
  - Independent observer (in particular RUS consumer) can check whether Service Level Objectives (SLOs) are fulfilled
  - Service registry depending on business requirements of SoS can either be
    - Another CS (operated by an SoS authority) to allow RUS composition during CPSoS runtime, or
    - Realized in an off-line manner where RUS providers and consumers are matched during e.g., manufacturing
- Emergent CPSoS service modeled as set of dependencies of required RUSs
  - Required RUSs must be provided by a CS that wants to benefit from emergent CPSoS service
  - CS does not need to provide RUS directly, but can use composition of other RUSs provided by other CSs (see [Frö16, Section 4] for an example)

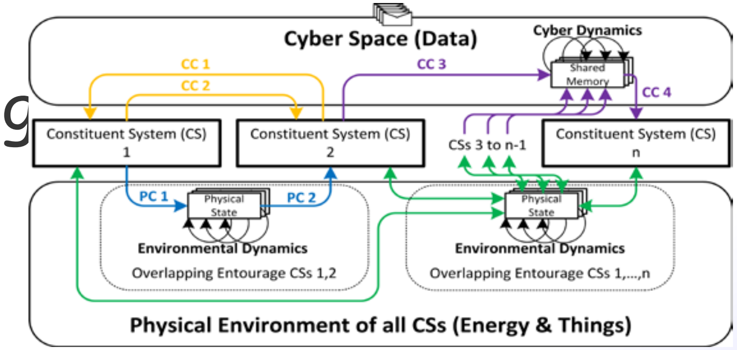
Connected RUS Interface Layers, Example

- Small artificial example of a CPSoS at all interface layers
- Demonstrated characteristics
  - Interacting n CSs
  - Direct cyber-channels
  - Indirect cyber-channels
  - Stigmergic channels
  - Visualized related cyber-physical channels, Itom channels, and service endpoints
    - Same color is used for related channels and service endpoints
    - Service endpoint is Itom port description from perspective of RUS provider

Connected RUS Interface Layers, Example Cyber-Physical Layer

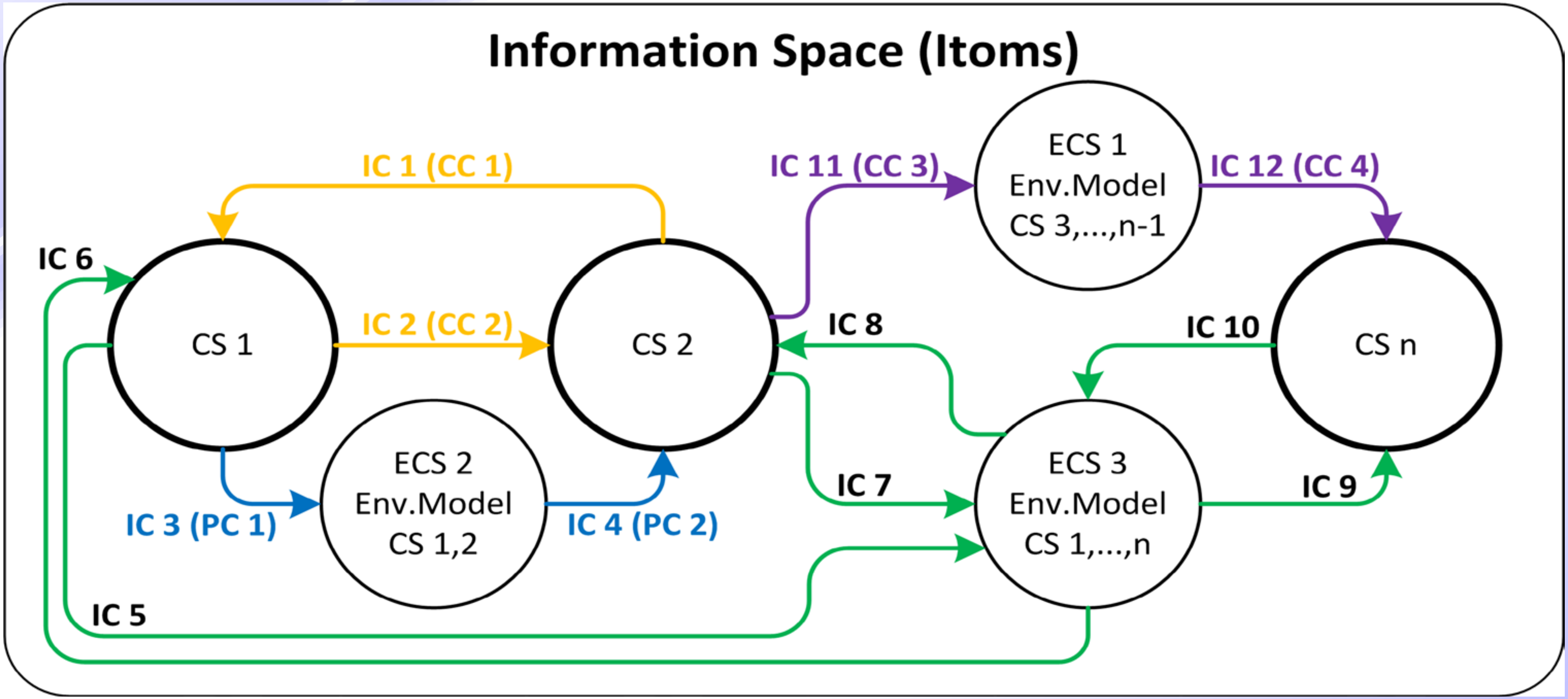


Connected RUS Interface Layers, Example Cyber-Physical Layer



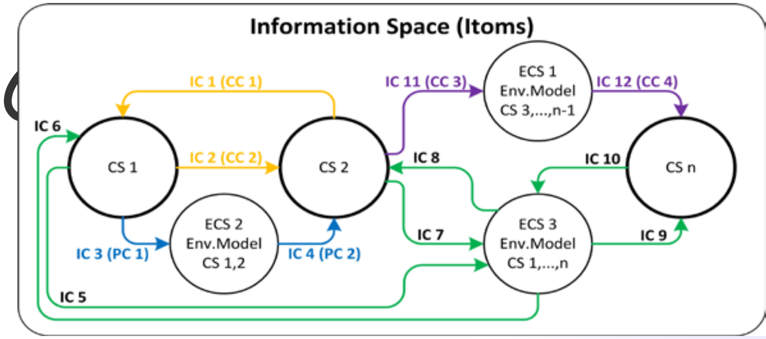
- Cyber-Physical interactions realized by some concrete technology
  - Example: TCP/IP stack, physical location of CS on street influenced by actuators
- Cyber Channels (CC) and Physical Channels (PC)
  - CC 1 and CC 2 are direct cyber channels of the same RUS Example: a database lookup service realized by request-response channels)
  - CC 3 and CCs originating from CS3 to n-1 are writers of an indirect channel, CS n is reader which observes shared memory via CC 4
    Example: writers publish whether an alarm occurred, CS n is alarm monitor
  - Stigmergic channel (green) where all CSs are able to influence physical state variables and also observe them
    Example: position of CSs on a street

Connected RUS Interface Layers, Example
Informational Layer



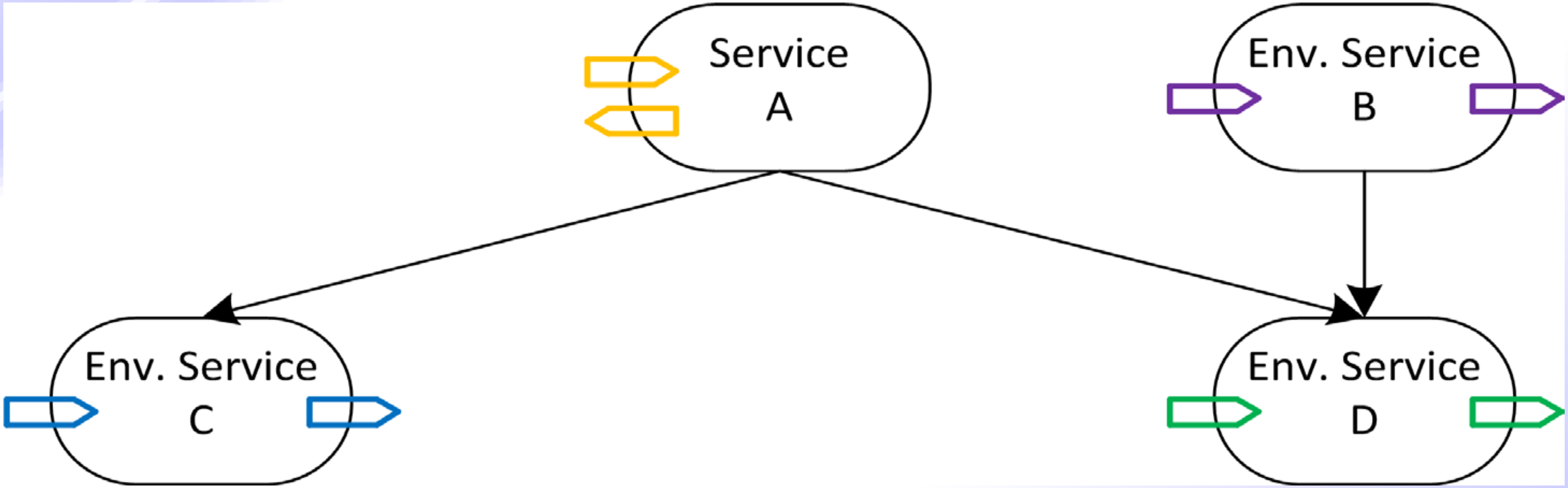
Connected RUS Interface Layers, Example Informational Layer

- All direct CCs have corresponding Itom Channel (IC
  - For example, IC 1 corresponds to CC 1

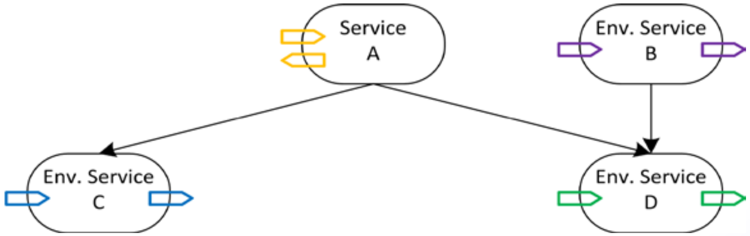


- Indirect CC is realized by additional Environmental CS (ECS)
  - ECS implements behavior of indirect CC described by environmental model (shared memory + cyber dynamics)
- For each stigmergic channel also an additional ECS is instantiated
  - ECSs described by environmental model (physical state variables + environmental dynamics)

Connected RUS Interface Layers, Example
Service Layer



Connected RUS Interface Layers, Example Service Layer



- 4 services in the shown dependency relation
  - Service A depends on Env. Services C and D
  - Env. Service B depends on Env. Service D
- Incoming and outgoing arrows on left of service vertex symbolizes Itom channel endpoints from perspective of service provider
  - Service A is, for example, a database lookup service provided by CS 2 and has one request input port and one response output port
    → Both are instantiated to Itom channels per service consumer
- 3 environmental services (B, C, D) provided by
  - ECS at informational layer, e.g., Env. Service D is provided by ECS 3
  - environment (cyber space or physical environment) at cyber-physical layer
- CSs that consume environmental services act either as influence/writer or observer/reader
  - Ports on left side of environmental services represent influence/writer service consumer
    Example: CS 1 is an influence/writer of ECS 2
  - Ports on the right side represent observer/reader service consumer
    Example: CS 2 is an observer/reader of ECS 2

Execution Semantics Informational RUI Model

- Interface model describes part of system behavior that is observable at interface
  - Interface specifications describes only interfacing properties regarding environment, but not behavior or CS environment itself

  →Need for an appropriate execution semantics
- Frame-based Synchronous Dataflow Model (FSDM)
  - Well defined semantics in value domain and temporal domain
    - Employed to model (for design and analysis) dependable, even safety-critical, distributed real-time systems, e.g., GIOTTO [Hen01], Lustre [Hal91]

FSDM is an appropriate execution semantics for studying behavioral properties of CPSoSs at informational layer

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Interfaces in Evolving Cyber-Physical Systems-of-Systems (CPSoSs)

- Evolution of CPSoSs concerns design modifications introduced into interacting CSs triggered by changes in environment
  - Advances in technology
  - Changes in societal or business needs
- Needs for change originating from
  - Wish towards increased efficiency
  - Introduction of new services
- Evolutionary changes to design and operation of CPSoS should
  - Counteract obsolescence to keep CPSoS relevant
  - Increase CPSoS *business value*
  - Not deteriorate already provided and still needed services
- In large systems like CPSoSs distinction between *unmanaged evolution* and *managed evolution* [Mur01]

Local and Global Evolution

- Local Evolution concerns changes within CS not affecting RUI
  - No modification of RUI specification
  - Important to optimize CS internals
  - Allows preparation of a global *evolutionary step*
  - Harbors risk of introducing hidden channels, i.e., unconsidered interactions, among CSs which could lead to emergent effects
  - Strict adherence to RUI specification required which forbids any undefined interactions
- Global Evolution affects interactions of CSs
  - Change of RUI specification and how changes come into effect
  - To support continuous evolution, changes to CPSoS carried out in evolutionary steps of limited scope with preferably predictable effects
  - Global evolution can be seen as a tree-like search towards adaptation to environmental changes, similar to Darwin and natural selection in biological evolution

Management of RUI Specifications

- Authorized Relied Upon Services (RUS) specifications (S-Specs) are administrated at service registry
- Only SoS authority can authorize and publish S-Specs
  - CS owner can participate in CPSoS by offering a RUS compliant to authorized S-Spec
- Service registry supports *version management*, i.e., multiple versions of a RUS can coexist
  - CS owners specify in the Service Level Agreement (SLA) to which version of S-Spec they refer to
  - Every supported S-Spec version has its own SLA

Conclusion

- Discussed time-aware CPSoSs for purpose to investigate behavioral properties of CPSoSs
  - Characterized relevant architectural elements of CPSoSs
  - Introduced three interface layers: cyber-physical layer, informational layer, service layer
  - Identified and discussed the Relied Upon Interface (RUI) of CSs as fundamental interface responsible for operational behavior of CPSoSs and managing CPSoS evolution
- Presented RUI model at introduced interface layers
  - Example how interface layers are connected
- Discussed CPSoS evolution and how to manage it by controlled modifications of RUI specifications

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