Software Architecture in the Era of Collective Intelligence: The Rise of Systems-of-Systems

Flavio Oquendo
flavio.oquendo@irisa.fr
http://people.irisa.fr/Flavio.Oquendo/

About me

M.Sc., Ph.D., and H.D.R. from Univ. of Grenoble, France

B.Eng. from ITA, São José dos Campos, SP, Brazil

Assistant/Associate Professor University of Grenoble, France

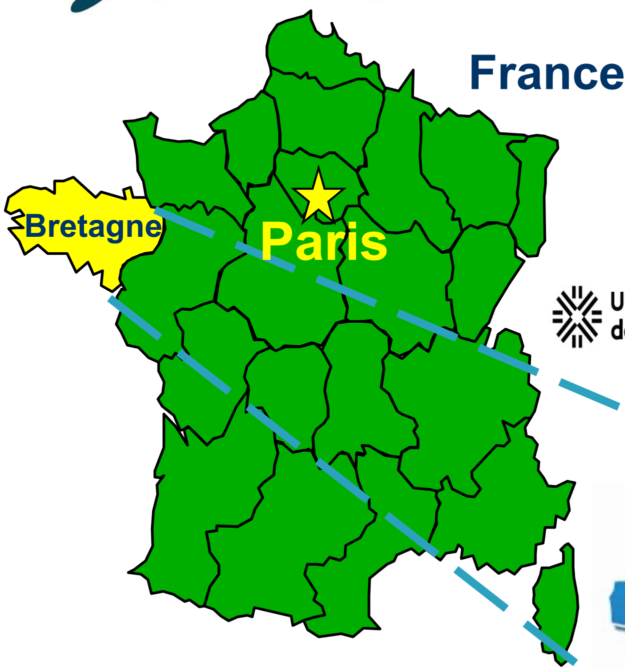
Full Professor from 1995 to 2005 at the University of Savoy, and since 2005 at the University of South Brittany, France

R&D Engineer at G.I.E. Emeraude [R&D group on advanced Software Engineering created by BULL, THALES IS, AT&T Europe], Paris, France

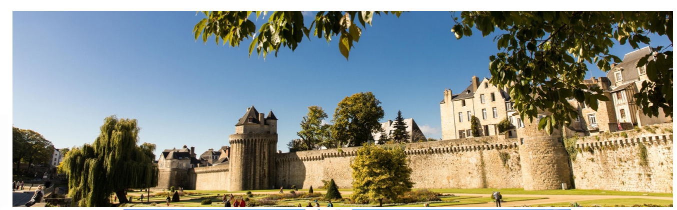
Research Direction on Software Architecture / Distinguished Full Professor (Professeur des universités de classe exceptionnelle)

About us

IRISA – The Computer Science Research Institute of Brittany, France



850 Research Staff
- 350 Research Academics
- 350 PhD Students & Post-docs
- 100 Supporting Staff



http://www.irisa.fr/en

Outline

I. Key notions and problematics of architecting Software-intensive Systems-of-systems (SoS)

II. Proposed solution for architecting SoS raising Collective Intelligence (CI)

III. Enhancing the proposed solution for raising Collective Intelligence under Uncertainty

IV. Summing up and takeaway message

I. Key Notions and Problematics of architecting Software-intensive Systems-of-systems (SoS)

1. What are Software-intensive Systems-of-Systems (SoS)

1.1a The advent of Software-intensive Systems-of-Systems: From Single Systems (SiS) to Systems-of-Systems (SoS)

- The past and present of Software-intensive Systems
  - They were stand-alone single systems in the past
  - They are often part of connected and automated systems in the present

- Systems (with no software)

- Systems (assisted by software)

Advanced driver-assistance systems

- Systems (automated by software)

Automated driving systems

- Connected systems

Connected and automated driving systems

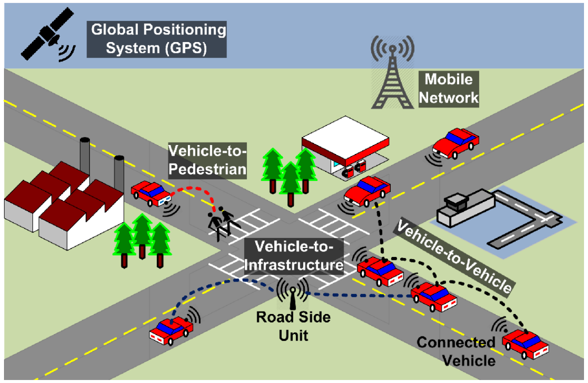
1.1b The advent of Software-intensive Systems-of-Systems: From Single Systems (SiS) to Systems-of-Systems (SoS)

- The upcoming future of Software-intensive Systems
  - They are increasingly becoming systems of systems in the upcoming future
    - A system whose constituents are systems and which are developed to achieve missions not possible by a constituent system alone
      - e.g. Vehicle platooning

Source: https://theconversation.com/coming-soon-to-a-highway-near-you-truck-platooning-87748

1.2a What is a Software-intensive System-of-Systems (SoS)

- A System-of-Systems (SoS) is a system that delivers unique capabilities formed by integrating independent useful systems [ISO/IEC/IEEE 24765:2010]
  - In its more evolved form, it can be perceived as a complex system in which its constituents, i.e. themselves systems, are possibly discovered, selected, and composed at run-time to fulfill a specific mission
- Note that constituent systems fulfill valid purposes in their own right and continue to operate to fulfill those purposes if disassembled from the encompassing SoS
  - They are managed, in part, for their own purposes rather than the purposes of the whole



What are Software-intensive Systems-of-Systems

1.2b Defining Characteristics of Systems-of-Systems (SoS)

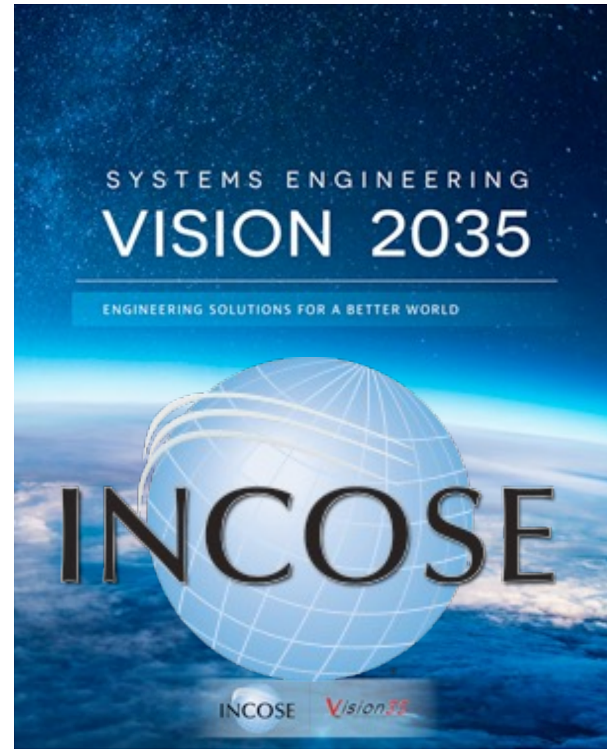
- Characteristics of SoS constituents
  1. Operational independence
  2. Managerial independence
  3. Geographical distribution

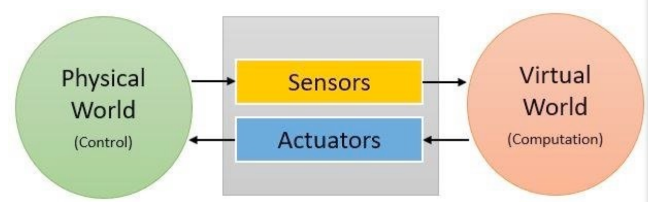
- Characteristics of an SoS as a whole
  4. Evolutionary development
  5. Emergent behavior

- Characteristics of SoS operational environments
  - Uncertainty
- SoS by its very nature has characteristics that are hard to address, in particular, emergent behavior

1.3 The Importance of Architecting Software-intensive Systems-of-Systems (SoS)

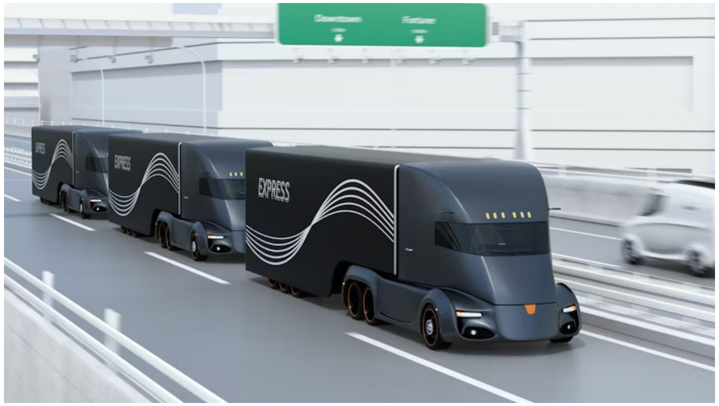
- **Architecting Software-intensive Systems-of-Systems has been identified as a major issue in the upcoming years**
  - **Systems Engineering Vision 2035 by the International Council on Systems Engineering (INCOSE)**
  - **Today, SoS architecting practices are often ad-hoc and do not effectively integrate required architectural concerns**
  - **By 2035, SoS architecting practices shall enable to master the complexity of SoS architectural design and evolutionary development, achieving open and resilient SoS**





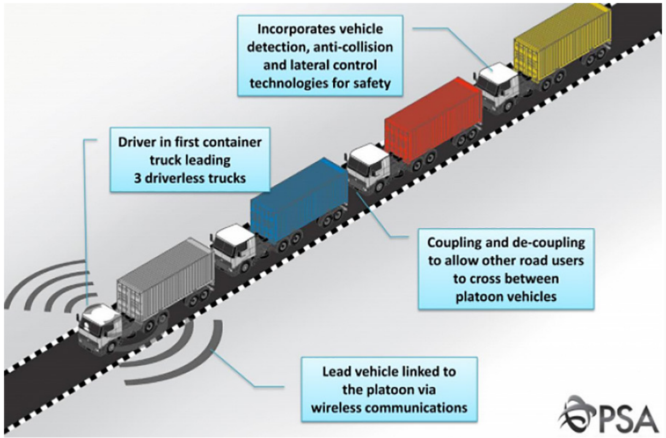
1.4a Setting the Motivation on Systems-of-Systems from the Software Architecture Perspective

- As stated, our lives and livelihoods increasingly depend on Software-intensive Systems-of-Systems
  - Systems-of-Systems being by definition complex systems, they need to be architected before engineered
    - Complexity poses the need for separation of concerns between architecture and engineering
- Remember that:
  - Architecture: focus on reasoning about interactions of parts and their emergent properties
  - Engineering: focus on designing and building the specified architecture



What are Software-intensive Systems-of-Systems

1.4b Setting the Motivation on Systems-of-Systems from the Software Architecture Perspective



Source: https://www.globalpsa.com/psa-to-start-truck-platooning-trials-in-singapore/

- How would you (as an architect) describe the architecture of a software-intensive system-of-systems such as the one of the vehicle platoon presented in this video? (from a technology-independent viewpoint)

2. What is Collective Intelligence (CI)

2.1 Artificial Intelligence: Individual vs Collective Intelligence

- There are different forms of Artificial Intelligence

- Artificial 'Individual' Intelligence in Single Systems
  - It is the notion of embedding AI-enabled capabilities in an individual system, e.g. an autonomous drone
- Artificial 'Collective' Intelligence in Systems-of-Systems (a.k.a. Swarm Intelligence)
  - It is the notion that a group of "single" systems operating in concert can operate as a collective intelligence with superior capabilities to any of the individual systems, e.g. satellite constellations

Source: https://scitechdaily.com/swarm-intelligence-in-space-nasas-starling-cubesats-ready-to-test-critical-technology/

2.2a The Notion of Collective Intelligence (CI)

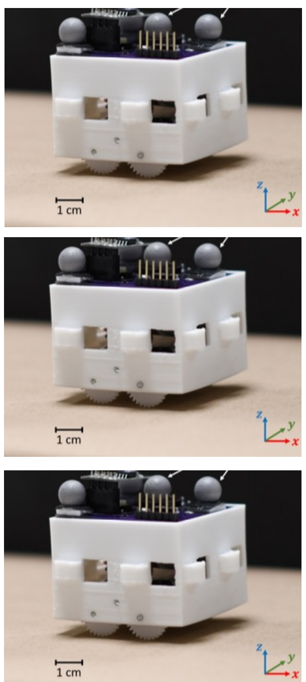
- **Collective Intelligence (CI) refers to the intelligence that emerges at the macro-level of a heterogeneous or homogenous collection of individuals and transcends that of the individuals**
  - **Collective intelligence is a kind of emergent property in which the interactions of single systems acting together produce an overall capability that exceeds that of the individuals**
  - **In SoS, its main purpose is for coordination, cooperation, and collaboration, rather than cognition**

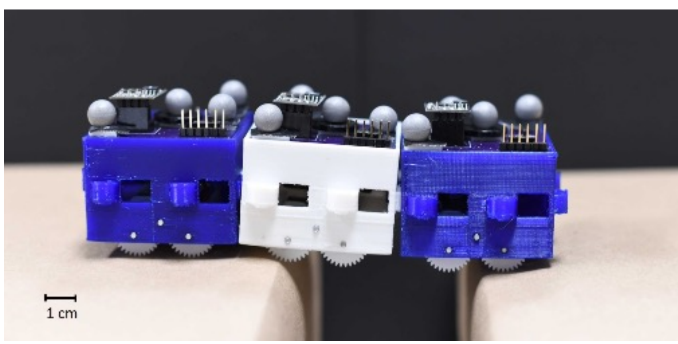
Collective Intelligence

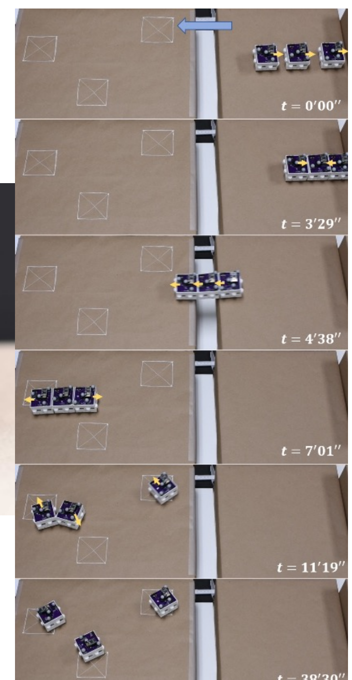
Cognition	Coordination	Cooperation	Collaboration

2.2b The Notion of Collective Intelligence (CI)

- In Software-intensive Systems-of-Systems, **Collective Intelligence is the result of emergent behavior, in general based on self-organization**
  - What is **Emergence** and in particular emergent behavior?
  - What is **Self-Organization** and how it supports emergent behavior?







Collective Intelligence

↑ raises

Emergence

↑ supports

Self-Organization

2.3a The Notion of Emergent Behavior

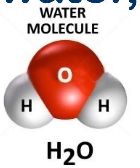
- What is exactly an Emergent Behavior
  - An emergent behavior is a global behavior that arises out of the interactions between parts of a whole and which cannot be predicted or extrapolated from the behavior of the individual parts
  - Stated simply: “The behavior of the whole is more (other) than the sum of the behaviors of its parts”
  - It arrives mostly in collective behaviors of groups of elementary constituent systems
  - Emergent behavior produces Collective Intelligence

What is Collective Intelligence: Emergence

2.3b The Theory of Emergence

- Emergence is a phenomenon occurring in Physics, in Chemistry, in Biology, in Sociology, in Engineering ...
- The nature of the relation between the whole and its parts (term coined by George Henry Lewes, 1875)

  - Aggregation: properties of a whole that can be calculated knowing its parts, e.g. the weight of a table given its parts
  - Emergence: properties of a whole that cannot be calculated knowing the parts of the whole, e.g. it is not possible to predict the properties of water, knowing the properties of the atoms of hydrogen and oxygen



    - studied since at least the time of Aristotle, 384 BC-322 BC
- The meaning of emergence is of ‘unexpected’ properties that arise out of more fundamental properties and yet are ‘irreducible’ with respect to them

  - In contrast, aggregative properties are always reducible to its fundamental entities, e.g. weight, spatial position and speed in physics

2.4a The Notion of Self-Organization

- Self-organization is a phenomenon occurring in Physics, in Chemistry, in Biology, in Sociology, in Engineering …
- What is exactly Self-Organization?
  - Self-organization is a pattern formation behavior that arises when some form of overall order emerges from local interactions between parts of an initially disordered system
- Examples of Self-Organization
  - Flock of drones
  - Swarm of robots

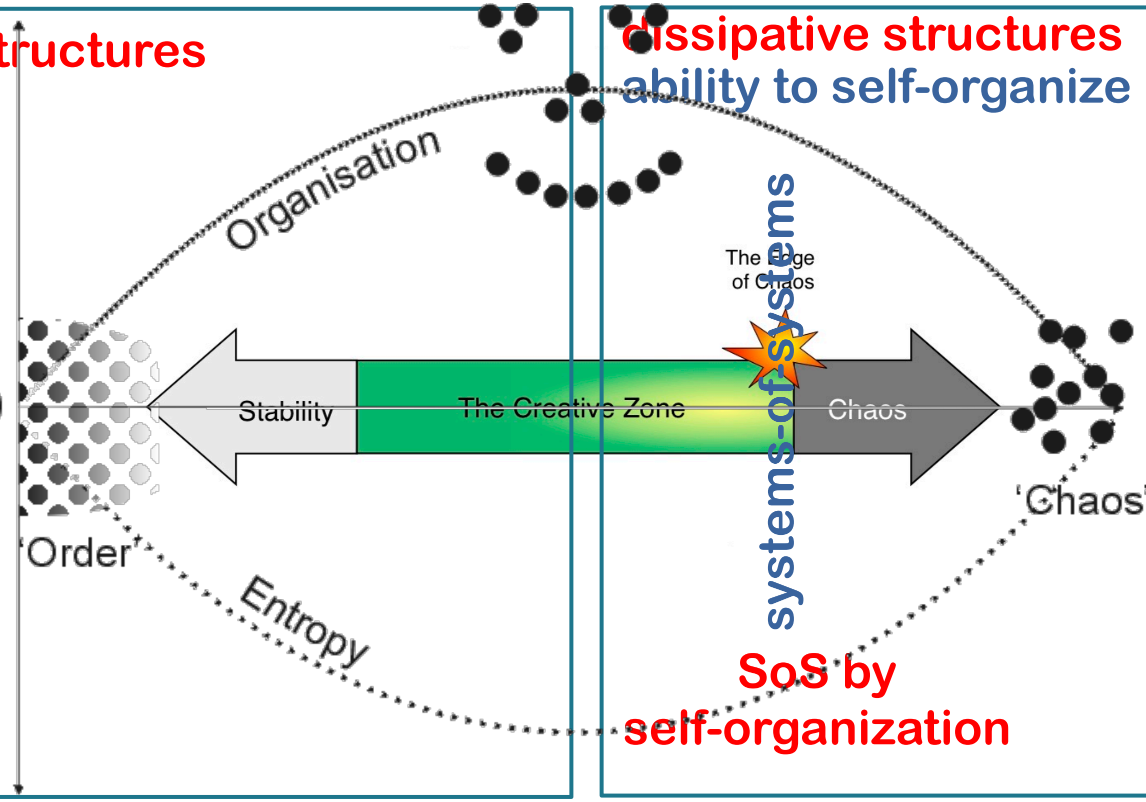
2.4b The Theory of Self-Organization

- The General Theory of Self-Organization
  - By Ilya Prigogine (Nobel Laureate in Chemistry, 1977)
  - Self-organization is spontaneous in dissipative structures

equilibrium structures

dissipative structures
ability to self-organize

a monolithic system

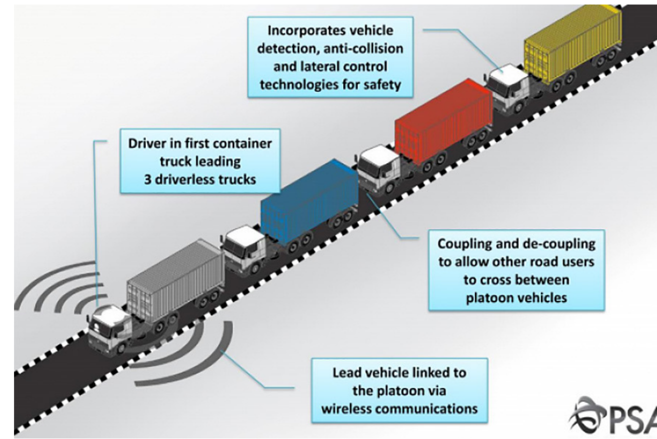


systems-of-systems

all independent systems

SoS by
self-organization

2.5b Refining the Motivation on Collective Intelligence from the Software Architecture Perspective



Source: https://www.globalpsa.com/psa-to-start-truck-platooning-trials-in-singapore/

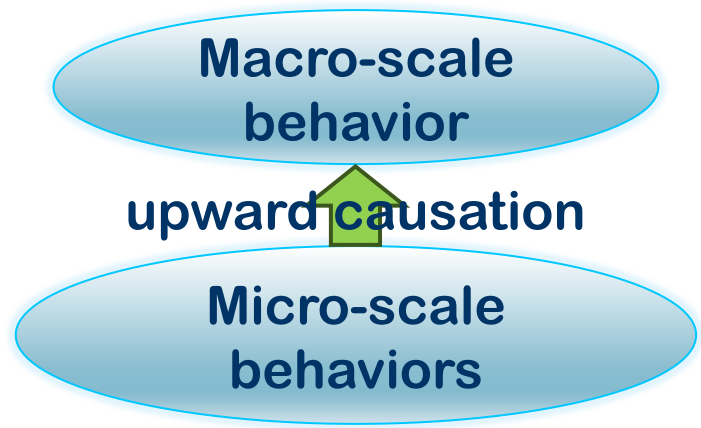
- Collective Intelligence is the result of emergence, in general based on self-organization
- How would you (as an architect) describe the architecture of a vehicle platoon in a way that enables raising the collective intelligence of platooning? (from a technology-independent viewpoint)
  - Relying on emergence and self-organization

II. Proposed solution for architecting Software-intensive Systems-of-systems (SoS) raising Collective Intelligence (CI)

3. How to achieve Collective Intelligence through Emergence and Self-Organization in Software-intensive Systems-of-Systems (SoS)

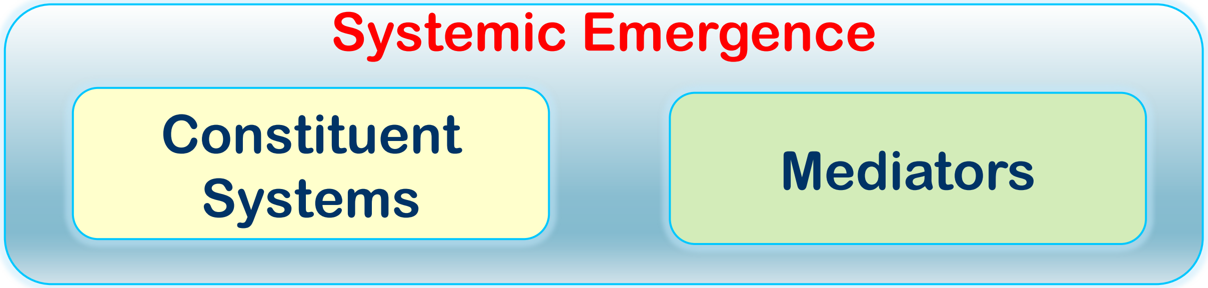
3.1 Architecting Emergence in SoS

- Question: How to describe an SoS architecture in terms of interacting constituents for enabling emergence?
- Proposed approach: Supervenience
  - Supervenience is the trans-ordinal relation that is used to describe emergence where the macro-scale properties are determined by its micro-scale properties, i.e. the emergent macro-properties supervene on the micro-properties
  - To describe emergent behavior in an SoS architecture, we need to define micro-scale behaviors that by supervenience (upward causation) will form the required macro-scale emergent behavior
  - The proposed approach supports systemic emergence



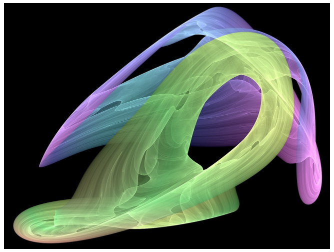
3.2 Architecting Systemic Emergence in SoS through Mediators

- Systemic emergence in complex systems is a systemic emergent property that arises from the interaction of constituents, among themselves as well as with their operational environment
- The proposed approach to support systemic emergence in SoS relies on the development of mediators among constituent systems
- The SoS has total control over mediators
  - Mediators are created, may evolve or may be discarded at run-time
  - Mediators are only known by the SoS: they provide duties for constituent systems
  - Mediators may enable communication, coordination, cooperation, and collaboration



3.3 Supporting Self-Organization with Concurrent Constraints

- Question: How to describe self-organized SoS architectures for supporting systemic emergence?
- Based on the General Theory of Self-Organization, SoS are perceived as complex systems far from equilibrium when compared to single systems that are essentially systems near equilibrium
  - To reach a valid SoS architecture, it is necessary to reach an "attractor"
    - An "attractor" is a set of states toward which a system tends to evolves
  - To reach an "attractor" it is needed to tie or relax constraints in dissipative structures, until the "attractor" is achieved
- Proposed approach for self-organization is based on:
  - The mechanism of concurrent constraints: To tell or untell constraints to make the order of the SoS constituents vary for reaching a target attractor
  - The architectural concept of mediator: mediators permit to tie or relax behaviors of constituent systems through concurrent constraints, managing the degree of freedom of these constituent systems



4. How to architecturally enforce Supervenience based on Concurrent Constraints in Software-intensive Systems-of-Systems (SoS)

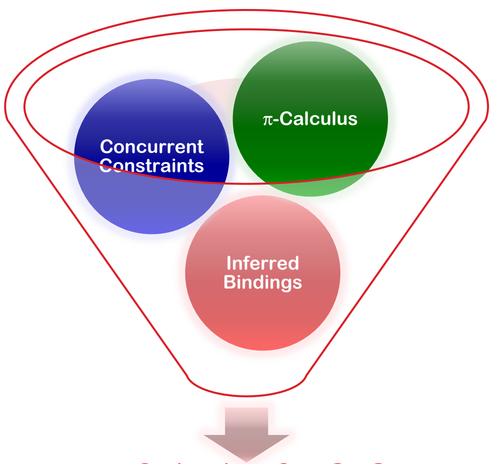
4.1 Defining a novel ADL for SoS based on the conceived Architectural Emergentist Framework

- SosADL: novel ADL for SoS
- SoS architecture description from different viewpoints:
  - Structure
  - Behavior
    - Including systemic emergence via supervenience
  - Self-organization is obtained by constraining structure and behavior in supervenience

- SoS architecture description in terms of:
  - Constituent systems
    - locus of operational capabilities for enabling functionalities
  - Mediators
    - locus of interaction capabilities for enabling emergent behavior
  - Coalition
    - composition of constituent systems coordinated by mediators for fulling specified missions
      - driven by specified constraints

4.2a Defining a Novel Formal Foundation for SosADL based on Process Algebra

- **The formal definition of SosADL is grounded in the π-Calculus for SoS**
  - **π-Calculus for SoS generalizes the π-Calculus with the notion of concurrent behaviors with concurrent constraints**



π-Calculus for SoS

Oquendo, F.: "The π-Calculus for SoS: Novel π-Calculus for the Formal Modeling of Software-intensive Systems-of-Systems", Proc. of 38th International Conference on Communicating Process Architectures 2016 (CPA), Copenhagen, DK, August 2016

Abstract syntax of behaviors

constrainedBehavior ::= behavior$_1$
  | valuing$_1$ **.** constrainedBehavior$_1$
  | **behavior** name$_1$ **is {** behavior$_1$ **}**
  | **constraint** name$_1$ **is {** constraint$_1$ **}**
  | **compose {** constrainedBehavior$_0$ … **and** constrainedBehavior$_n$ **}**
behavior ::= baseBehavior$_1$
  | valuing$_1$ **.** behavior$_1$
  | **repeat {** behavior$_1$ **}**
  | **apply** name$_1$ **(** value$_0$ …, value$_n$ **)**
  | **compose {** behavior$_0$ … **and** behavior$_n$ **}**
baseBehavior ::= action$_1$ **.** behavior$_1$
  | **choose {** action$_0$ **.** baseBehavior$_0$
  or action$_1$ **.** baseBehavior$_1$ … **or** action$_n$ **.** baseBehavior$_n$ **}**
  | **if** constraint$_1$ **then {** baseBehavior$_1$ **} else {** baseBehavior$_2$ **}**
  | **done**
action ::= baseAction$_1$
  | **tell** constraint$_1$
  | **untell** constraint$_1$
  | **check** constraint$_1$
  | **ask** constraint$_1$
baseAction ::= **via** connection$_1$ **send** value$_0$
  | **via** connection$_1$ **receive** name$_0$ **:** type$_0$
  | **do** internalAction$_1$
  | **unobservable**
connection ::= name$_1$ | name$_1$…::name$_n$
valuing ::= **value** name$_1$ **is** type$_1$ **=** value$_0$ | typing
typing ::= **datatype** name$_1$ **is** type$_0$ **{** function$_0$ … **and** function$_n$ **}**

4.2b Defining a Novel Formal Foundation for SosADL based on Process Algebra

Actions:

- **tell** constraint to local environment
- **untell** constraint from local environment
- **check** if constraint is consistent with local environment
- **ask** if constraint can be entailed from local environment
- **send** value via connection
- **receive** value via connection
- **unobservable** internal actions

Transition rule:

$$\frac{P_1 \xrightarrow{\alpha_1} P_1' \; \ldots \; P_n \xrightarrow{\alpha_n} P_n'}{C \xrightarrow{\alpha} C'}$$

where *side conditions*

Formal semantics of π-Calculus for SoS: labeled transition rules for actions

Output:

$$\frac{}{\textbf{compose}\left\{\begin{array}{l}\text{constraint}_{0..n}\\ \textbf{and}\ (\textbf{via}\ \text{connection}_1\ \textbf{send}\ \text{value}_1.\text{behavior}_1)\end{array}\right\} \xrightarrow{\textbf{via}\ \text{connection}_1\ \textbf{send}\ \text{value}_1} \textbf{compose}\{\text{constraint}_{0..n}\ \textbf{and}\ \text{behavior}_1\}}$$

Input:

$$\frac{}{\textbf{compose}\left\{\begin{array}{l}\text{constraint}_{0..n}\\ \textbf{and}\ (\textbf{via}\ \text{connection}_1\ \textbf{receive}\ \text{value}.\text{behavior}_1)\end{array}\right\} \xrightarrow{\textbf{via}\ \text{connection}_1\ \textbf{receive}\ \text{value}_1} \textbf{compose}\left\{\begin{array}{l}\text{constraint}_{0..n}\\ \textbf{and}\ (\text{value} = \text{value}_1)\\ \textbf{and}\ \text{behavior}_1\end{array}\right\}}$$

where (constraint$_{0..n}$ **and** (value = value$_1$)) *is consistent, i.e. binding* (value = value$_1$) *can be consistently asserted together with* constraint$_{0..n}$

Unobservable:

$$\frac{}{\textbf{compose}\{\text{constraint}_{0..n}\ \textbf{and}\ (\textbf{unobservable}.\text{behavior}_1)\} \xrightarrow{\tau} \textbf{compose}\{\text{constraint}_{0..n}\ \textbf{and}\ \text{behavior}_1\}}$$

Tell:

$$\frac{}{\textbf{compose}\{\text{constraint}_{0..m}\ \textbf{and}\ (\textbf{tell}\ \text{constraint}_n.\text{behavior}_1)\} \xrightarrow{\tau} \textbf{compose}\{\text{constraint}_{0..m}\ \textbf{and}\ \text{constraint}_n\ \textbf{and}\ \text{behavior}_1\}}$$

where (constraint$_{0..m}$ **and** constraint$_n$) *is consistent, i.e.* constraint$_n$ *can be consistently asserted with* constraint$_{0..m}$

Untell:

$$\frac{}{\textbf{compose}\{\text{constraint}_{0..n}\ \textbf{and}\ (\textbf{untell}\ \text{constraint}_m.\text{behavior}_1)\} \xrightarrow{\tau} \textbf{compose}\{(\text{constraint}_{0..n} - \text{constraint}_m)\ \textbf{and}\ \text{behavior}_1\}}$$

where (constraint$_{0..n}$ – constraint$_m$) *is consistent, i.e.* constraint$_m$ *can be consistently retracted from* constraint$_{0..n}$

Check:

$$\frac{}{\textbf{compose}\{\text{constraint}_{0..n}\ \textbf{and}\ (\textbf{check}\ \text{constraint}_m.\text{behavior}_1)\} \xrightarrow{\tau} \textbf{compose}\{\text{constraint}_{0..n}\ \textbf{and}\ \text{behavior}_1\}}$$

where (constraint$_{0..n}$ **and** constraint$_m$) *is consistent, i.e.* constraint$_m$ *is checked to be consistent with* constraint$_{0..n}$

Ask:

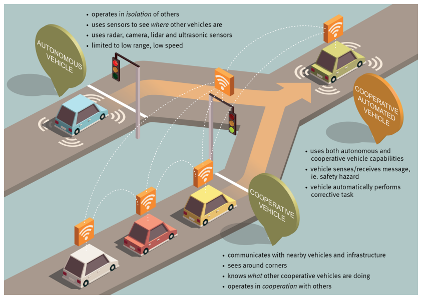
$$\frac{}{\textbf{compose}\{\text{constraint}_{0..m}\ \textbf{and}\ (\textbf{ask}\ \text{constraint}_n.\text{behavior}_1)\} \xrightarrow{\tau} \textbf{compose}\{\text{constraint}_{0..m}\ \textbf{and}\ \text{behavior}_1\}}$$

where constraint$_{0..m}$ |- constraint$_n$, *i.e.* constraint$_n$ *can be derived from* constraint$_{0..m}$

Oquendo, F.: "The π-Calculus for SoS: Novel π-Calculus for the Formal Modeling of Software-intensive Systems-of-Systems", Proc. of 38th International Conf. on Communicating Process Architectures (CPA), Copenhagen, DK, Aug. 2016

5. The SosADL: Key Concepts for architecting Software-intensive Systems-of-Systems (SoS)

5.1 The Notion of Software Architecture of Software-intensive Systems-of-Systems



SoS Architecture: fundamental conception of an SoS in its environment, embodied in its constituents, their relationships to each other and to the environment, and principles guiding the SoS design and evolution

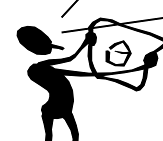
Mission

fulfills

Operational Environment — influences / situated in — System-of-Systems (SoS) — has — SoS Architecture

SoS Architecture — described by — SoS Architecture Description

System-of-Systems (SoS) — has — Stakeholders



SoS Architecture Description Language (SosADL)

[Adapted from ISO/IEC/IEEE 42010 Systems and software engineering — Architecture description]

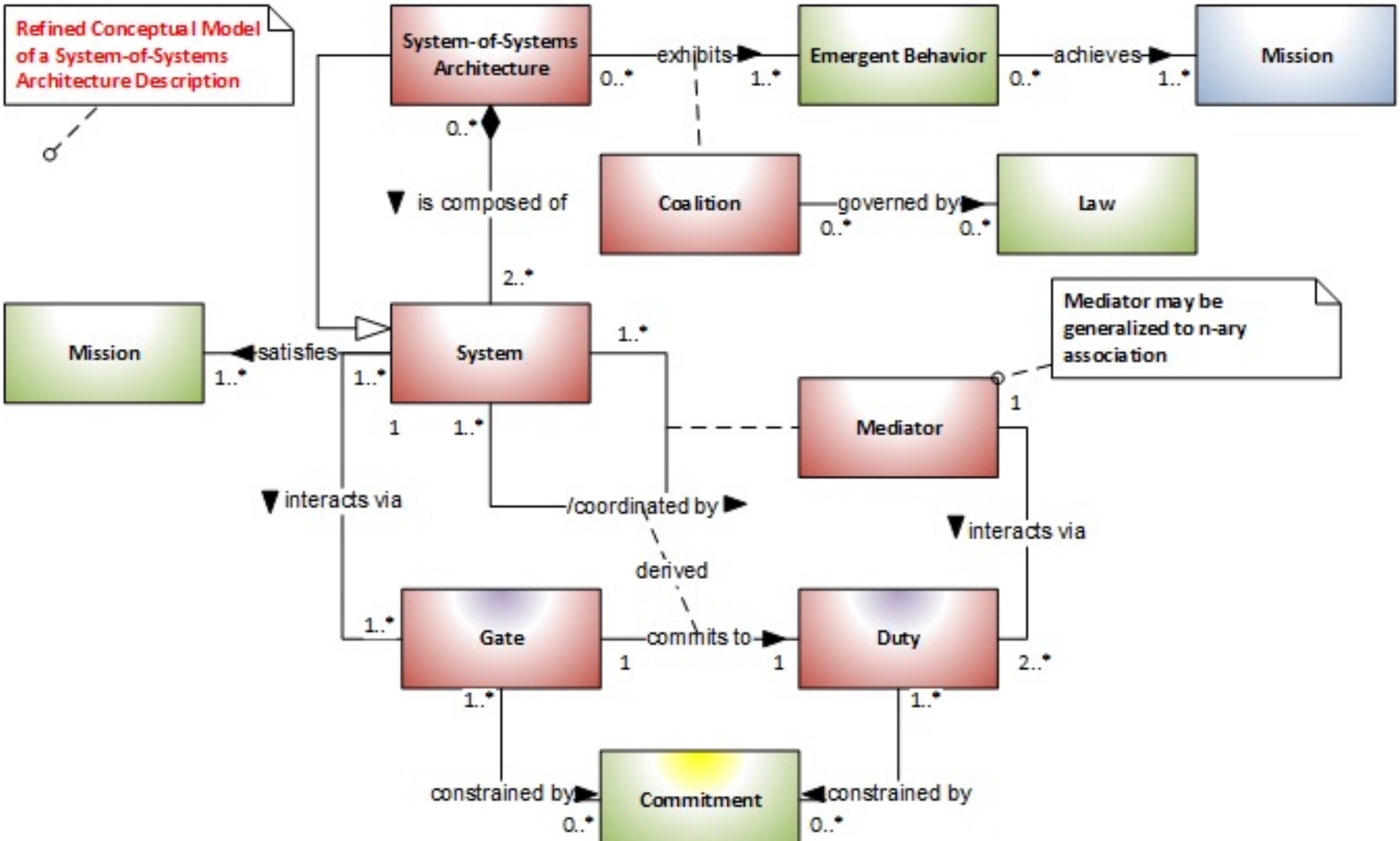
Architectural design of software-intensive systems-of-systems

5.2 SosADL: A specific-purpose Architecture Description Language (ADL) for SoS

- SosADL comprises a new paradigm for architecture description of Software-intensive Systems-of-Systems
  - Enables to describe SoS software architectures abstractly at design-time without knowing which will be the actual concrete systems in the SoS at run-time
  - Enables to describe emergent behavior of evolutionary developed SoS through self-organization
  - Captures the formal semantics of the behavior of SoS architecture descriptions
    - based on a formal foundation: π-Calculus for SoS
      - π-Calculus enhanced with concurrent constraints

SosADL

5.3 SosADL: Conceptual Model of SoS Architecture Description



Architecture description language for systems-of-systems

5.4 SosADL: Key Concepts in Software-intensive SoS Architecture Description

- An SoS ADL needs to cope with the issue that concrete constituent systems are in general not known at design-time, being only identified at run-time, and may evolve unexpectedly
- SosADL: an ADL for Software-intensive SoS
- SosADL describe the Software Architecture of SoS in terms of
  - Constituent systems: architectural components of SoS
    - Defined by intention (declaratively, abstractly)
    - Identified at run-time (concretized)
  - Mediators: architectural connectors of SoS
    - Defined by intention (declaratively, abstractly)
    - Created at run-time (concretized) to achieve a goal
  - Coalition: architectural configurations of SoS
    - Defined by intention (declaratively, abstractly)
    - Created at run-time (concretized) to achieve a mission

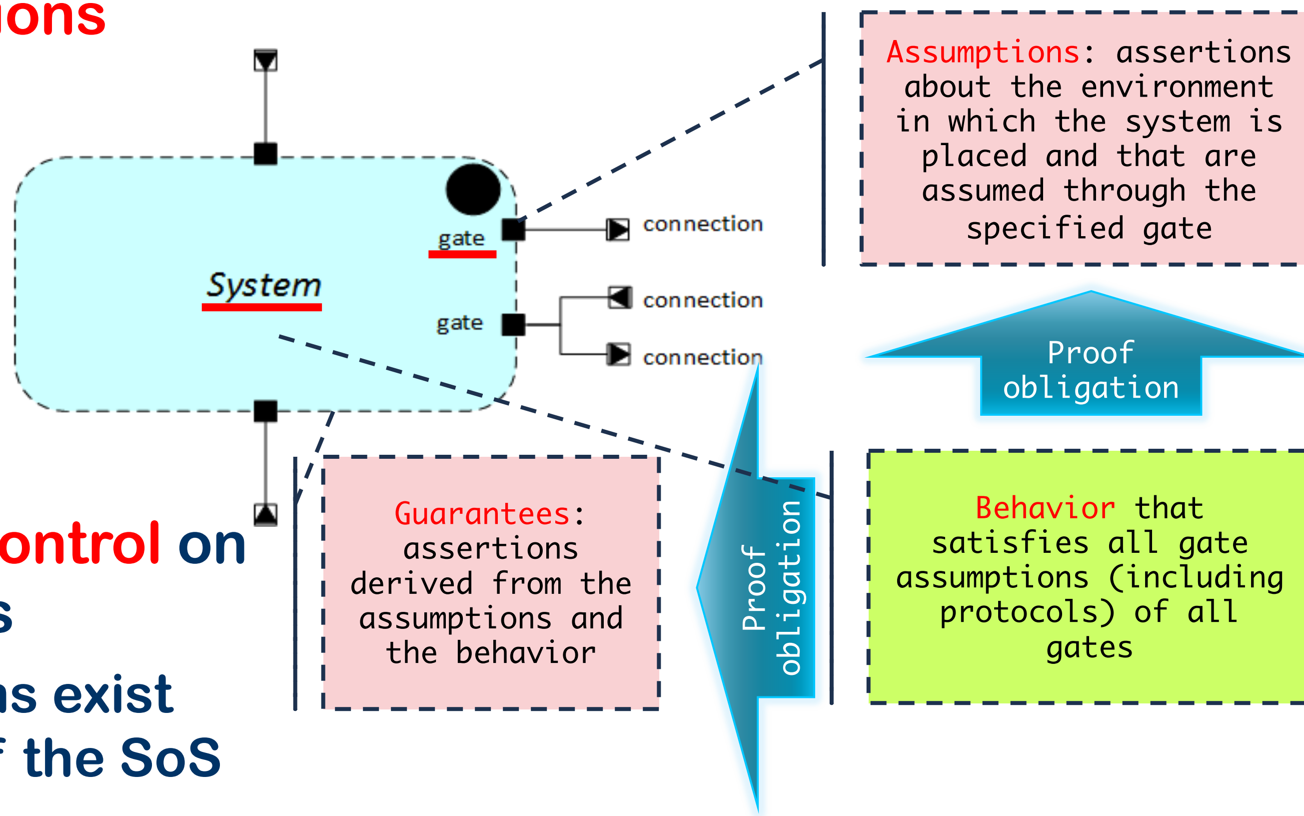
5.5 Difference between Systems Architecture and SoS Architecture described by SosADL

- Single system architectures are described by extension
- SoS architectures are described by intention
- Single system architectures are described at design-time
  - for developing the system based on design-time components
- SoS architectures are described at design-time
  - for developing the SoS based on discovered constituents at run-time
- Single system architectures generally evolve offline
- SoS architectures generally evolve online
- Single system architectures generally support evolution
- SoS architectures generally support coevolution

Single System Architecture vs SoS Architecture

5.6a The SosADL Constructs: Constituent Systems

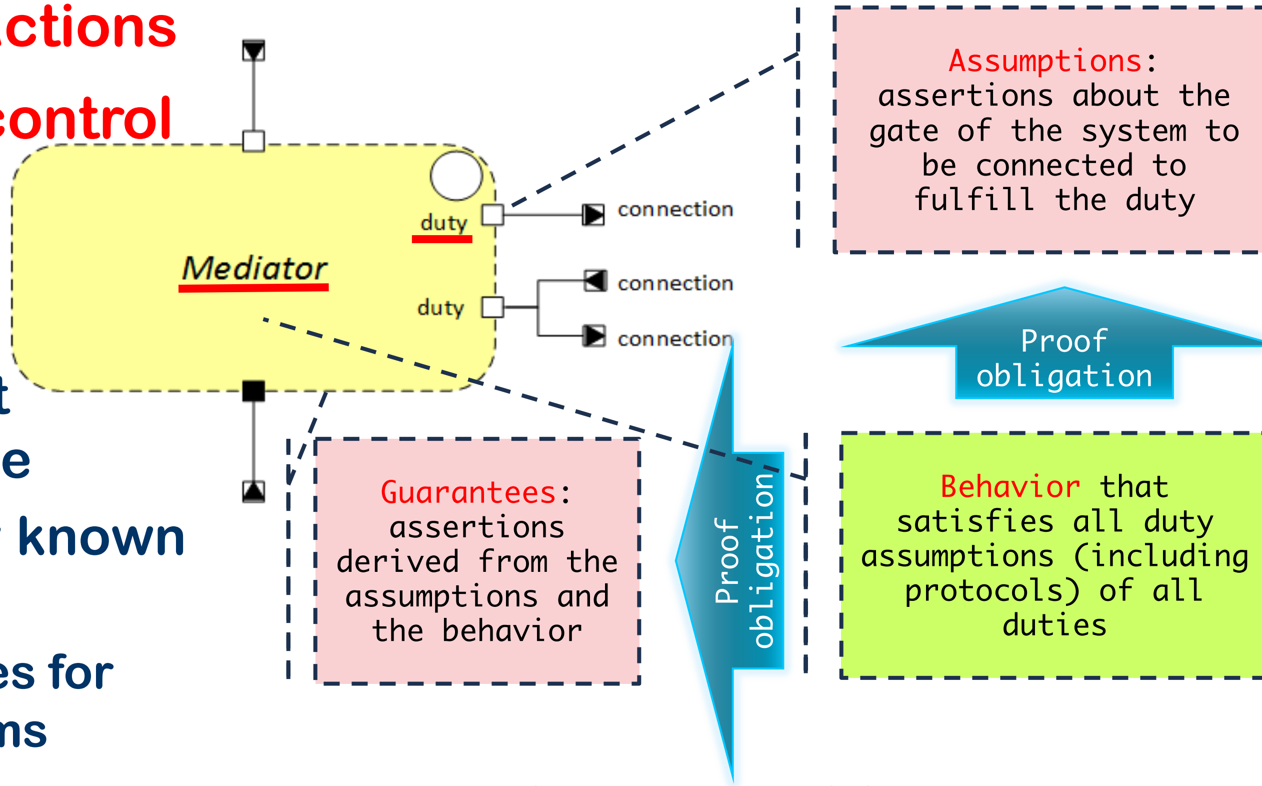
- Constituent systems of an SoS are specified by **System Abstractions**



- The SoS has **no control** on concrete systems
  - Concrete systems exist independently of the SoS
  - Concrete systems are identified at run-time

5.6b The SosADL Constructs: SosADL: Mediators among Constituent Systems

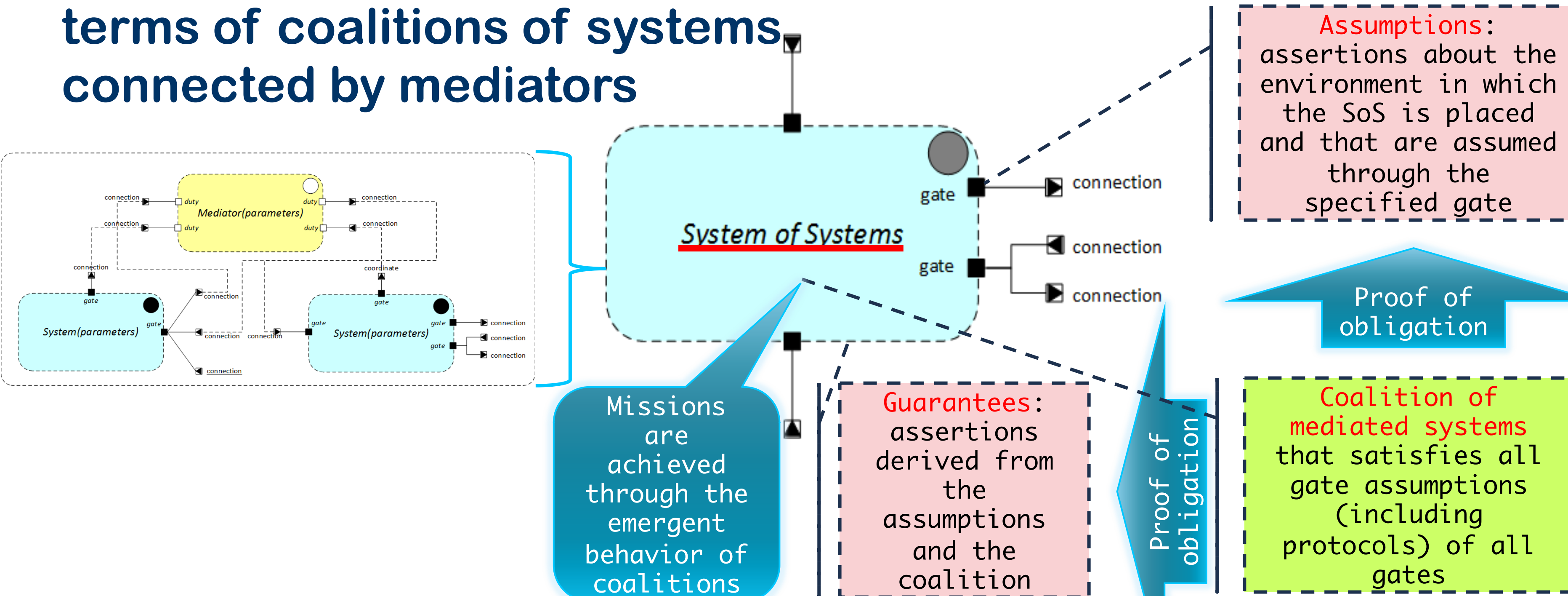
- Mediators among constituent systems in an SoS are specified by **Mediator Abstractions**
- The SoS has **total control** over mediators
  - Mediators control the interactions among constituent systems at run-time
  - Mediators are only known by the SoS
    - They provide duties for constituent systems



- Mediators enable
  - Communication, Coordination, Cooperation, Collaboration

5.6c The SosADL Constructs: Coalitions of Mediated Systems

- System-of-Systems are specified by **Coalition Abstractions**
- An SoS is abstractly defined in terms of coalitions of systems connected by mediators

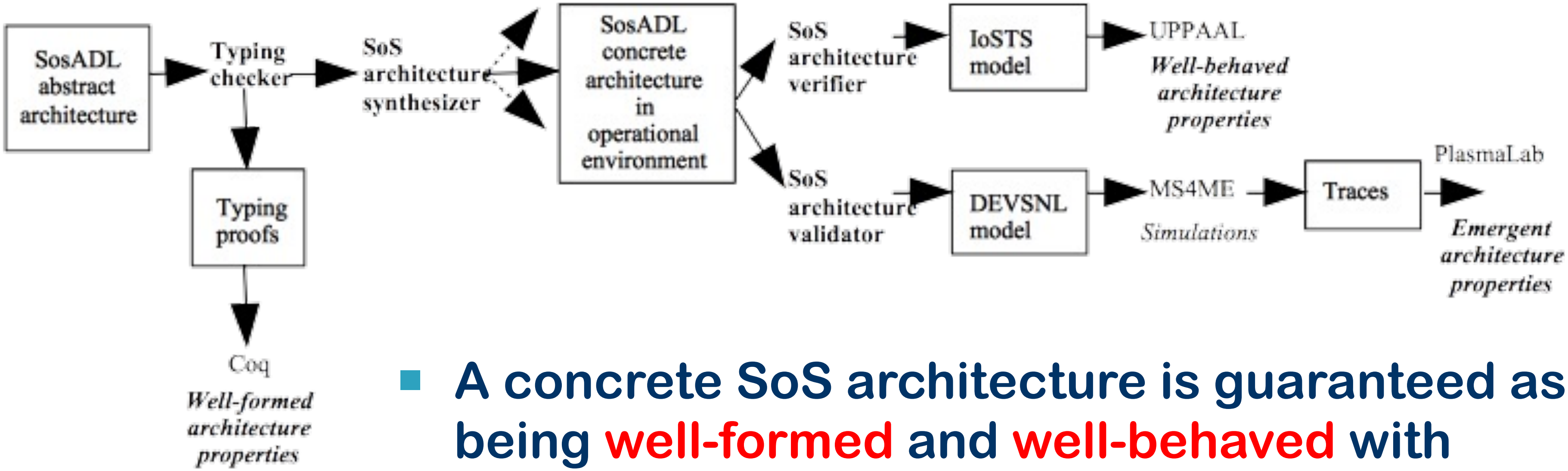


- SoS are concretized and evolve dynamically at runtime
  - Coalitions are defined by policies for operation and evolution

6. Guarantees of Correctness of Software-intensive System-of-Systems (SoS) Architectures

6.1 SosADL Studio: Formal Architectural Development of SoS using SosADL

- SosADL Studio supports the application of SosADL for description and analysis of SoS architectures



- A concrete SoS architecture is guaranteed as being well-formed and well-behaved with guaranteed emergent behavior under the assumptions of the abstract SoS architecture description and the given operational environment

6.2a Guarantees of Correctness by SosADL Studio

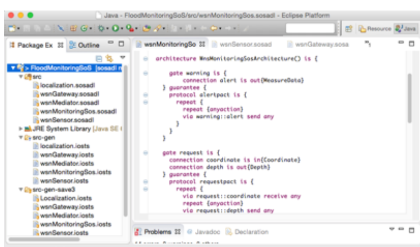
- Question: What are the guaranteed properties of an SoS architecture when applying SosADL, using SosADL Studio?
- Proposed solution for enforcing guarantees of correctness:
  - Formal type system and mechanisms for type checking
    - Proof-carrying code techniques for ensuring correctness with respect to the mechanized type system
    - Machine-checkable proof that the resulting outcome conforms to the type system (verified using the Coq proof assistant and Gallina/Vernacular as language for proofs)
  - Formal behavior system and mechanisms for model checking
    - Assume-guarantee properties are verified by model checking, with Uppaal
      - Properties are expressed in Timed CTL temporal logics
      - Assume-guarantees asserted in constituent systems and mediators as well as in coalitions

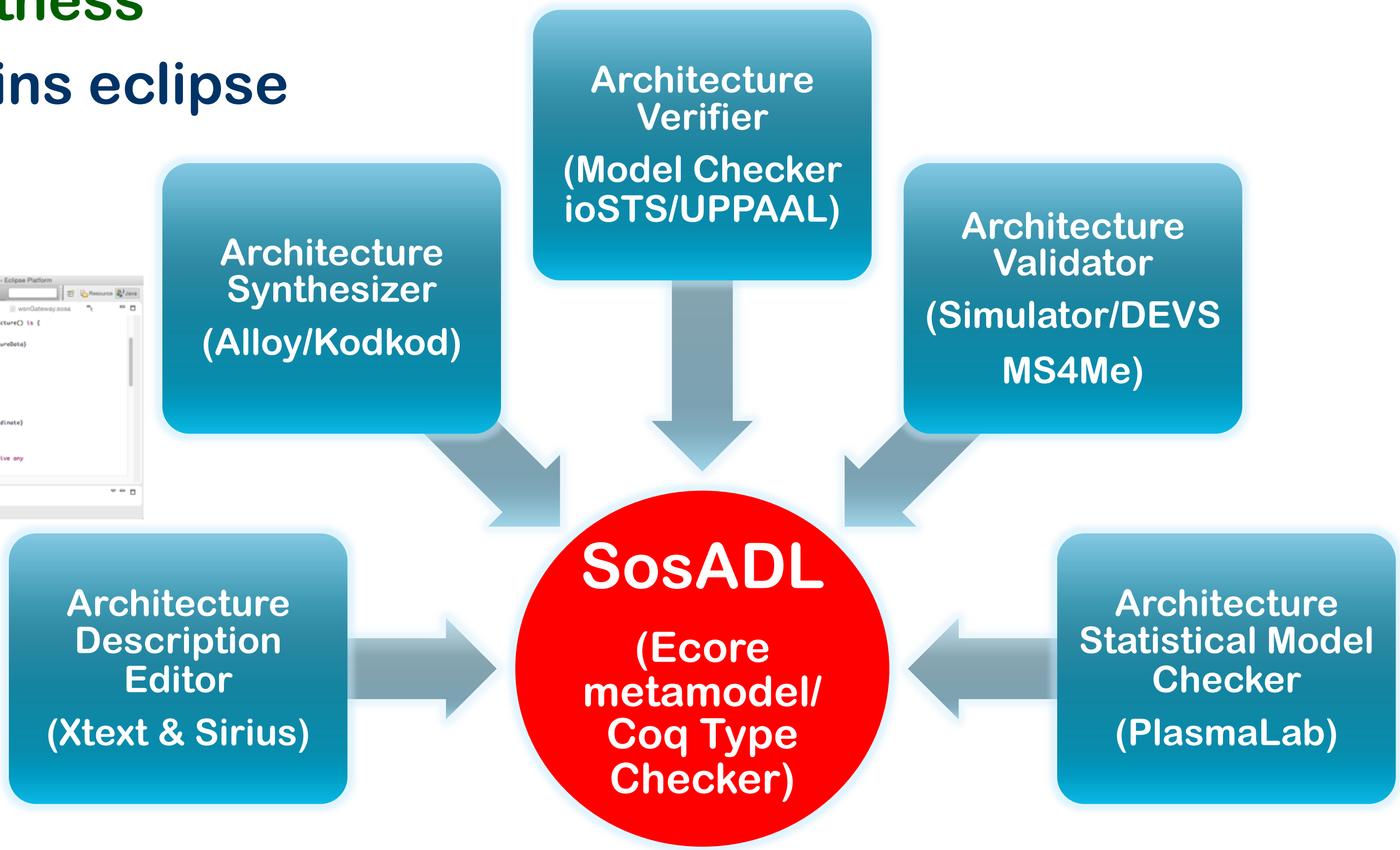
6.2b: Guarantees of correctness by SosADL Studio Emergent behaviors

- With SosADL supported by SosADL Studio, the SoS architect can guarantee that the SoS architecture description is able to raise the targeted emergent behavior
  - Validation of emergent behavior supported by simulation mechanisms
  - Distributed simulation of SoS architecture based on Discrete Event System Specification (DEVS)
    - MS4Me simulation engine
  - The simulation engine is interfaced with PlasmaLab, a Statistical Model Checker, which enables the verification of correctness properties of the architected emergent behaviors
    - Including analysis of extreme cases

6.3 SosADL Studio: The Toolset for Formal Architectural Development of SoS using SosADL

- SosADL Studio integrates tools for describing and analyzing SoS architectures with SosADL, supporting guarantees of correctness
  - Plugins eclipse





Guarantees of Correctness by SosADL Studio

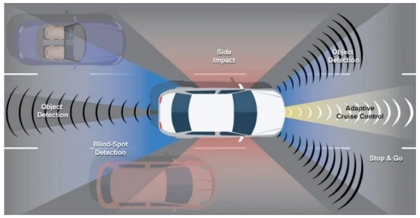
III. Enhancing the proposed solution for raising Collective Intelligence(CI) under Uncertainty in Software-intensive Systems-of-systems (SoS)

7. Enhancing SosADL for handling Uncertainty in Software-intensive Systems-of-Systems (SoS)

7.1 Architecting SoS under Uncertainty

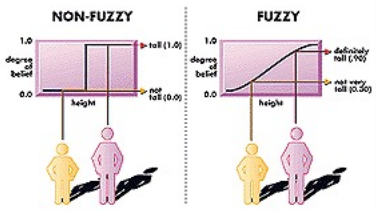
!?

- Software-intensive Systems-of-Systems (SoSs) operate in inherently uncertain operational environments
- Epistemic Uncertainty
  - Epistemic uncertainty is due to partial knowledge
  - In a SoS, each constituent system has only partial knowledge of its local environment, perceived via its sensors & actuated upon via its actuators
- SoSs need to be designed and operated in the presence of epistemic uncertainty (indeed, uncertainty cannot be avoided as it is intrinsic to SoS)
  - Measures from sensors are subject to uncertainty
  - Effects from actuators are subject to uncertainty

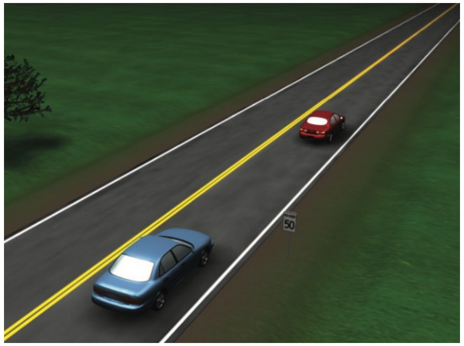


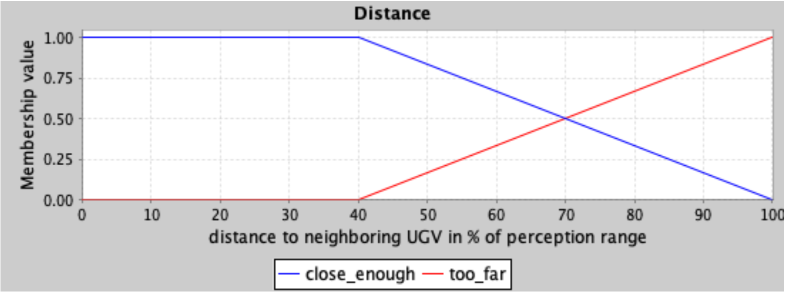
7.2 Which Formal Theory for Handling Uncertainty?

- **The proposed approach relies on Fuzzy Theory for handling uncertainty when architecting SoS under epistemic uncertainty**
  - **Fuzzy sets are used to represent epistemic uncertainty, by representing partial or incomplete knowledge**
  - **It can represent partial information on the operational environment**
  - **It provides several calculi for the fusion of partial information from different sources, e.g. different sensors of a self-driving vehicle, as well as for computing relevant steering commands to be executed by vehicle actuators**



Are these two cars close enough or too far?

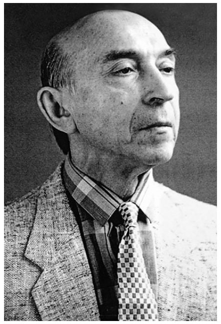




7.3 The Fuzzy Theory for supporting Epistemic Uncertainty

- Fuzzy Theory is composed of a collection of different related theories:
  - The seminal one is Fuzzy Sets, the basis for Fuzzy Logics, which underlines different approaches for Fuzzy Control Systems, supported by Fuzzy Inference Systems
- Fuzzy Theory encompasses different types of Fuzzy Sets and Systems

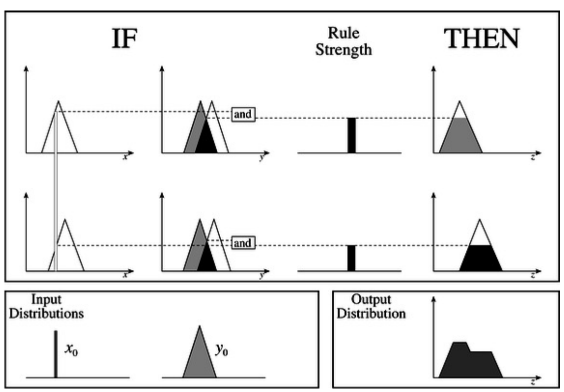
- Fuzzy Theory has been developed since the sixties:
  - In 1965, Lotfi A. Zadeh published the Theory of Fuzzy Sets
  - Zadeh L. A.: "Fuzzy Sets", Information and Control, Vol. 8, 1965, pp. 338-353 (seminal paper with over 48,000 citations)



- The Theory of Fuzzy Sets has given rise to over 50,000 patents in Japan and the United States
  - Most of these applications apply Fuzzy Theory for addressing Uncertainty
  - Highly applied for Fuzzy Control Systems (control systems based on Fuzzy Logic)

7.4 Fuzzy Constructs: Fuzzy Actions and Fuzzy Rules in Fuzzy SosADL

- Fuzzy SosADL extends SosADL with Fuzzy Constructs:
  - Fuzzy action can be a fuzzify action, a rulefy action, or a defuzzify action
  - Fuzzy rule expressing whenever-do-else



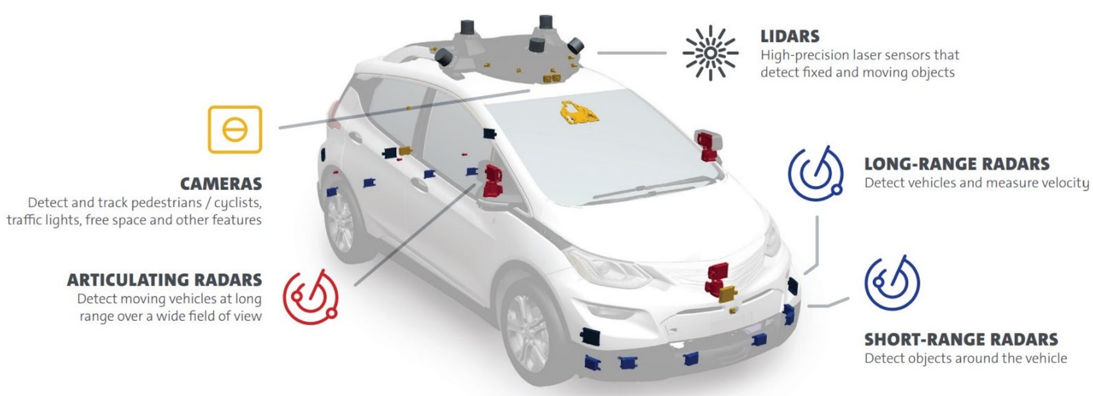

```
fuzzyAction := fuzzifyAction | rulefyAction | defuzzifyAction
fuzzifyAction ::= fuzzify name1 { term0 …, termn }
rulefyAction ::= rulefy name1(name0 : type0 …,
name_n : type_n) : [name0 : type0 …, name_n : type_n]
aggregating by operationMethod0..2 activating by activationMethod0
accumulating by accumulationMethod0 { fuzzyRule1 … fuzzyRulen }
defuzzifyAction ::= defuzzify name1 [inf1..sup1]
by defuzzifierMethod1 { term0 …, termn } default real0
operationMethod ::= andMethod | orMethod
// t-norm for logical operator and
andMethod ::= #and 'minimum' | 'product' | 'bounded difference'
| 'drastic product' | 'einstein product' | 'hamacher product'
| 'nilpotent minimum' | …
// t-conorm for logical operator or
orMethod ::= #or 'maximum' | 'probabilistic sum' | 'bounded sum'
| 'drastic sum' | 'einstein sum' | 'hamacher sum'
| 'nilpotent maximum' | …
activationMethod ::= andMethod
accumulationMethod ::= orMethod
defuzzifierMethod ::= 'mean of maxima' | 'left most maximum'
| 'right most maximum' | 'centre of gravity' | 'centre of area'
| 'centre of gravity on singletons' | …
```

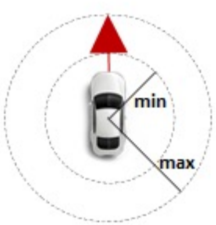
```
fuzzyRule ::= whenever fuzzyAntecedent1
 do { fuzzyConsequent1 } else { fuzzyConsequent2 } weighted real0
fuzzyAntecedent ::= and-or-fuzzy-clause-expression
fuzzyConsequent ::= and-or-fuzzy-clause-expression
fuzzyClause ::= name1 is hedge term1
hedge ::= above | any | below | extremely | intensify | more-or-less
      | norm | not | plus | seldom | slightly | somewhat | very | …
```

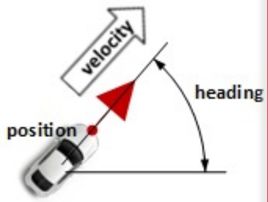
8. A Case study of architecting a Software-intensive System-of-Systems (SoS) under Uncertainty: Vehicle Platoons

8.1a Architecting Platoons under Uncertainty: Self-Driving Vehicles as Platoonmates

- Self-driving vehicles are equipped with **sensors**, e.g. radars/lidars (light detection and ranging devices) as well as steering **actuators**
- Using these devices, a self-driving vehicle can sense information from its operational environment, including other vehicles in its perception range, as well as command its steering actuators

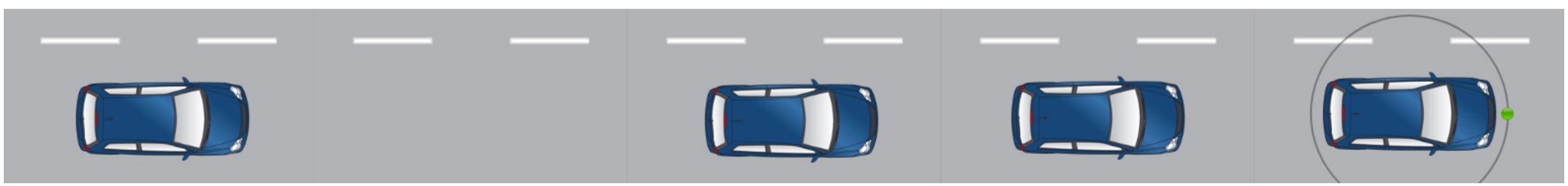


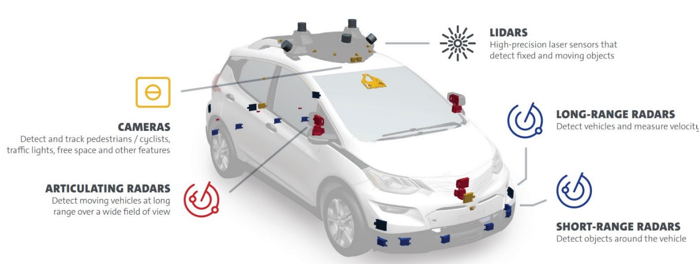


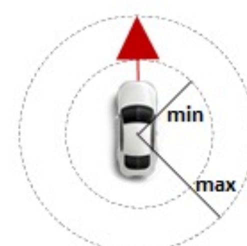


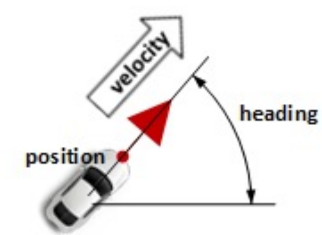
8.1b Architecting Platoons under Uncertainty: Platooning of Self-Driving Vehicles

- **Vehicle Platooning:** platooning is the process of vehicles (in this case self-driving vehicles) autonomously forming road convoys
  - Each vehicle in the platoon follows the platoonmate in front of it, except the leader that drives to the destination
  - It requires that each vehicle in the platoon control its velocity and the relative distance to the vehicle in front of it



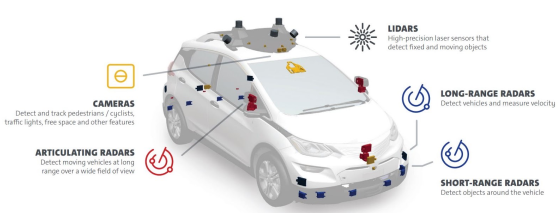


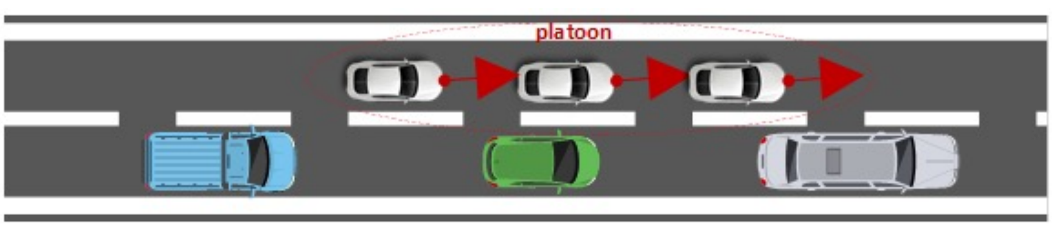




8.2 How to Architect Platoons of Self-Driving Vehicles as an SoS under Uncertainty?

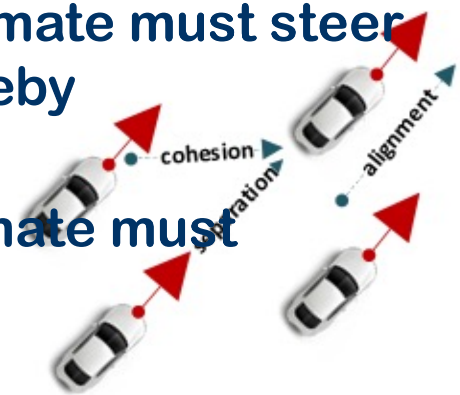
- Recall that architects describe SoS architectures at design-time specifying how SoS constituents will architecturally enable to create and maintain emergent behaviors at run-time
- Challenge to describe Platooning as an SoS architecture
  - The challenge in the architectural design of a Platooning SoS is to conceive an SoS architecture that is able to create, on the fly, and maintain emergent behaviors from self-driving vehicles, including creating platoons as well as having platoonmates joining or leaving the platoon, where the actual vehicles and the operational environment are not known at design-time





8.3 Fuzzy Architecture Description for Platooning SoS: Micro-scale Behaviors for Creating the Emergent Behavior of Platooning

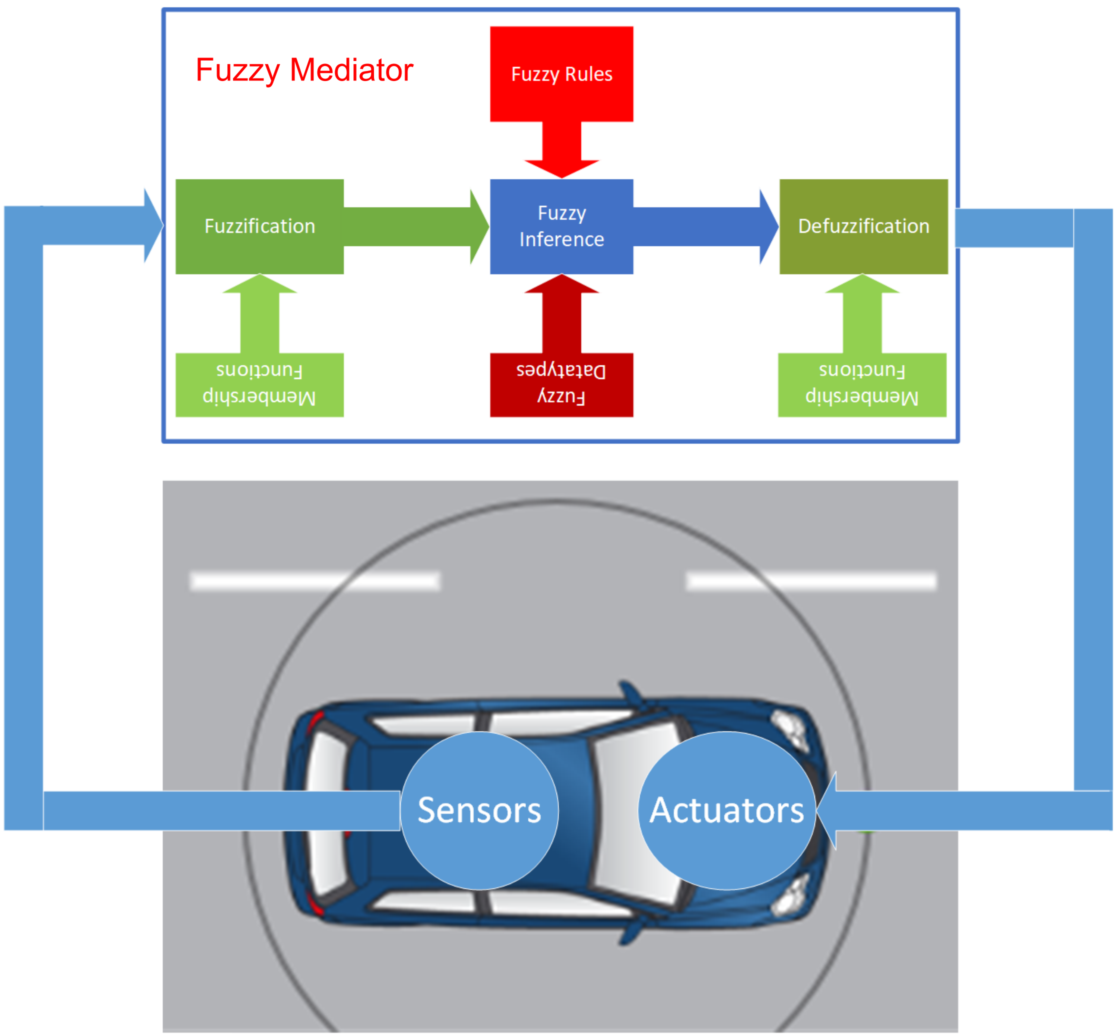
- The described solution for Platooning SoS with SosADL: Systemic Emergence with Supervenience based on Self-Organization
  - The emergent behavior of platooning results from three micro-scale behaviors of platoonmates which together enforce the constraints that are required for enabling self-organization
  - Cohesion micro-scale behavior: every platoonmate must steer to follow the platoonmate just in front of it (if any)
  - Separation micro-scale behavior: every platoonmate must steer to avoid the near platoonmate in front of it, thereby avoiding collision
  - Alignment micro-scale behavior: every platoonmate must steer to move towards the platoonmate in front of it, or towards the destination if no near platoonmate is in front of it while attempting to match velocity (heading and speed) with nearby platoonmates



8.4a Architecture Description for Platooning SoS: Constituents and Mediators in Vehicle Platoon

- The Platooning SoS architecture is described in terms of
  - Self-driving vehicles: they are the SoS constituents identified at run-time: they are declared at design-time by their system capabilities in SosADL
  - Mediators for platooning: they are the SoS mediators created at run-time: they are declared at design-time by their mediation capabilities
    - Mediators are created at run-time (concretized by the SoS) to achieve a goal (in this case forming and maintaining platoons), part of an encompassing mission
    - From the viewpoint of the self-driving vehicle, each mediator generates an independent request for a steering maneuver to be executed by the mediated self-driving vehicle as a micro-scale behavior
  - The architectural role of mediators is to mediate the interaction of constituent systems for creating the requested emergent behavior, in this case, platooning

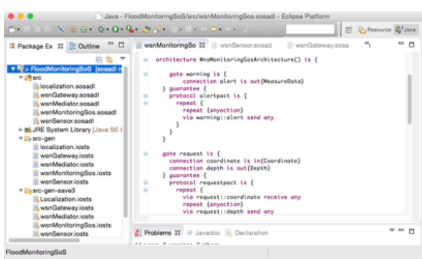
8.4b Fuzzy Architecture Description for Platooning SoS: Inside of Fuzzy Mediators

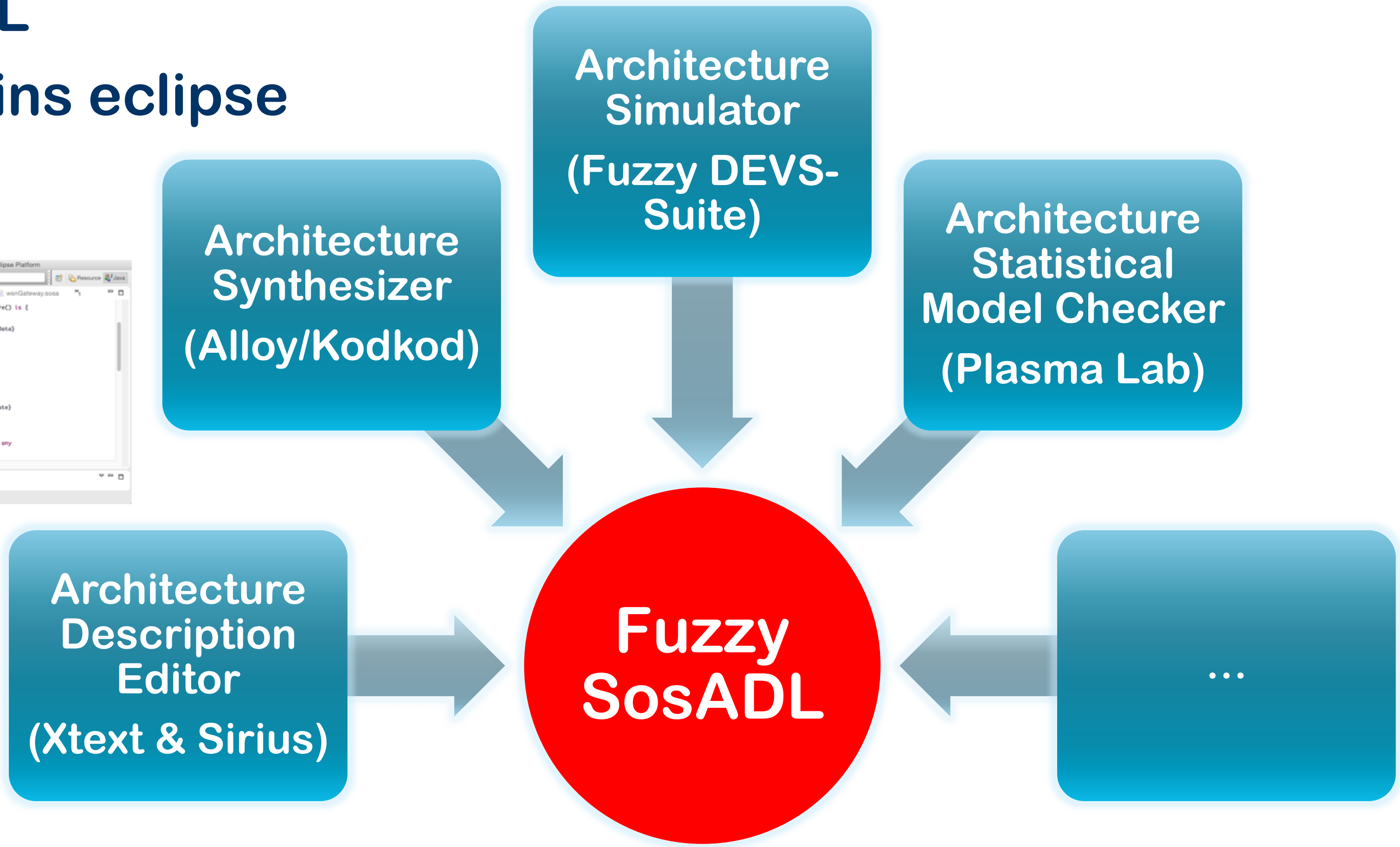


- With the data received from the sensors, the **Fuzzy Mediator** applies the three fuzzy rule sets (cohesion, separation, alignment) to determine how the mediated self-driving vehicle must behave
- Each resulting **fuzzy value** determines through a vector of speed and heading how the self-driving vehicle will be commanded to achieve cohesion, separation, and alignment
- Achieving collectively platooning

8.5 Fuzzy SosADL Studio: Formal Architectural Development of SoS under Uncertainty using Fuzzy SosADL

- The Fuzzy SosADL Studio supports the application of Fuzzy SosADL
  - Plugins eclipse





IV. Summing Up on architecting Software-intensive Systems-of-systems (SoS) for raising Collective Intelligence (CI)

9. Summing Up and Take Away Message

9.1 Summing Up

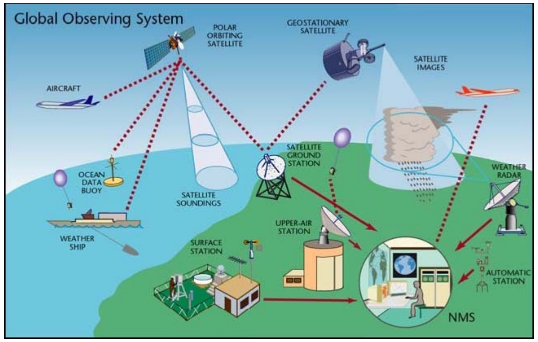
- Single Systems and Systems-of-Systems (SoS) are of different nature
  - SoS raises numerous challenges due to their defining characteristics, including independence of the constituent systems, evolutionary development, and intrinsic complexity implied by emergence
- SoS architecture calls for novel approaches
  - For mastering SoS complexity
    - Formalizing Emergent Behavior
  - For raising SoS emergent behaviors
    - Formalizing Self-Organization
  - For coping with uncertainty in operational environments
    - Formalizing Uncertainty

Summing Up

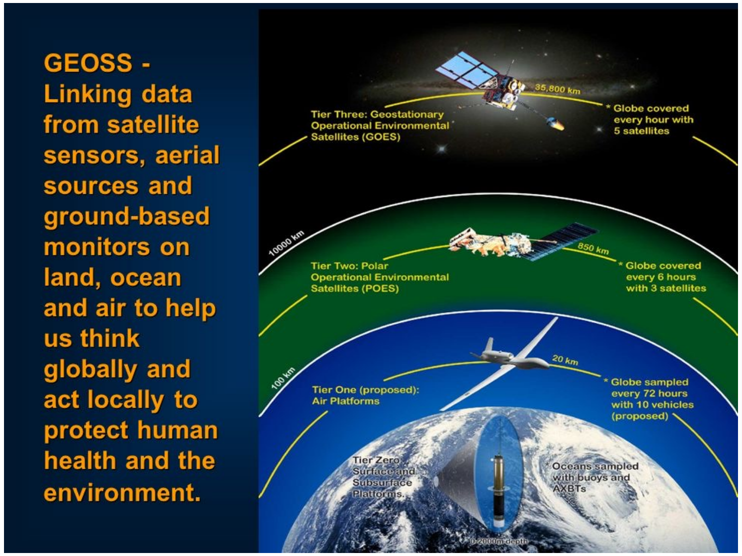
9.2 Summing Up: Emergence and Self-Organization as the basis for a novel ADL for SoS

- SosADL comprises a new paradigm for architecture description of Software-intensive Systems-of-Systems
  - Enables to describe SoS software architectures abstractly at design-time without knowing which will be the actual concrete systems in the SoS at run-time
- SosADL supports the description of emergence
  - Supervenience enables to describe systemic emergence
  - Self-organization enables to create spontaneous systemic emergence
- SosADL captures the formal semantics of the behavior of SoS architecture descriptions, based on a formal foundation: the π-Calculus for SoS
- Fuzzy SosADL handles epistemic uncertainty in the description of SoS architectures

9.3 Summing Up:
Engineering a Worldwide SoS: GEOSS



- **Global Earth Observation SoS (GEOSS)**
  - http://www.earthobservations.org/geoss.php
  - GEOSS is a set of coordinated, independent Earth observation, information and processing systems that interact and provide access to diverse information for a broad range of stakeholders
    - It targets missions for biodiversity and ecosystem sustainability



Summing Up

9.4 Take Away Message

- The Software Architecture of Software-intensive Systems-of-Systems calls for novel paradigms
- Single System and System-of-Systems are of different nature
  - Systems-of-Systems bring complexity to architecture
    - Emergent behavior
  - Systems-of-Systems bring independence of constituents to architecture
  - Systems-of-Systems call for new architectural approaches
    - For mastering Supervenience
    - For mastering Self-Organization
    - For handling Epistemic Uncertainty
- Architecting SoS has been identified as a major issue in the upcoming years, e.g. INCOSE Vision 2035

9.5 For More Information

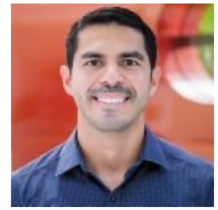
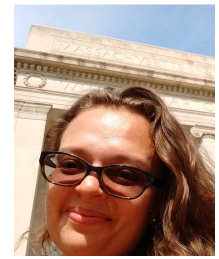
- Contact me at flavio.oquendo@irisa.fr
- Consult the different publications: search for Flavio Oquendo at DBLP

Main publication venues on SosADL and the worked presented:

- Systems Engineering Journal
- Software and Systems Modeling (SoSyM) Journal
- The Computer Journal
- Science of Computer Programming (SCP) Journal
- IEEE International Conference on System-of-Systems Engineering (SoSE)
- European Conference on Software Architecture (ECSA)
- International Conference on Engineering of Complex Computer Systems (ICECCS)
- IFIP International Internet of Things Conference (IFIP IoT)
- International Conference on Communicating Process Architectures (CPA)
- International Symposium on Leveraging Applications of Formal Methods, Verification and Validation (ISoLA)

Acknowledgment to the members of my research team who contributed to this research thread on Software-intensive System-of-Systems Architecture

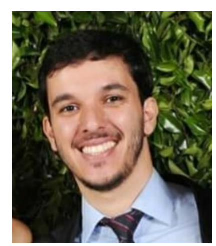
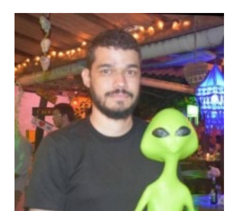
- Jérémy Buisson
- Everton Cavalcante
- Lina Garcés
- Marcelo Gonçalves
- Valdemar Graciano Neto
- Milena Guessi
- Elena Leroux
- Gersan Moguérou
- Lucas de Oliveira
- Jean Quilbeuf
- Eduardo Silva







Thank You

Questions?

Software Architecture in the Era of Collective Intelligence: The Rise of Systems-of-Systems

Flavio Oquendo

flavio.oquendo@irisa.fr

http://people.irisa.fr/Flavio.Oquendo/