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Achieving System-of-Systems Interoperability Levels Using Linked Data and Ontologies

Jakob Axelsson, Mälardalen University & RISE Research Institutes of Sweden
jakob.axelsson@mdh.se

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SoS common concerns

Klein and van Vliet (2013): Survey of 200 research papers on SoS architecture.

- **Interoperability** (45)
- Security (14)
- Evolution (13)
- Performance (9)
- Safety (8)
- Testability (6)
- Quality of service (5)
- Reusability (5)
- Risk (5)

Bianchi et al. (2015): Survey of 40 research papers on SoS quality attributes.

- **Interoperability** (14)
- Security (14)
- Performance (14)
- Reliability (13)
- Safety (10)
- Availability (8)
- Maintainability (6)
- Complexity (5)
- Dependability (5)

Interoperability

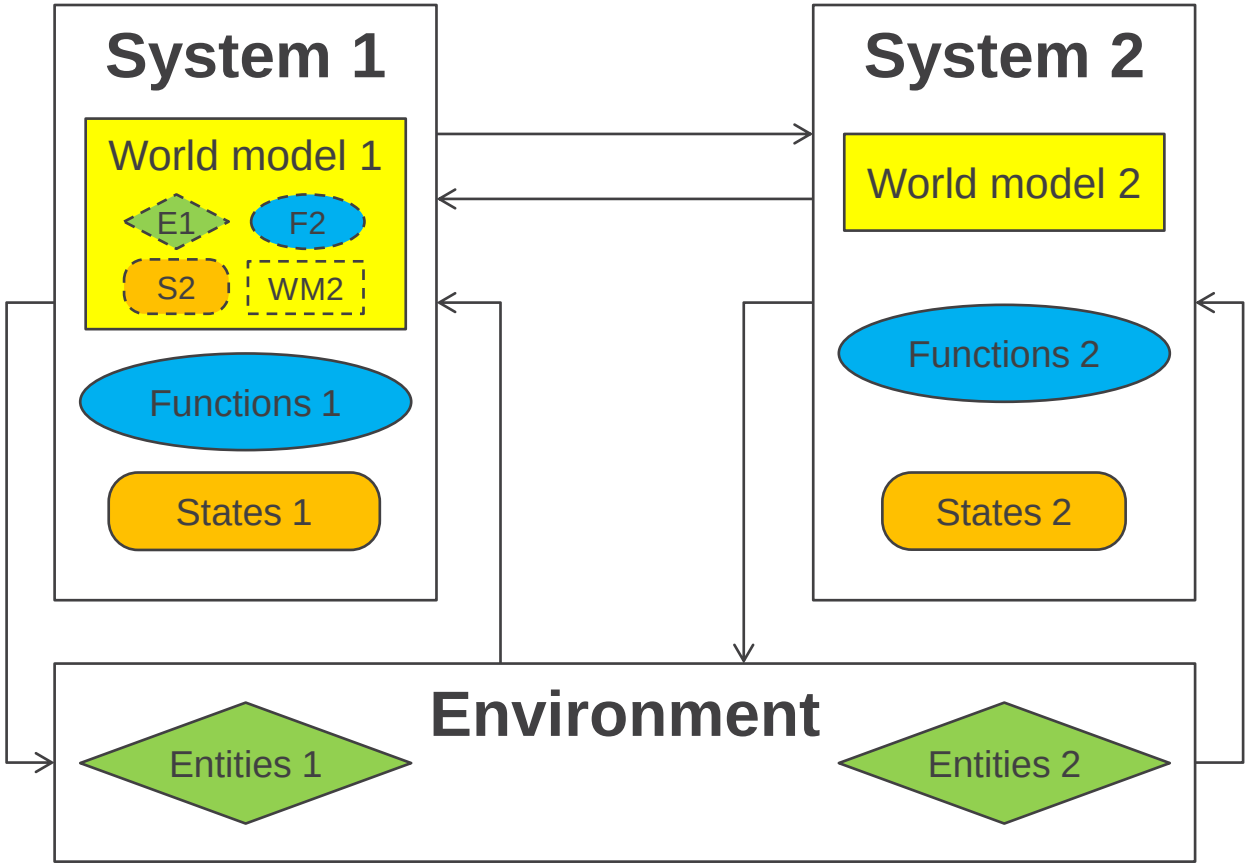
“The ability of two or more systems or components to exchange information and to use the information that has been exchanged.”

(IEEE standard glossary of software engineering terminology, 1990)

SoS engineering considerations

- Analysis: Levels of Conceptual Interoperability Model (LCIM).
- Technology: Linked data and ontologies.
- Trade-offs: Functionality vs. performance and lifecycle cost.

A basic system(-of-systems) model

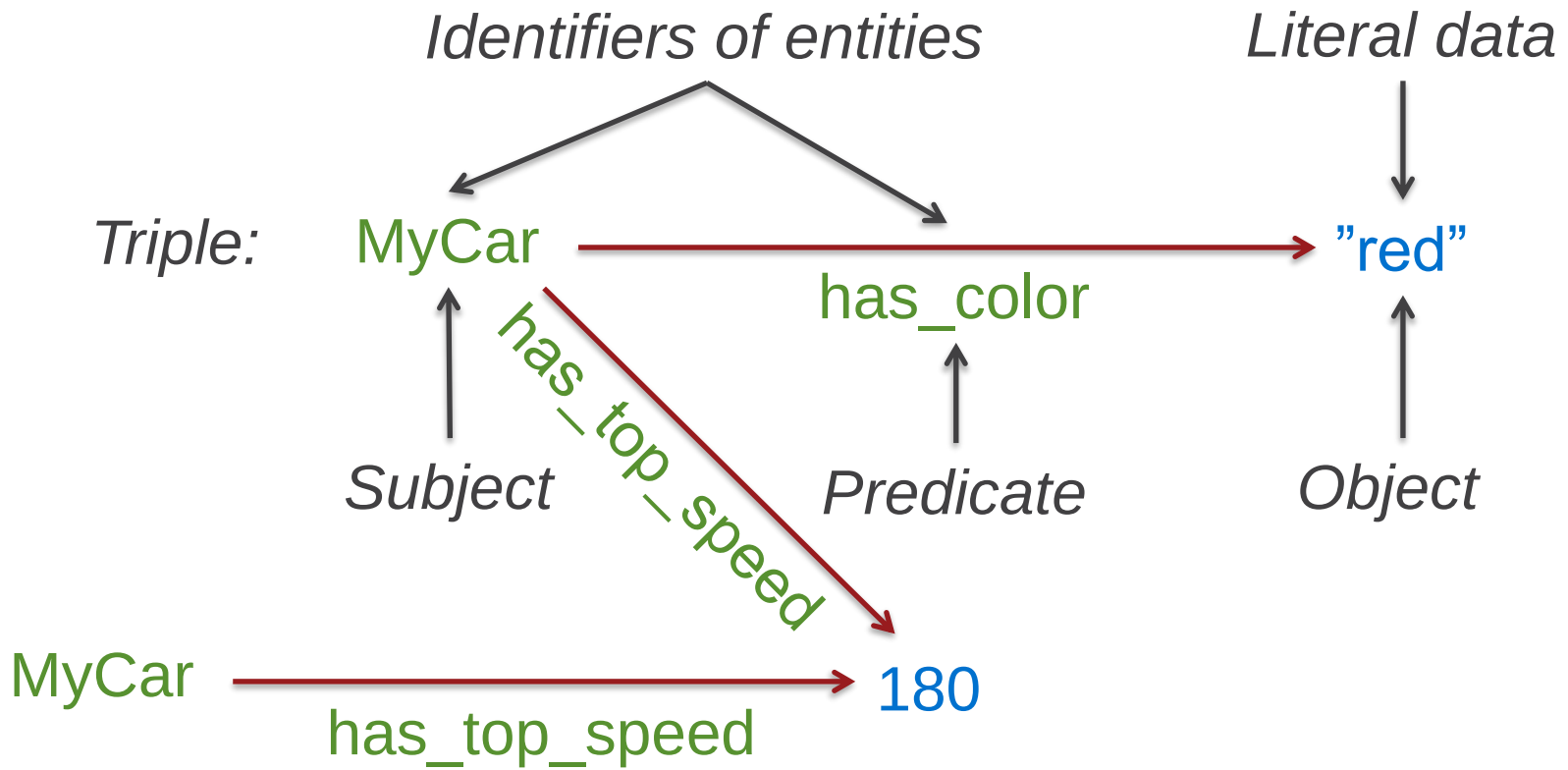


Levels of conceptual interoperability (LCIM)

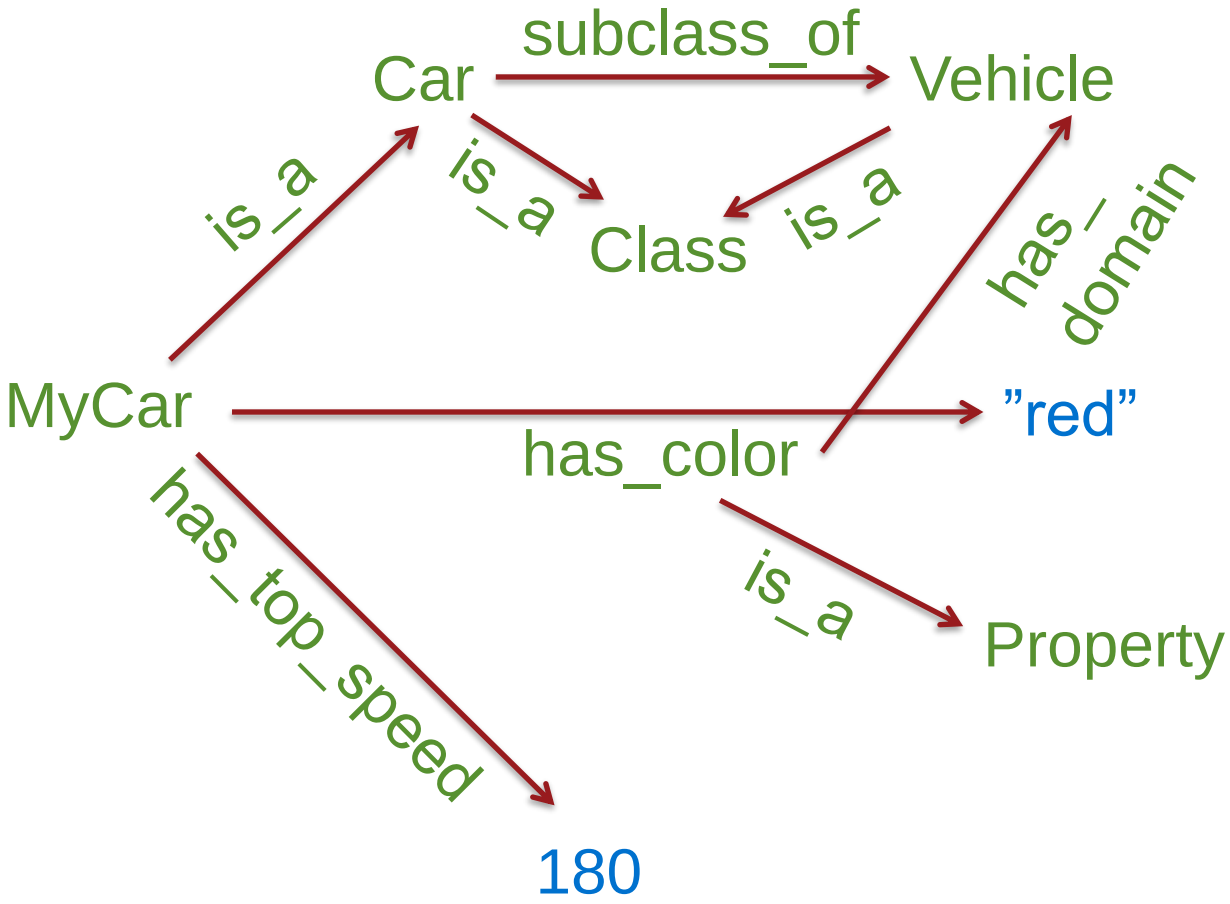
Level	Layer	Premise	Information defined
6	Conceptual	Conceptual model	Assumptions, constraints
5	Dynamic	Execution model	Effect of data
4	Pragmatic	Workflow model	Use of data
3	Semantic	Reference model	Meaning of data
2	Syntactic	Data structure	Structured data
1	Technical	Communication protocol	Bits and bytes
0	No	No connection	None

(Tolk et al., 2006; Wang et al., 2009)

Semantic web: Linked data



Semantic web: Ontologies



Level 1: Technical interoperability

Level	Layer	Premise	Information defined
6	Conceptual	Conceptual model	Assumptions, constraints
5	Dynamic	Execution model	Effect of data
4	Pragmatic	Workflow model	Use of data
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Level 1: Technical interoperability

- Transferability of data
- Open Systems Interconnection (OSI) model
- Internet/WWW protocols:
  - IoT
  - Cloud

Level 2: Syntactic interoperability

Level	Layer	Premise	Information defined
6	Conceptual	Conceptual model	Assumptions, constraints
5	Dynamic	Execution model	Effect of data
4	Pragmatic	Workflow model	Use of data
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Level 2: Syntactic interoperability

- Serialization of linked data:
  - XML, Turtle, Json, etc.
- Triple databases:
  - In memory or persistent.
  - SPARQL query language.

Level 3: Semantic interoperability

Level	Layer	Premise	Information defined
6	Conceptual	Conceptual model	Assumptions, constraints
5	Dynamic	Execution model	Effect of data
4	Pragmatic	Workflow model	Use of data
3	Semantic	Reference model	Meaning of data
2	Syntactic	Data structure	Structured data
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Level 3: Semantic interoperability

- Basic ontology concepts (metamodel):
  - Classes, subclasses, instances
  - Properties
- UML and SysML.
- Reasoning.

Levels 4: Pragmatic interoperability

Level	Layer	Premise	Information defined
6	Conceptual	Conceptual model	Assumptions, constraints
5	Dynamic	Execution model	Effect of data
4	Pragmatic	Workflow model	Use of data
3	Semantic	Reference model	Meaning of data
2	Syntactic	Data structure	Structured data
1	Technical	Communication protocol	Bits and bytes
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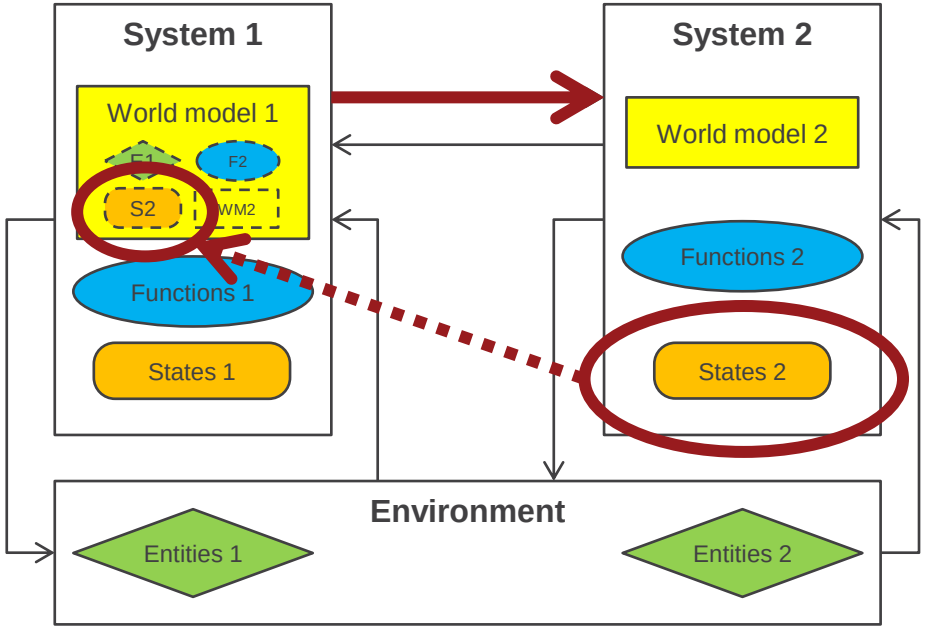
Level 4: Pragmatic interoperability

World model:

- States and transitions
- Workflows
- Modes
- Configurations
- Services offered



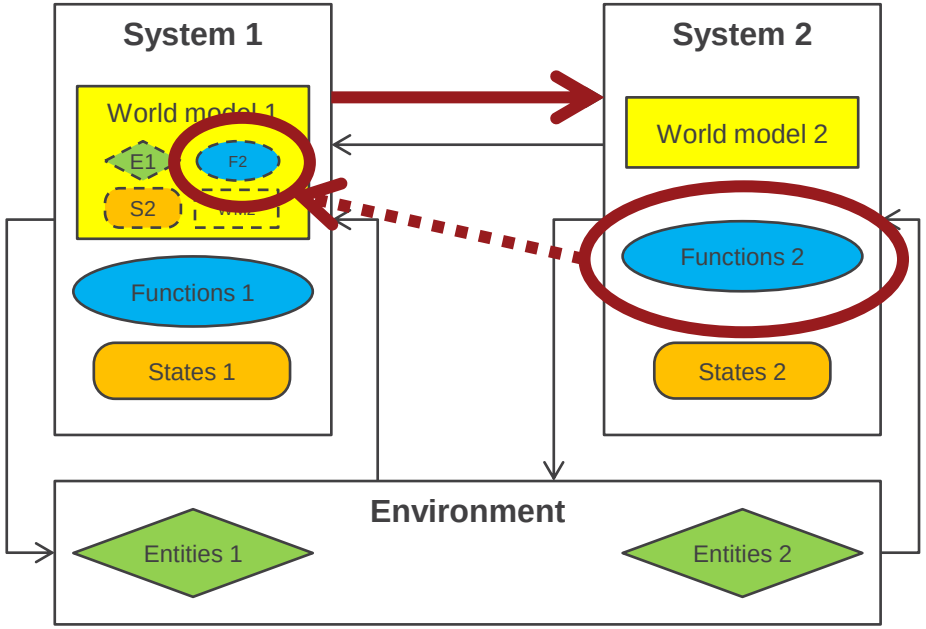
Levels 5: Dynamic interoperability

Level	Layer	Premise	Information defined
6	Conceptual	Conceptual model	Assumptions, constraints
5	Dynamic	Execution model	Effect of data
4	Pragmatic	Workflow model	Use of data
3	Semantic	Reference model	Meaning of data
2	Syntactic	Data structure	Structured data
1	Technical	Communication protocol	Bits and bytes
0	No	No connection	None

Level 5: Dynamic interoperability

World model:

- Functions
- Missions
- Capabilities
- Properties



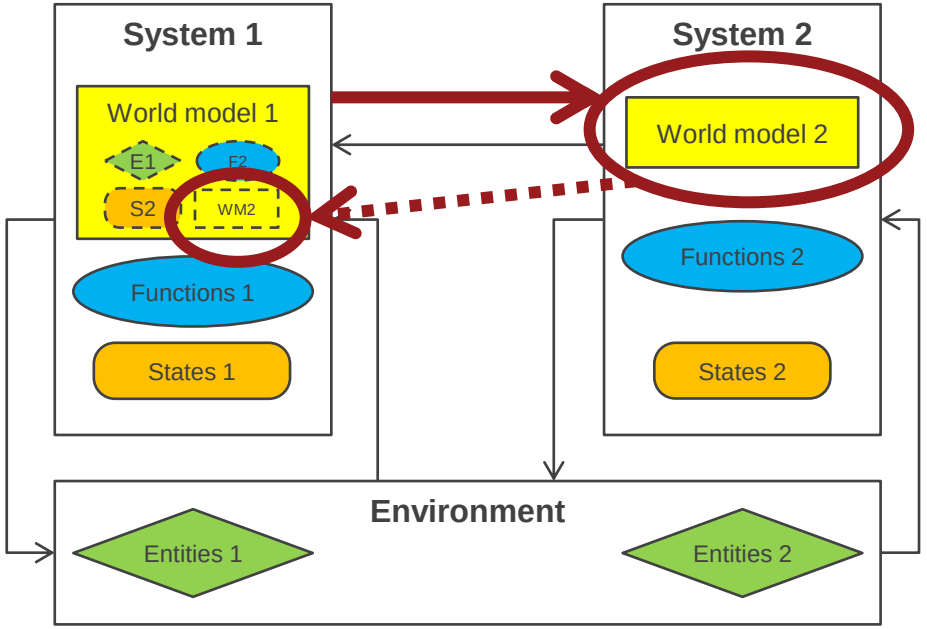
Levels 6: Conceptual interoperability

Level	Layer	Premise	Information defined
6	Conceptual	Conceptual model	Assumptions, constraints
5	Dynamic	Execution model	Effect of data
4	Pragmatic	Workflow model	Use of data
3	Semantic	Reference model	Meaning of data
2	Syntactic	Data structure	Structured data
1	Technical	Communication protocol	Bits and bytes
0	No	No connection	None

Level 6: Conceptual interoperability

World model:

- Mutual awareness of other systems' knowledge.
- If I know that you know my plans, I can expect you to act in a different way.
- Reification.
- Laws of parsimony and requisite variety.



Discussion

- Cost of using linked data:
  - Memory, communication, computation.
- Curation of data.
- Value of data, willingness to share.
- Open Services for Lifecycle Collaboration (OSLC).
- Digital twins.
- Industry 4.0.

Conclusions

- Interoperability is a cornerstone of SoS engineering.
- Trade-off: functionality vs. performance and lifecycle cost.
- Analysis: Levels of conceptual interoperability.
- Technology: Linked data and ontologies.
  - Standardized
  - Reusable software libraries
  - Focus effort on domain ontologies
  - Model-based systems engineering

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