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Semantically-enabled Model-based Systems Engineering of Safety-critical Network of Systems

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Outline

1. Problem Statement
2. State-of-the-Art Capability
3. Semantic Foundations for MBSE
4. Problem Solving Strategies
5. Simple Example (Family-School-Urban Dynamics)
6. Temporal and Spatial Logic
7. Integration Challenge (Safety at Traffic Intersections)
8. Scaling things up (Work in Progress)
9. References

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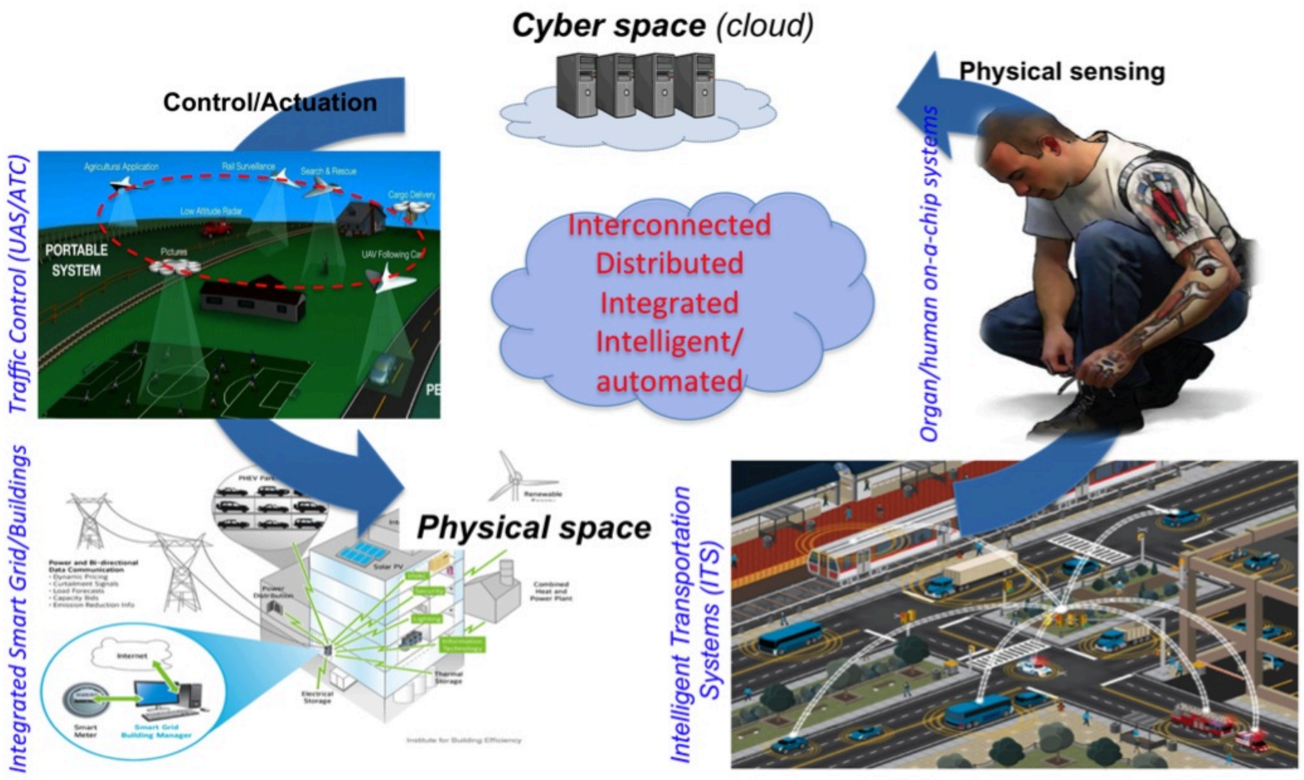
Problem Statement

Need for Model-Based Systems Engineering Approaches for Network of Systems (NoS)

What is a Network of Systems (NoS)?



Definition: Aggregation of system of systems (SoS) and complex cyber-physical sytems (CPSs) operating in a networked environment.

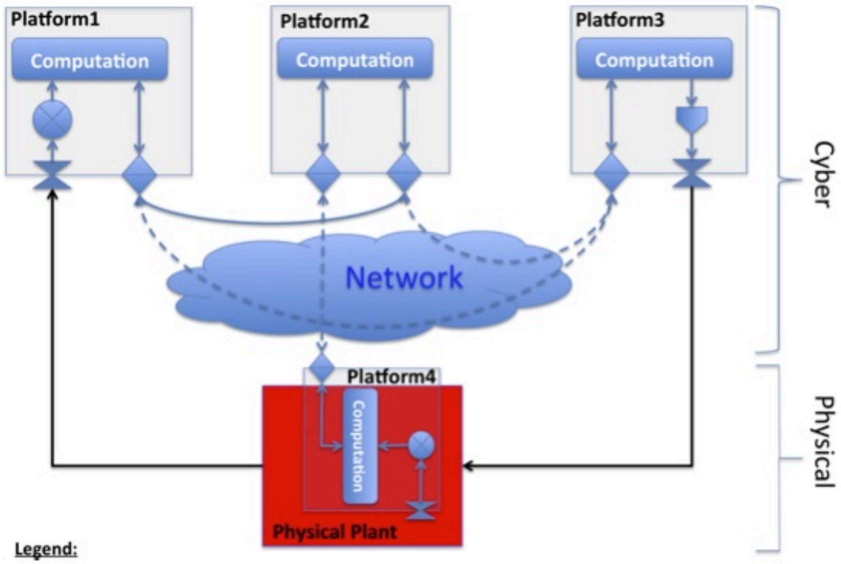
Network of Systems Backbone: CPS and SoS

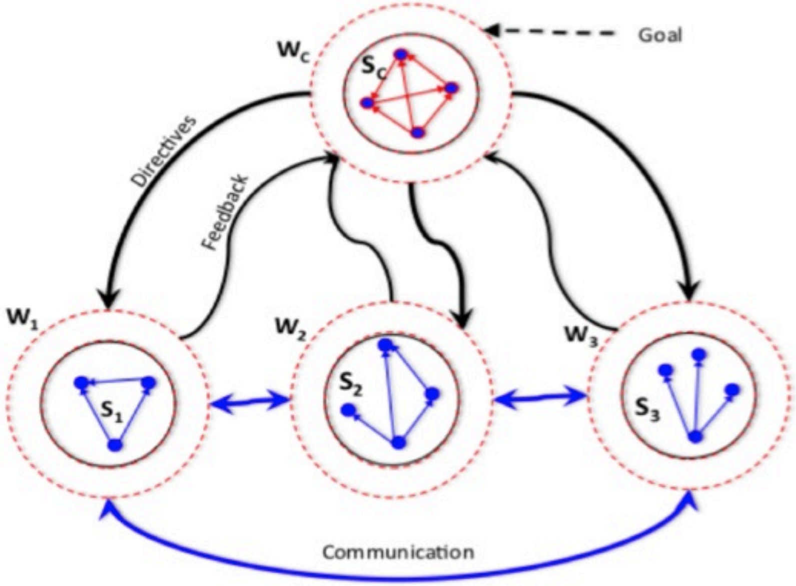
Local: Cyber-Physical Systems(CPS)

- Tight integration of cyber and physical elements
- Distributed/networked system components
- Embedded computational platforms

Global: System of Systems(SoS)

- Arrangement of systems into an independent, larger system
- Mission oriented, with weak (and/or tight) coupling of components
- Might have human in the loop



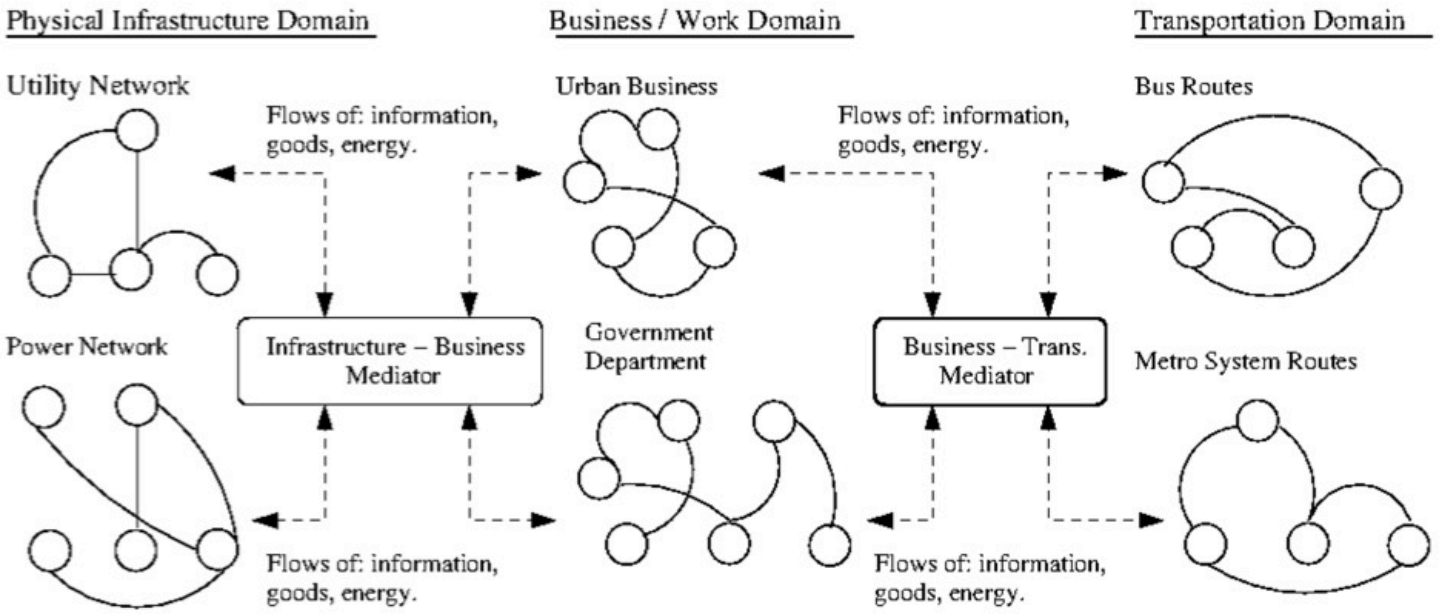


Distributed System Behavior Modeling for NoS

Enabling Distributed System Control

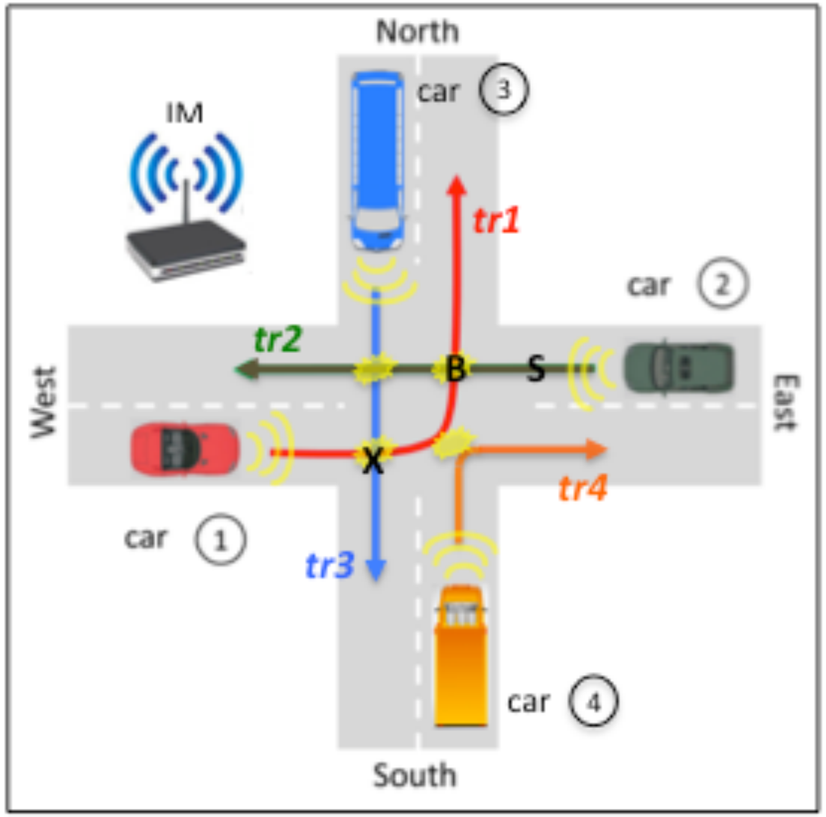
- **Research Question**: How should decision makers cooperate to achieve system-wide performance and management objectives in large scale NoS?
- **Solution strategy**: behavior modeling with ontologies, rules and message-passing mechanisms ⇒ many-to-many interactions in the SP

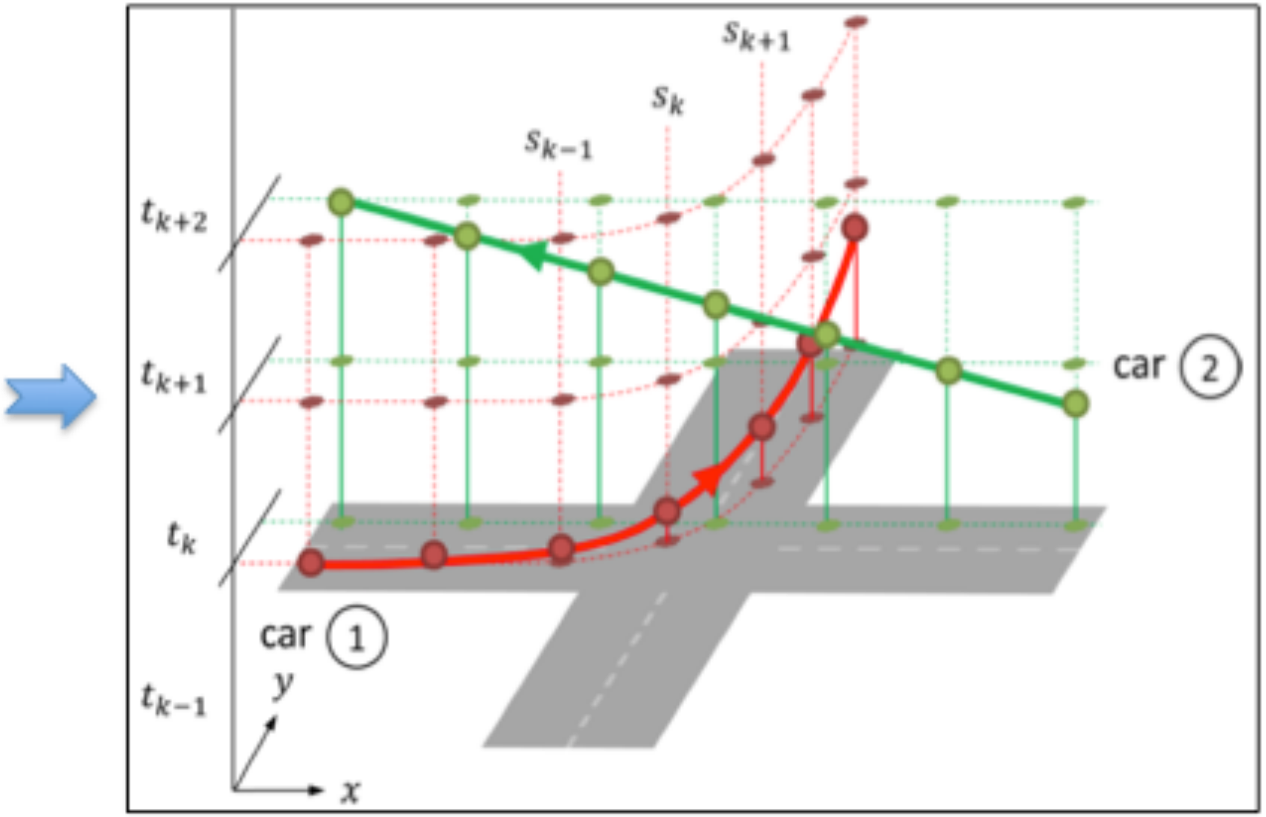
  [Austin,2015]



Source: Coelho, Austin and Blackburn, 2017.

Motivating Application: Safety of Self-driving Cars





Key Challenges: Distributed and concurrent behaviors; networking obstructions; delays; safety-critical operations; need for formal approaches to analysis.

Transition to Semantically-enabled MBSE

Two basic questions: 1. What does state-of-the-art MBSE for NoS look like? 2. How efficient are the semantic foundations?

State-of-the-Art MBSE Capability

Figure: Big picture MBSE [Austin, 2011]

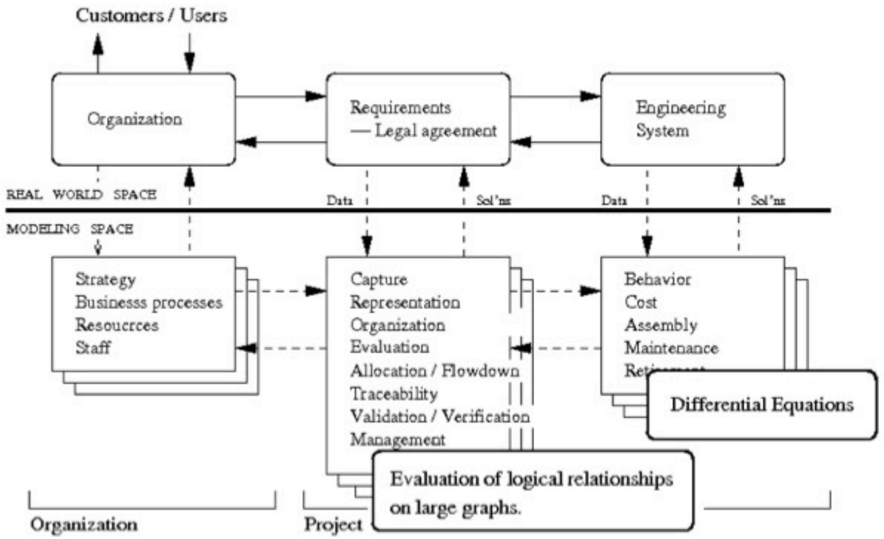
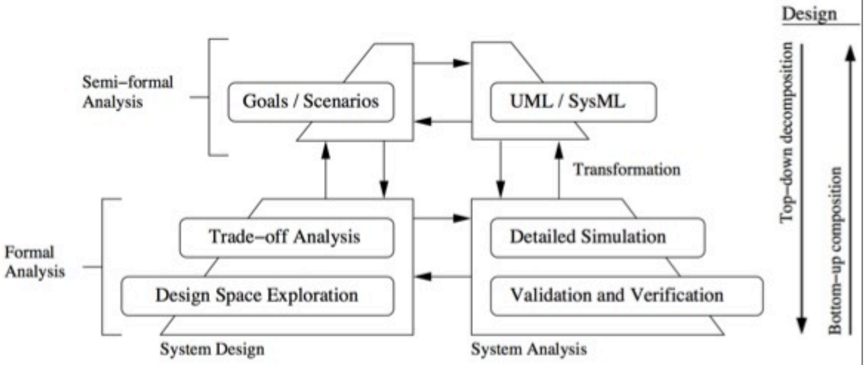


Figure: Multi-level approach [Mosteller, 2014]



Design correctness ⇒ semantic-driven approach to modeling/integration

MBSE ill-equipped for decision making/reasoning

- Requirements elicitation/specification, weak language/physical semantics
- Separation of concerns ⇒ loose coupling
- Broken integration approaches formal vs semi-formal models.

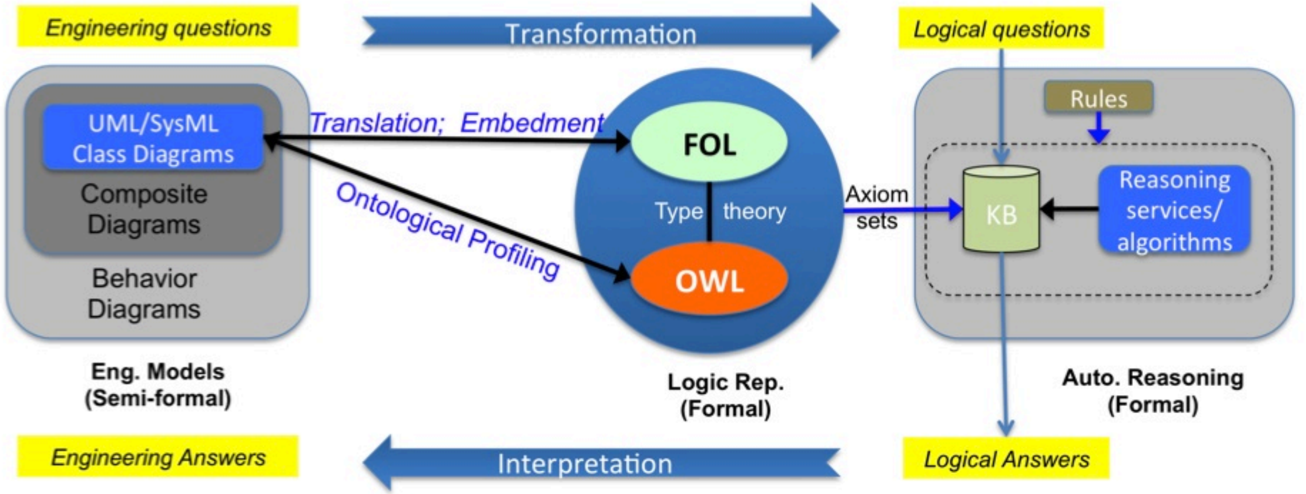
Semantics in MBSE

Why semantics for MBSE?

- **Meaning of models:** formal VS lexical VS conceptual
- **In practice:** precise def. of intended behavior of ontology-based tools/systems;
- Semantics defined in terms of models in the sense of model theory

Semantics Support Approaches for MBSE

- **Language retrofitting:** logic strengthens semantics of UML, SysML [Graves, 2012]
- **Ontological profiling:** profile in the modeling tool (OWL-SysML) [Wagner, 2012]



Ans.: Model inconsistencies, redundancies. **Q.: System level req. (safety)?, Dynamics?**

Strategic Approaches to Development

Basic issue: How to remain productive in the face of rapidly increasing system complexity?

Tenets of Our Approach

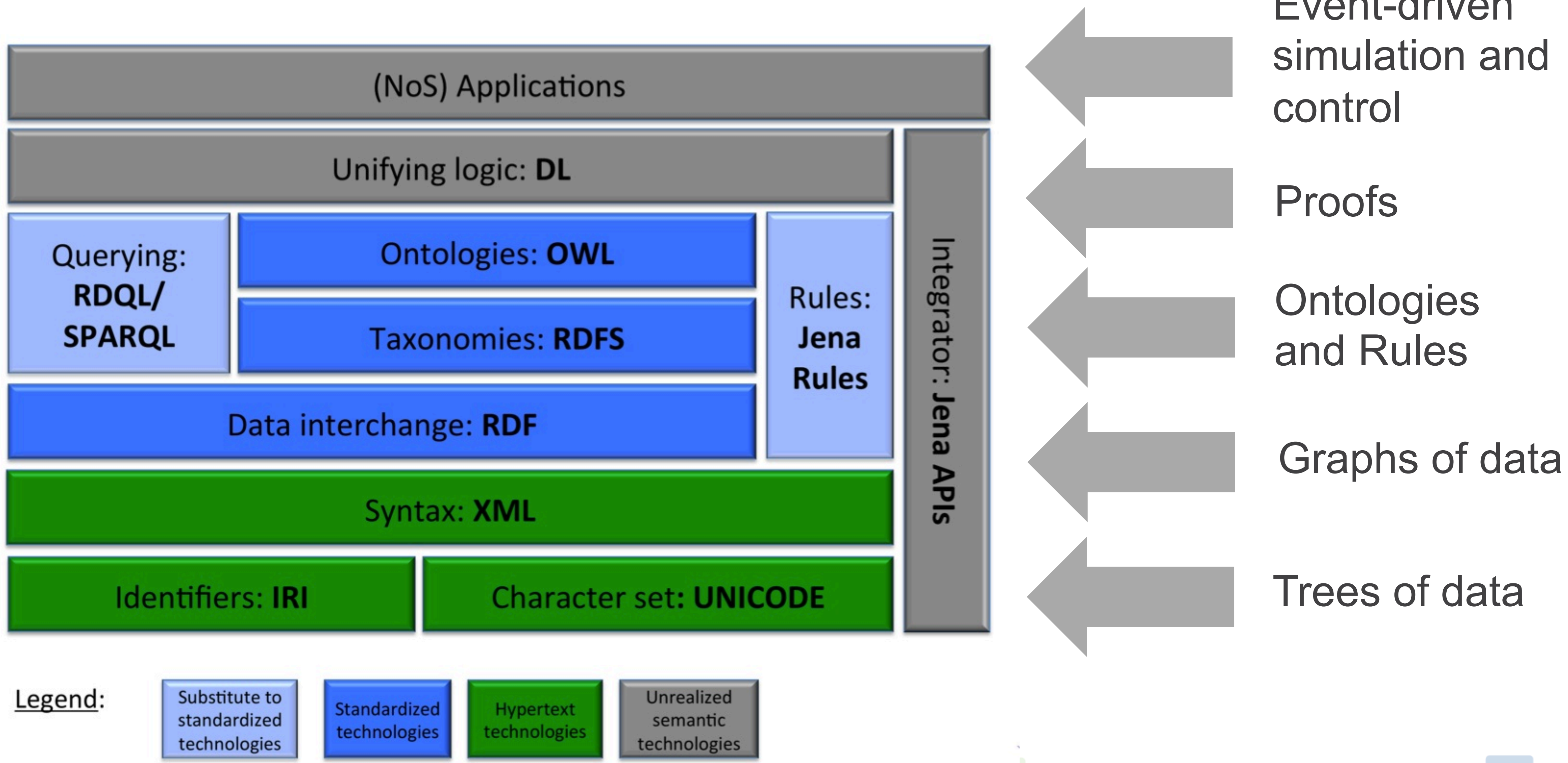
Tenet 1: NoS should be designed and managed through the use of models, as opposed to documents

- Bang for the bucks: minimal mechanism, maximal function
- Reliable operation in a wide range of environments
- Ease of accommodation for future technical improvements

Tenet 2: NoS design methodologies need to employ semantic descriptions of domains and formal reasoning

- Adaptive validation of requirements
- Multidiscipline/models communication and integration
- "Data" instead of "Tool-to-tool" interoperability
- Assessment of system capability in uncertain environments

Enabling Infrastructure: Semantic Web Layer Cake



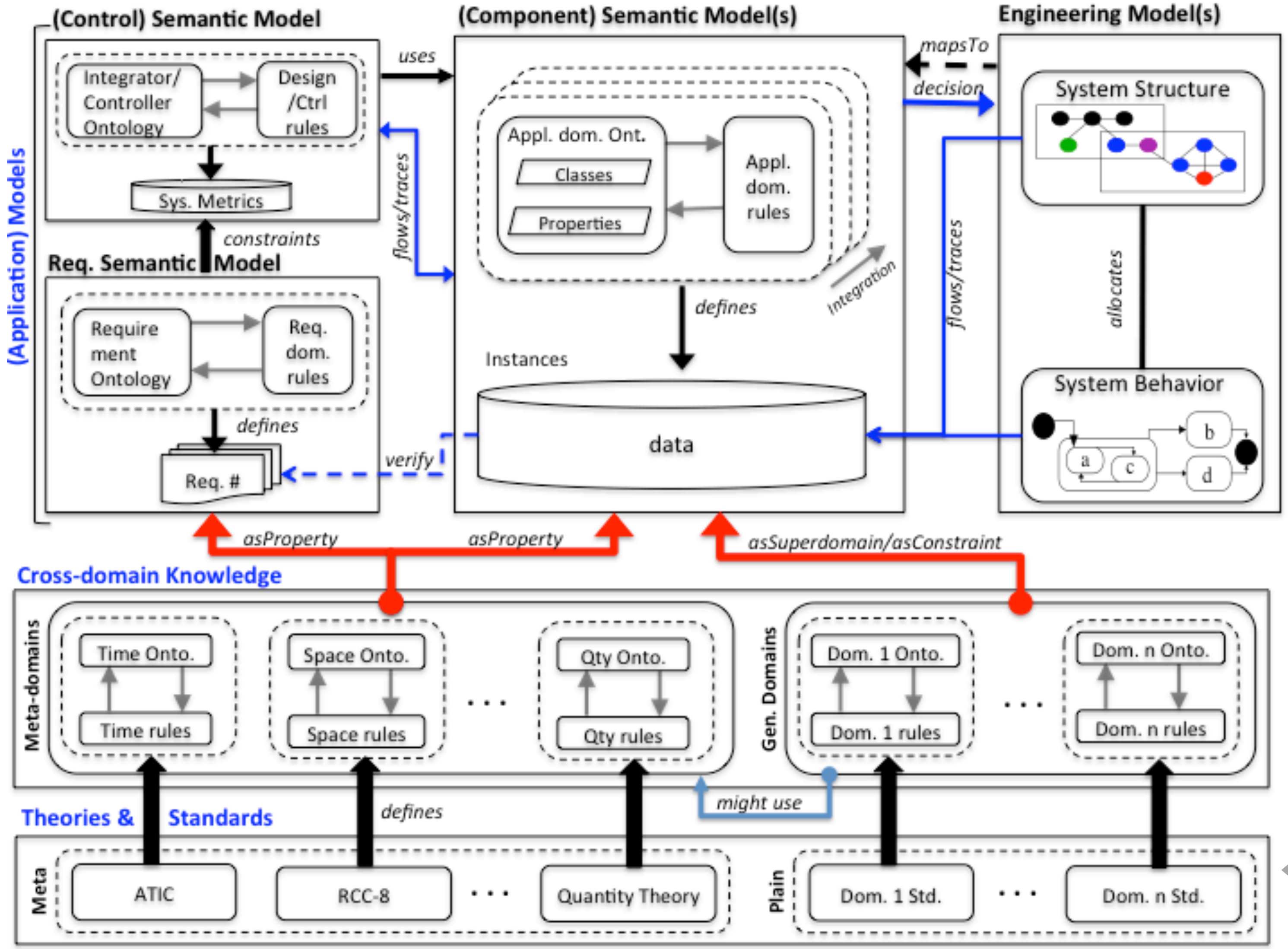
System Architecture (Work in Progress)

Semantic Model

Cross-domain knowledge

Engineering Models

Theories and Standards



Simple Example

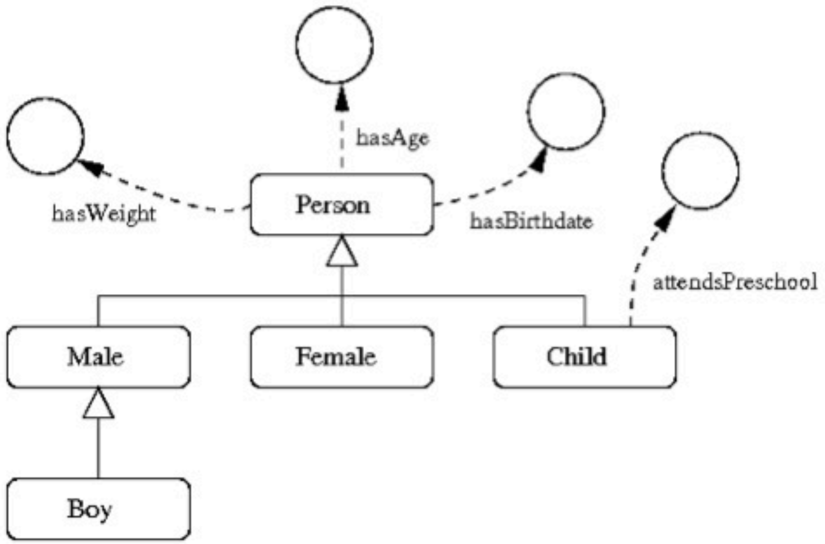
Simplified Semantic Modeling of a Family ….

Fact. Sam is a boy. He was born October 1, 2007.

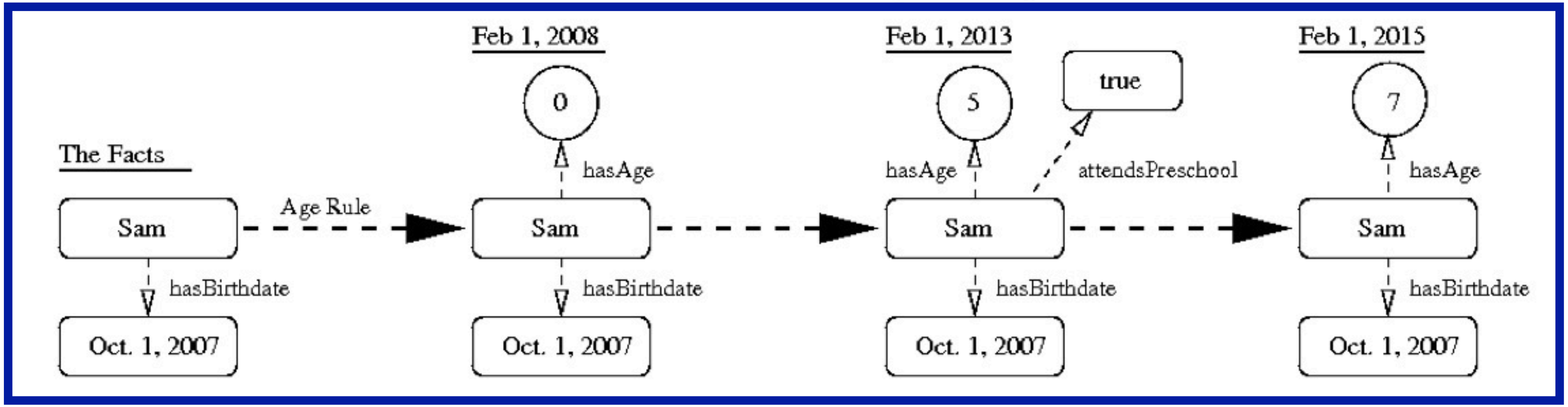
Rule 1: For a given date of birth, a built-in function getAge() computes a person's age.

Rule 2: A child is a person with age < 18.

Rule 3: Children who are age 5 attend preschool.



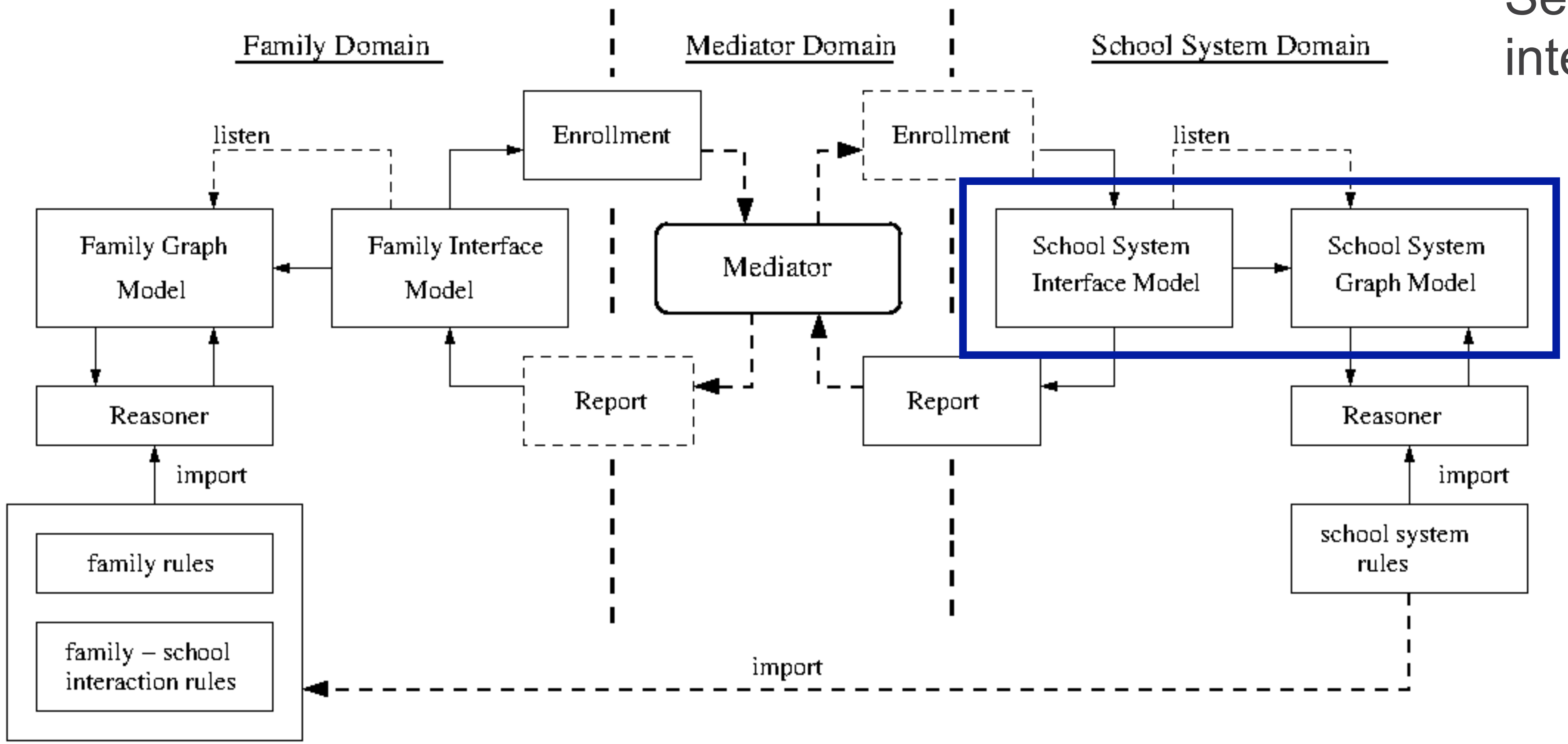
Ontology



Event-driven evolution of semantic graph.

Source: Delgoshaei, Austin, Pertzborn 2014.

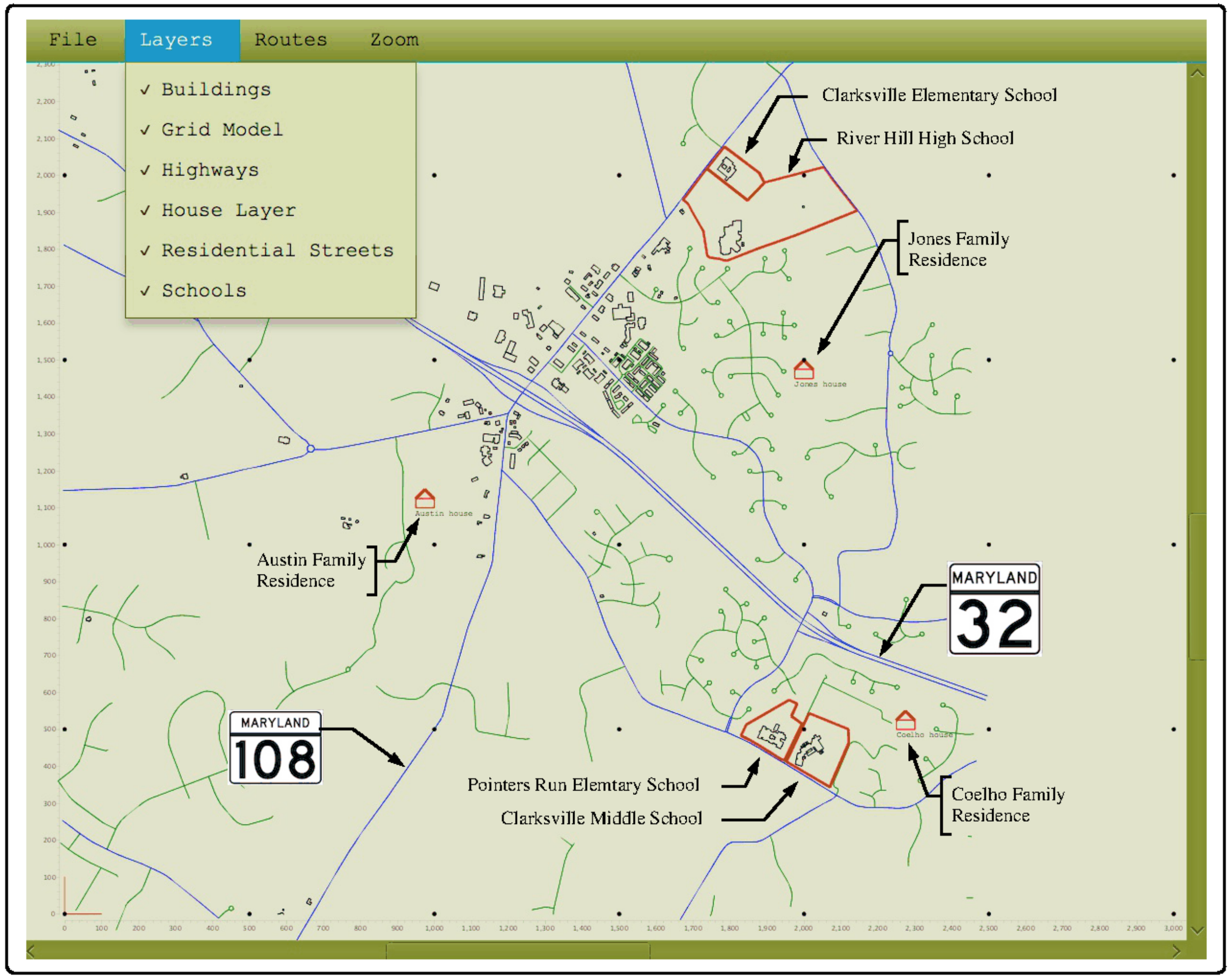
Behavior Modeling of Family-School Interactions

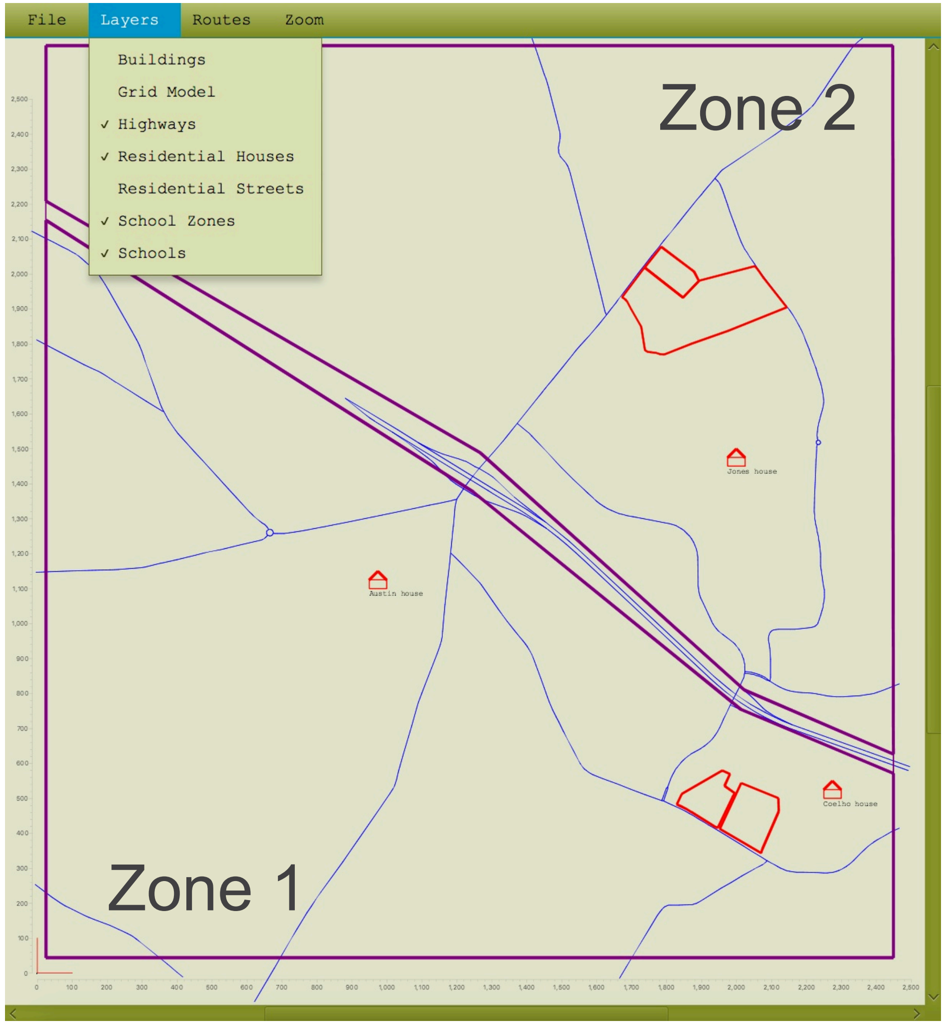


Semantic graph and interface model

Source: Coelho, Austin and Blackburn, 2017.

Family-School-Urban System Dynamics





Temporal and Spatial Logic

Basic issue: How do notions of space and time affect safety in safety-critical NoS? How should we reason with spatial and temporal phenomena?

Hierarchies of Logic

Temporal Logic: Describes how the conditions of a system changes over time:

We want to know what is true, and when?

Spatial Logic: Is concerned with regions and their connectivity, allowing one to address issues of the form:

We want to know what is true, and where?

Spatio-Temporal Logic: Spatial logics are combined with temporal logics, allowing one to address issues of the form:

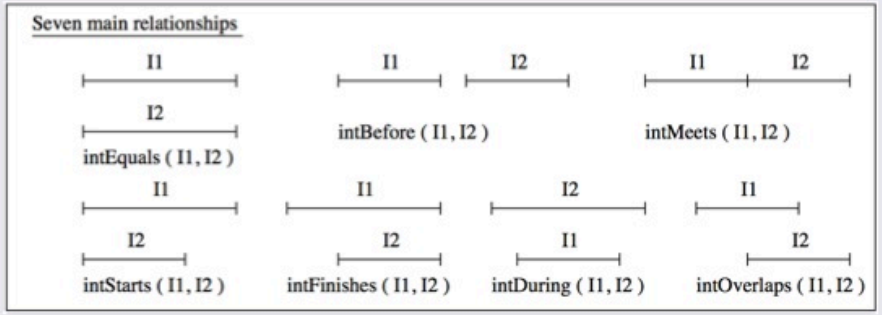
We want to know not only what is true, but when and where?

Allen's Temporal Interval Calculus (ATIC)

Features

- **Interval-based models:** formal analysis having time-dependent behavior
- **Proper Time Intervals** with fully specified Time-points for reasoning
- **Restricted axioms ensuring time reasoning decidability** (in OWL DL)
- **Temporal properties and their evolutions:**
  - **(1) Mereology** (part-of): Does t occur within I_1?,
  - **(2) Topological**(connects): Do intervals I_1 and I_2 meet? and,
  - **(3) Logical** (rules-based) : Does proposition ϕ hold within the interval I_1?

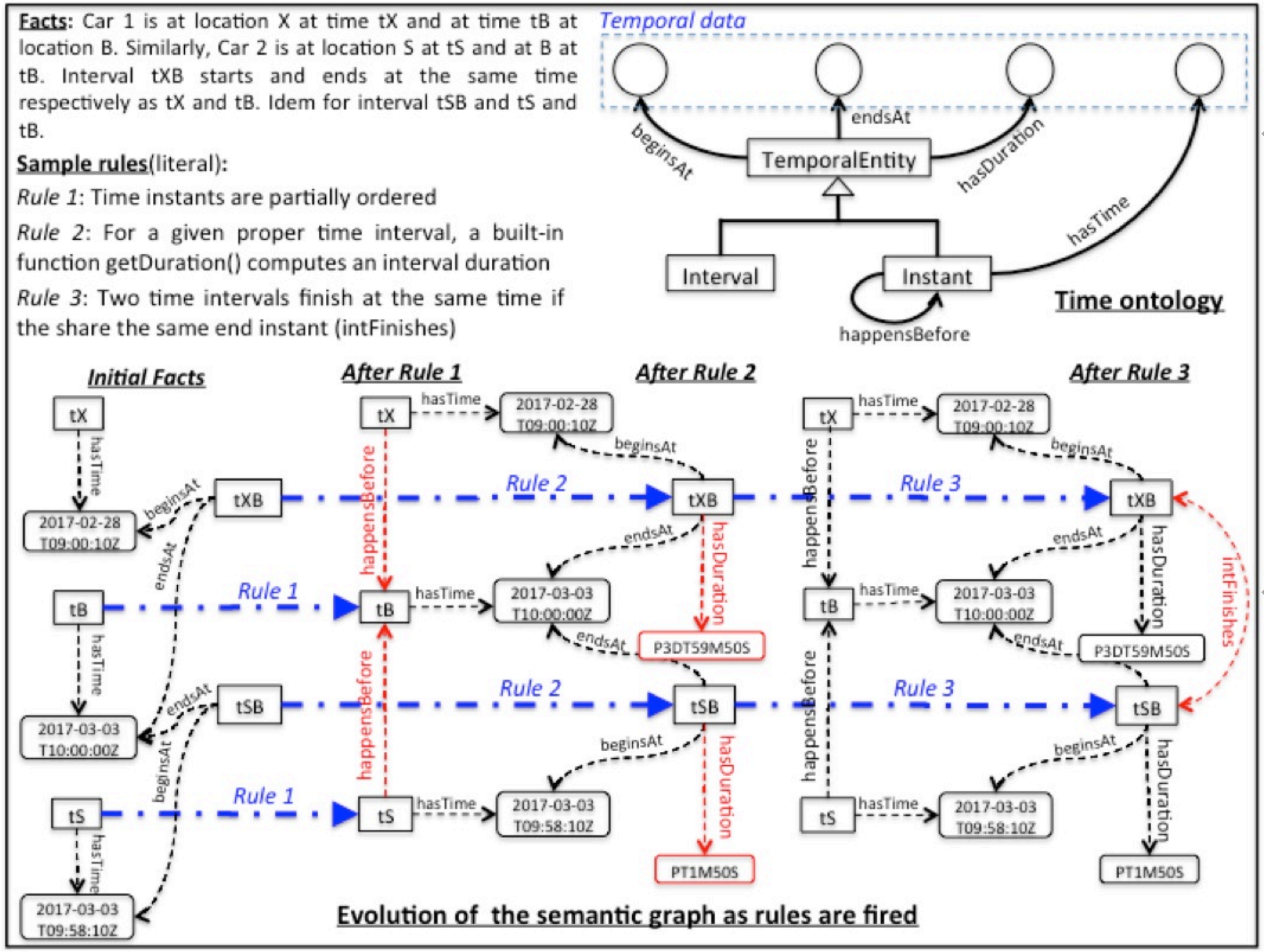
Thirteen (13) relations



Example (intOverlaps)

$$intOverlaps(I_1, I_2) \equiv [ProperInterval(I_1) \wedge ProperInterval(I_2)]$$
$$\wedge\ (\exists\, t_2,\ t_3)[ends(t_2,\ I_1\ ) \wedge begins(t_3,\ I_2\ ) \wedge before(t_3,\ t_2)$$
$$\wedge\ (\forall\, t_1\ )[begins(t_1,\ I_1\ ) \Rightarrow before(t_1,\ t_3\ )]$$
$$\wedge\ (\forall\, t_4\ )[ends(t_4,\ I_2\ ) \Rightarrow before(t_2,\ t_4\ )]]]]$$

Illustration: ATIC-based Time Ontology and Reasoning



Time Ontology

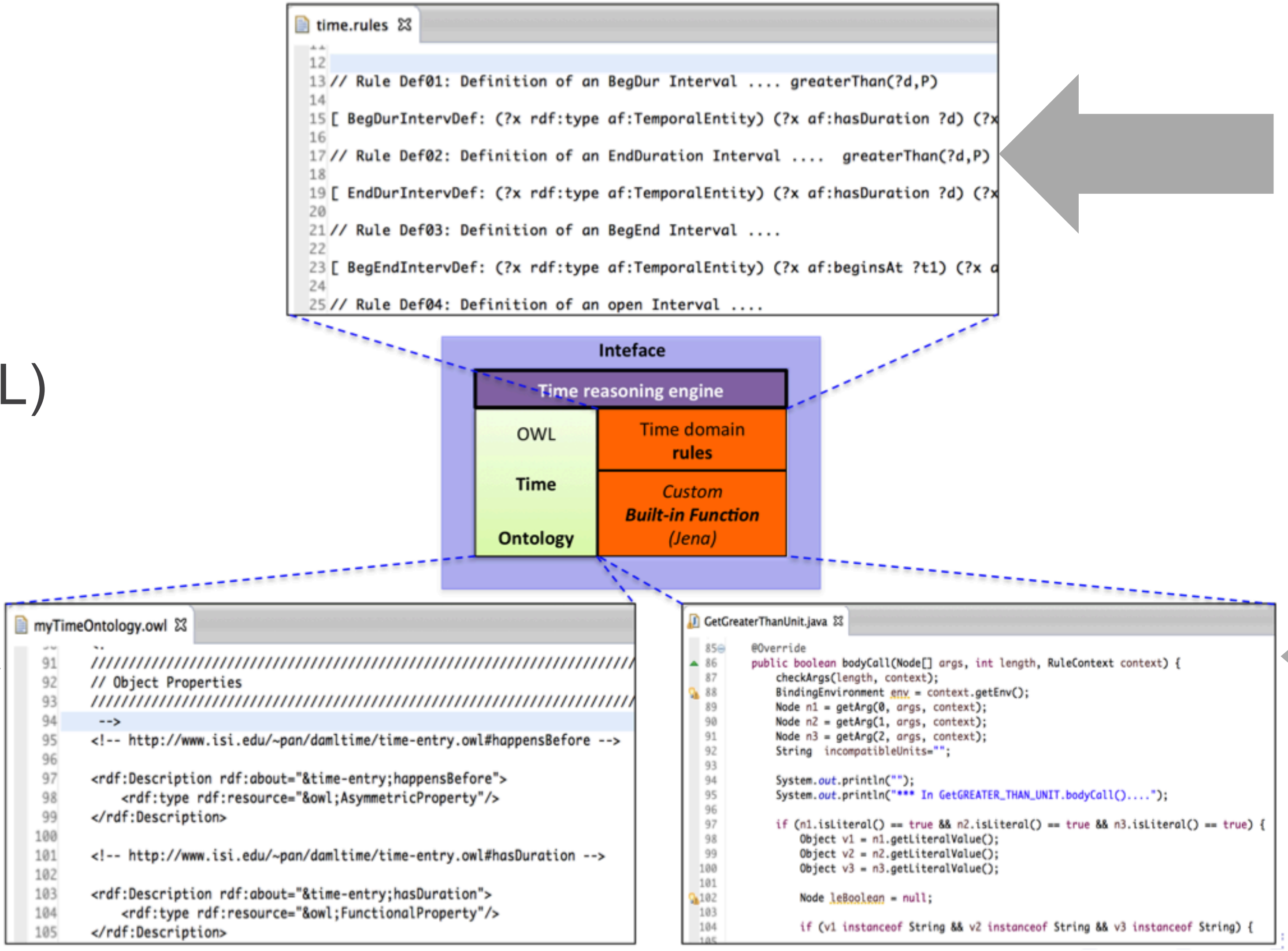
Event-driven evolution of the Semantic Graph

Reusable Semantic Block (Time)

Jena Rules

Ontology (OWL)

Built-in Functions



Region Connectedness Calculus (RCC)

Features of RCC- 8

1. **Space-region theory:** convex region of any shape with $D \geq 1$
2. **Mereotopological** description;
3. Boundaries; static and dynamic-based **reasoning support**

R_1(X,Y) \ R_2(Y,Z)	DC	EC
DC	No info.	DR,PO,PP
EC	DR,PO,PPi	DR,PO,TPP,TPi

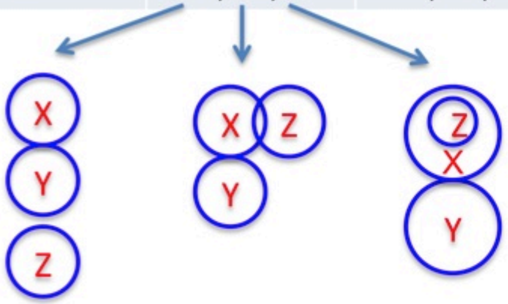


Figure: Composition table(excerpt)

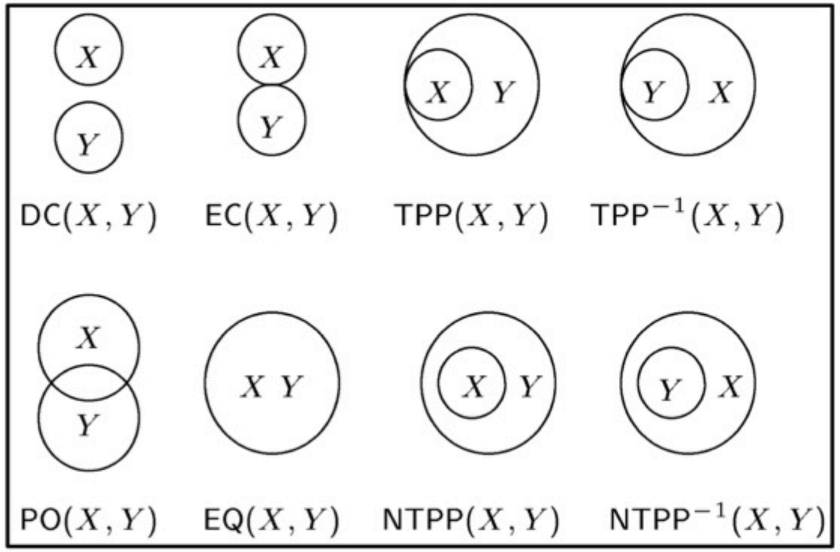


Figure: RCC-8, possibly -5 relations

Example (Restrictions - for decidability)

1. 3D abstraction with 0, 1, 2D rep.
2. Closed convex spatial entities;
3. Regular shapes; No transitivity deductions;

Illustration: RCC8-based Ontology and Rules

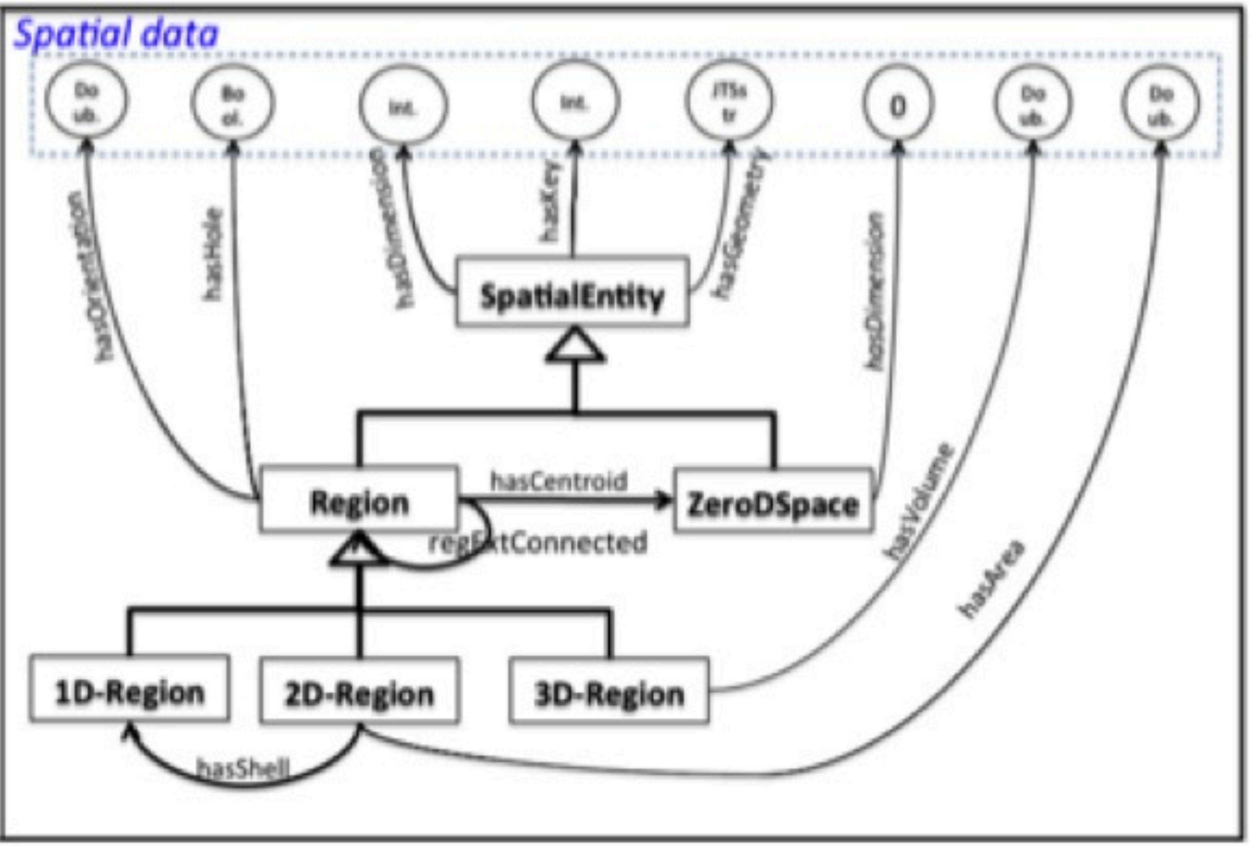
Facts: At a given instant t, cars, as spatial entities c1, .., c4 are traveling through a subset of the intersection as spatial entities s1,…, s4 respectively along trajectories tr1,…,tr4. Spatial entities types and (JTS) geometries - e.g., Point LineString, Polygon - are known

Sample rules (literal):

Rule 1: From a given JTS geometry, a built-in function getGeometryType() infers the type of a spatial entity

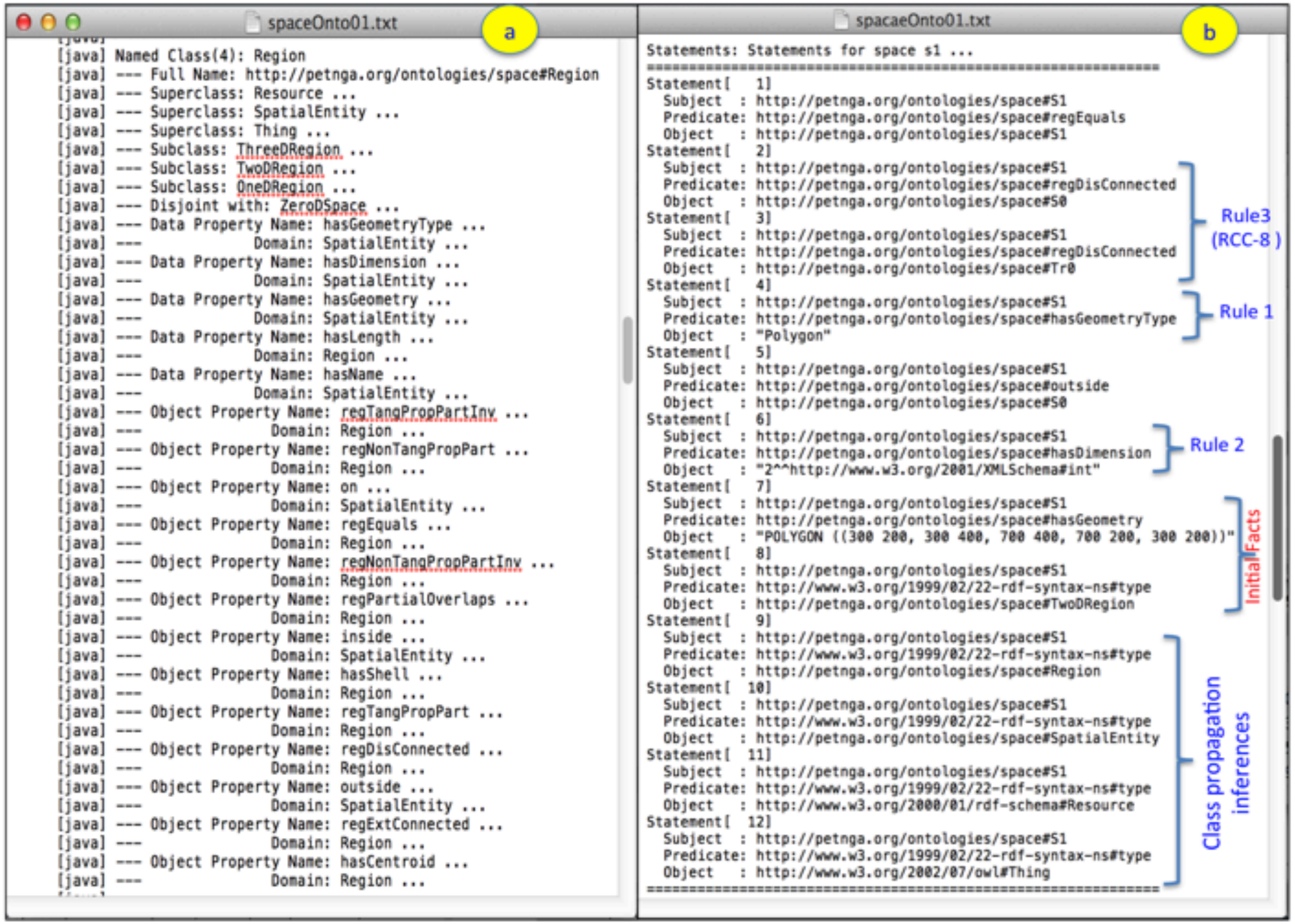
Rule 2: For a given type of space, a built-in function getDimension(), computes the dimension of a spatial entity

Rule 3: Two spatial entities are disconnected if their geometry are disjoints



Spatial Reasoning with Jena and Jena Rules

Excerpt of Region Class



Statements associated with Spatial Reasoning

Model Integration

Basic issue: How to integrate models in the semantic framework for effective simulation and analysis of NoS?

Whistle: System Integration Language

Language capabilities

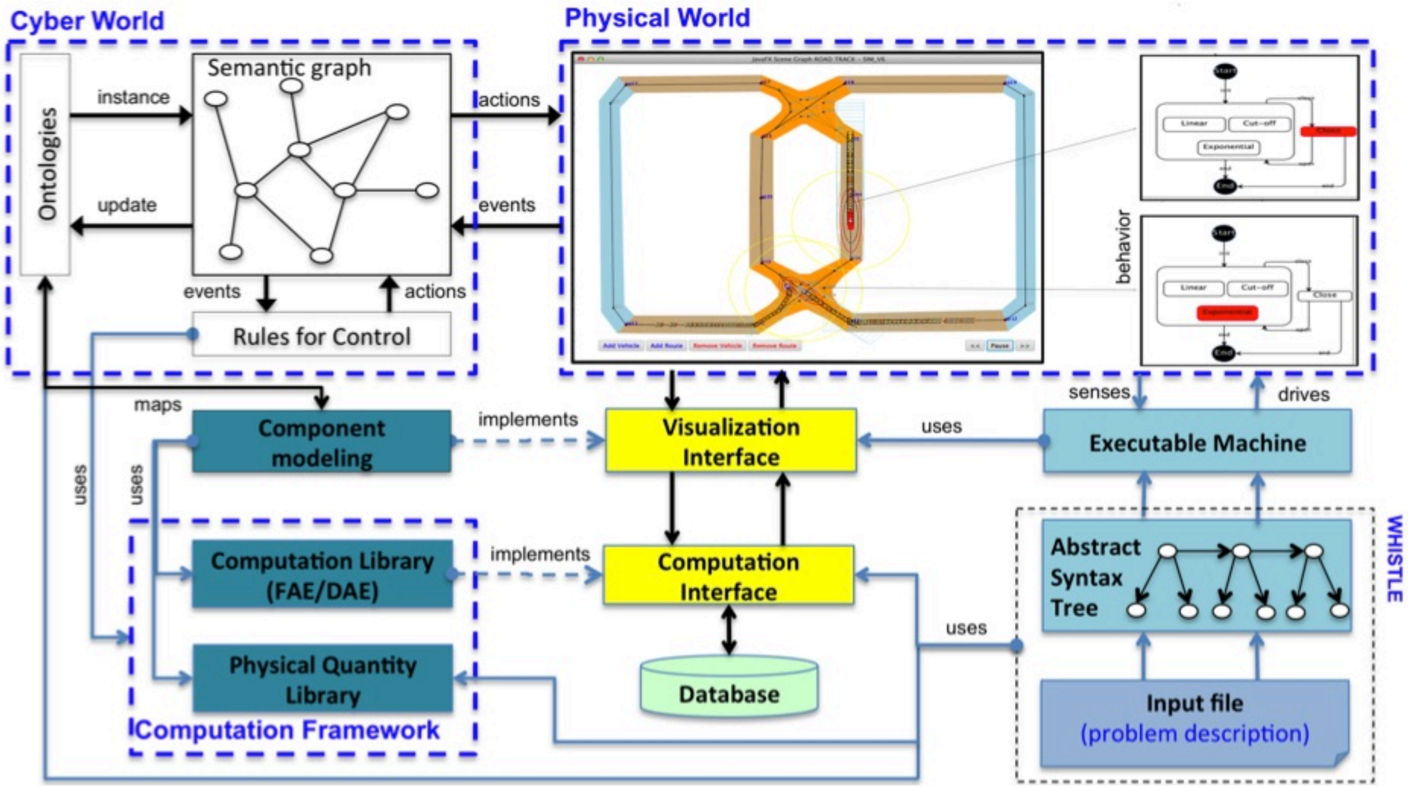
1. Integration of models of physical components & computation
2. Simulation and analysis of continuous & discrete behaviors
3. Support: Units, branching, looping, Multi-format(XML,OSM,..)

Looping Constructs

```
x = 0 cm;
while ( x <= 10 cm ) {
   print "*** x = ", x;
   if ( x <= 5 cm ) {
      x = x + 1 cm;
   } else {
      x = x + 2 cm;
   }
}
```

Networks of finite state machine behaviors

Systems Integration

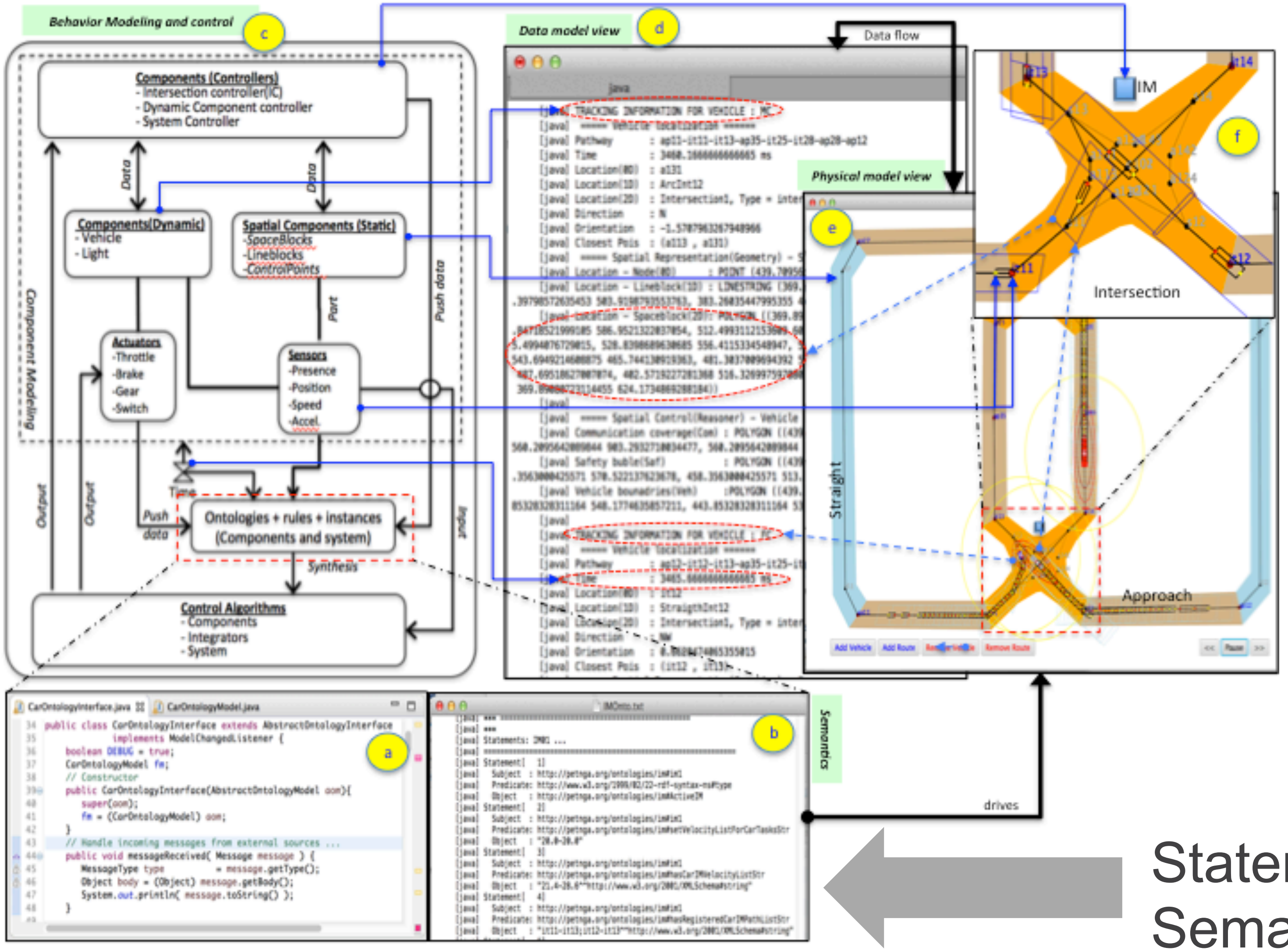


For a description of Whistle, see Delgoshaei, Austin and Pertzborn [2014].

Application: Traffic Intersection with No Traffic Lights

Behavior modeling and control.

Car Ontology Interface

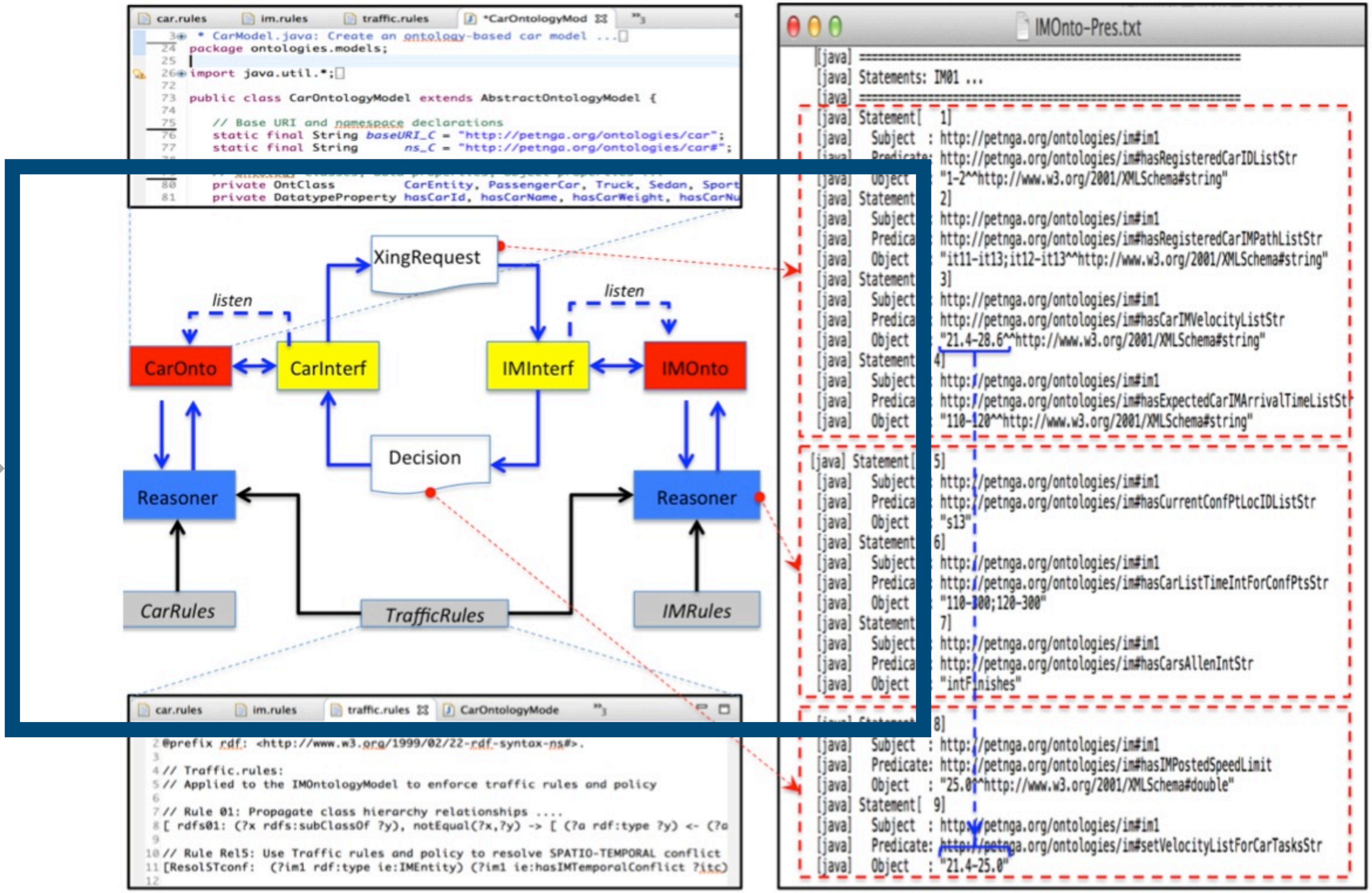


Visualization of race track pathways and geometry

Statements in the Semantic Model

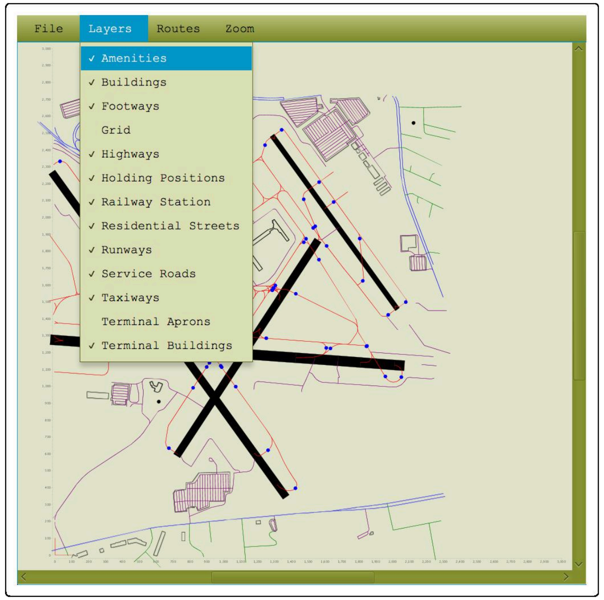
Spatio-Temporal: Reasoning, Communication and Control

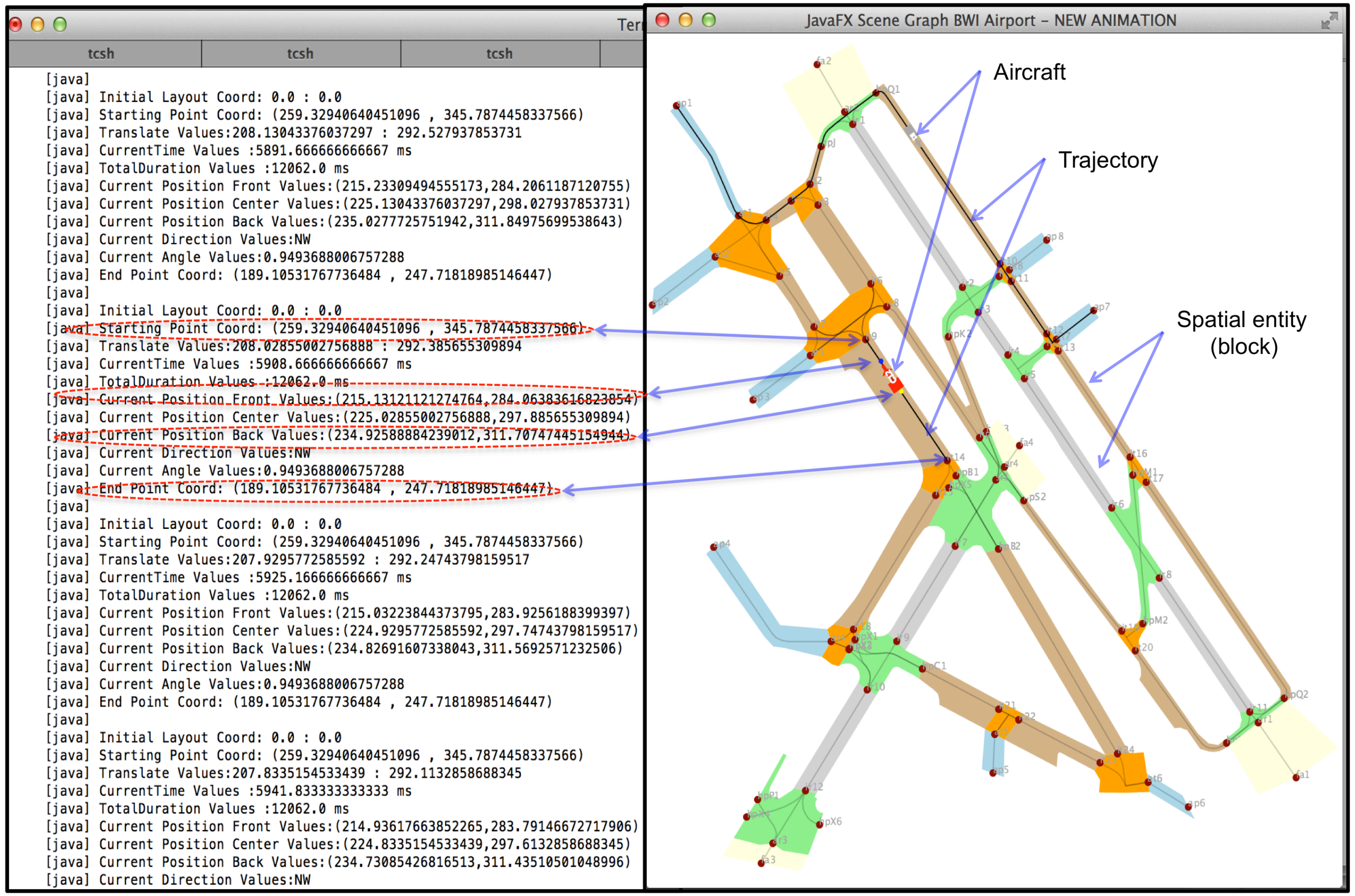
Intersection Manager / Vehicle Communication



Scaling Things Up

Work in Progress (2017-2018)





Research Challenges: Large volumes of data; semi-automated synthesis of semantic models; dynamic integration of ontologies and rules in decision making.

Summary

Design challenges of Network of Systems

- Increasingly complex, heterogeneous, distributed and connected
- **Limitations MBSE:** weak domain & language semantics, model inconsistencies

Semantic-based platform for MBSE of NoS

- Formal model of systems (i.e domains and metadomains) using decidable OWL
- Allen's Temporal Intervals Calculus & restricted Region Connection Calculus
- Modular, flexible, reusable reasoning-enabled semantic blocks
- System integration with Whistle scripting language (under development)

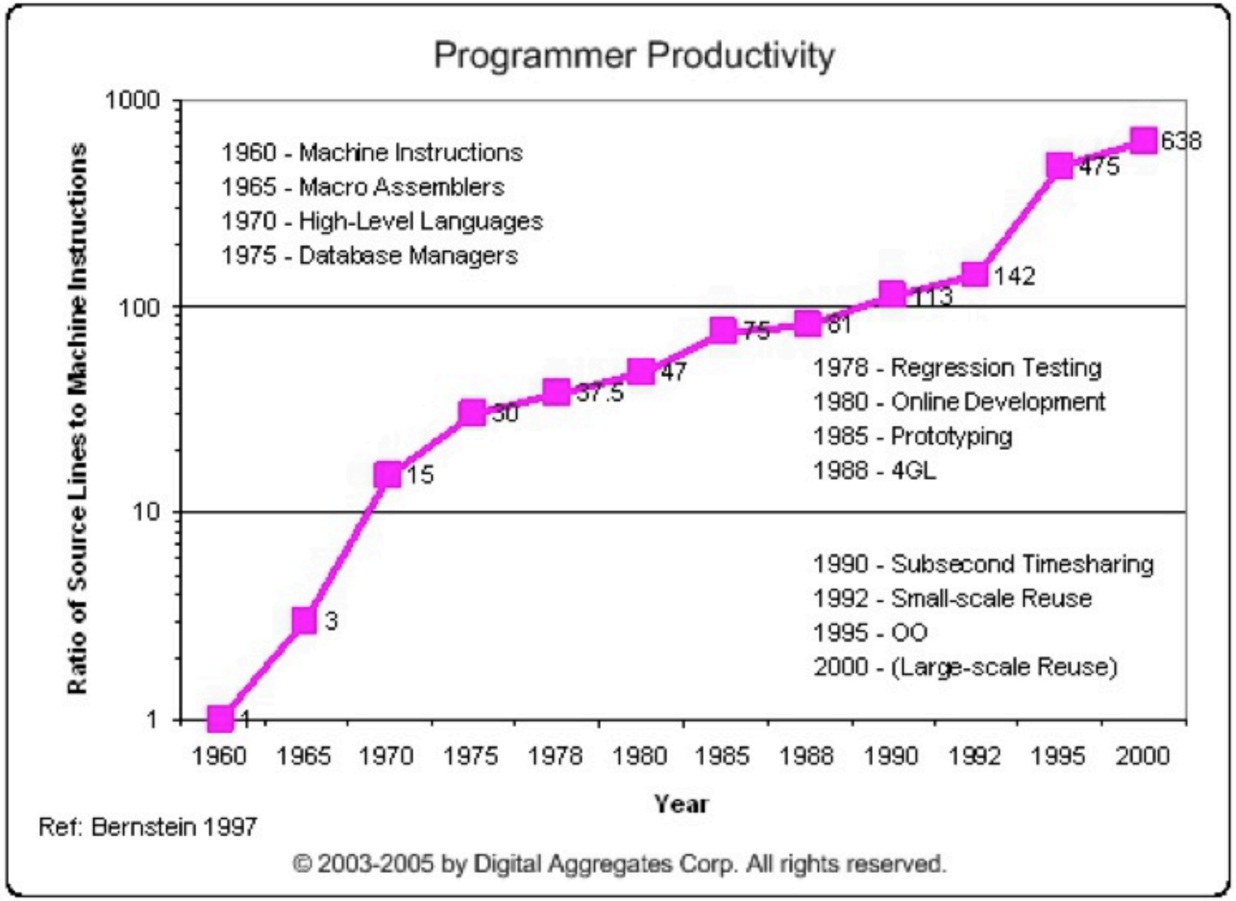
Select Publications

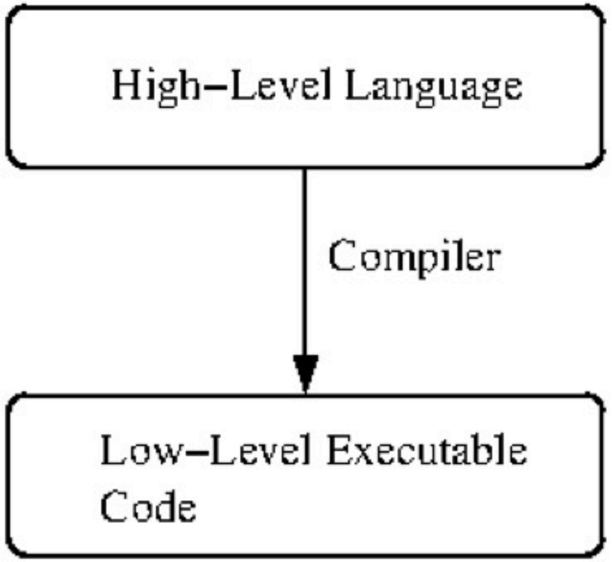
- Petnga L. and Austin M.A., An Ontological Framework for Knowledge Modeling and Decision Support in Cyber-Physical Systems, Advanced Engineering Informatics, Vol. 30, No. 1, January 2016, pp. 77-94.
- Petnga L. and Austin M.A., Ontologies of Time and Time-Based Reasoning for MBSE of Cyber-Physical Systems, 11th Annual Conference on Systems Engineering Research (CSER 2013), Georgia Institute of Technology, Atlanta, GA, March 19-22, 2013. **Best Conference Paper Award.**
- Petnga L. and Austin M.A., Cyber-Physical Architectures for Modeling and Enhanced Operations of Connected-Vehicle Systems, 2nd IEEE/TRB International Conference on Connected Vehicles (ICCVE 201), Las Vegas, December 2-6, 2013
- Delgoshaei P., Austin M.A., and Pertzborn A., A Semantic Framework for Modeling and Simulation of Cyber-Physical Systems, International Journal On Advances in Systems and Measurements, Vol. 7, No's 3-4, December 2014.
- Austin M.A., Delgoshaei P. and Nguyen A., Distributed Systems Behavior Modeling with Ontologies, Rules, and Message Passing Mechanisms, 13th Annual Conference on Systems Engineering Research (CSER 2015), Stevens Institute of Technology Campus, Hoboken, New Jersey, March 17-19, 2015, pp. 373-382, **MITRE Best Transition in Systems Engineering Research Award.**
- Coelho M., Austin M.A. and Blackburn M., Distributed System Behavior Modeling of Urban Systems with Ontologies, Rules and Many-to-Many Association Relationships, The 12th International Conference on Systems (ICONS 2017), Venice, Italy, April 23 - 27, 2017, pp. 10-15. **Best Paper Award.**

Backup Slides

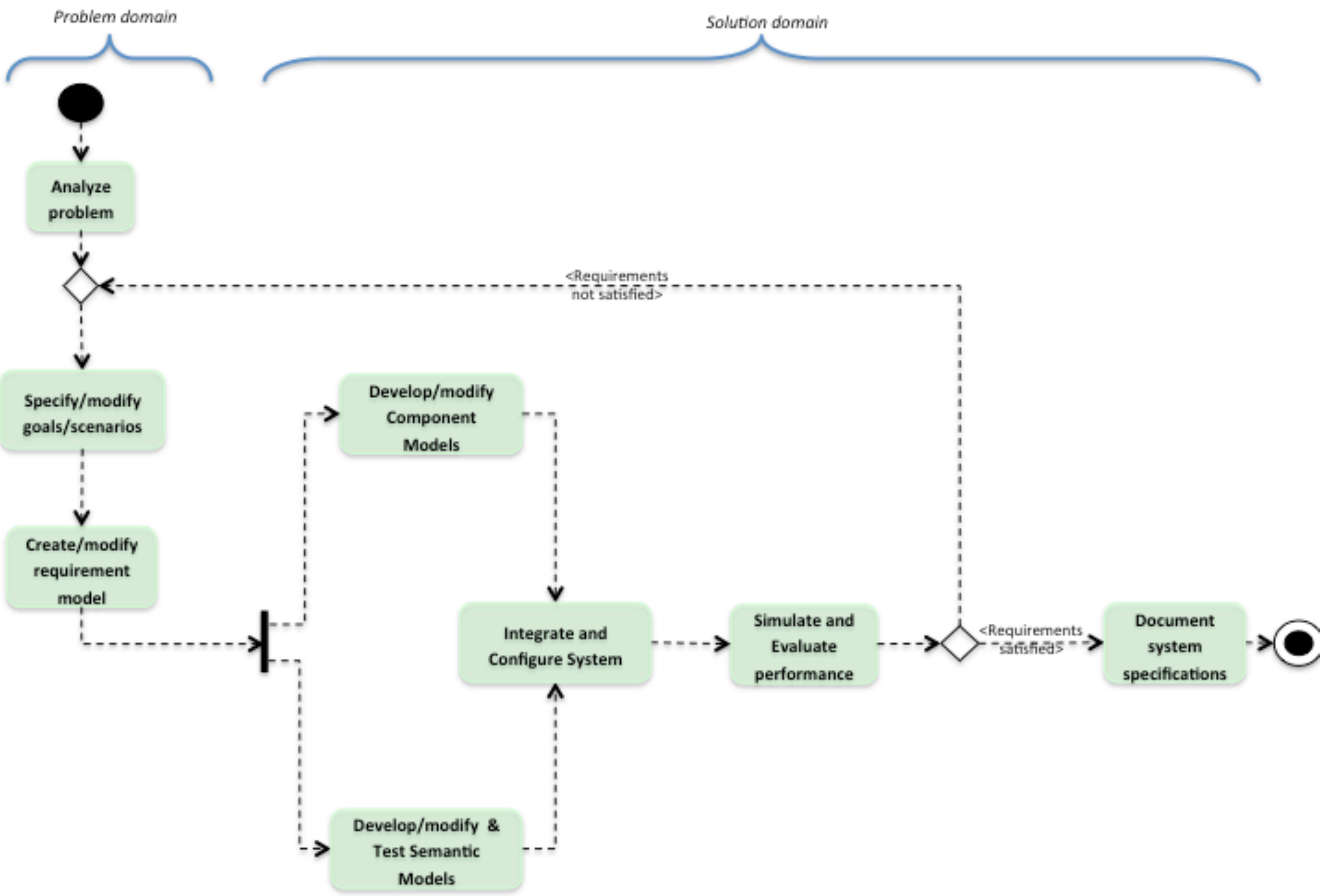
Management of Software Complexity

Increasing System Complexity: Software programmers need to find ways to solve problems at high levels of abstraction.





Proposed Implementation Process



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