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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

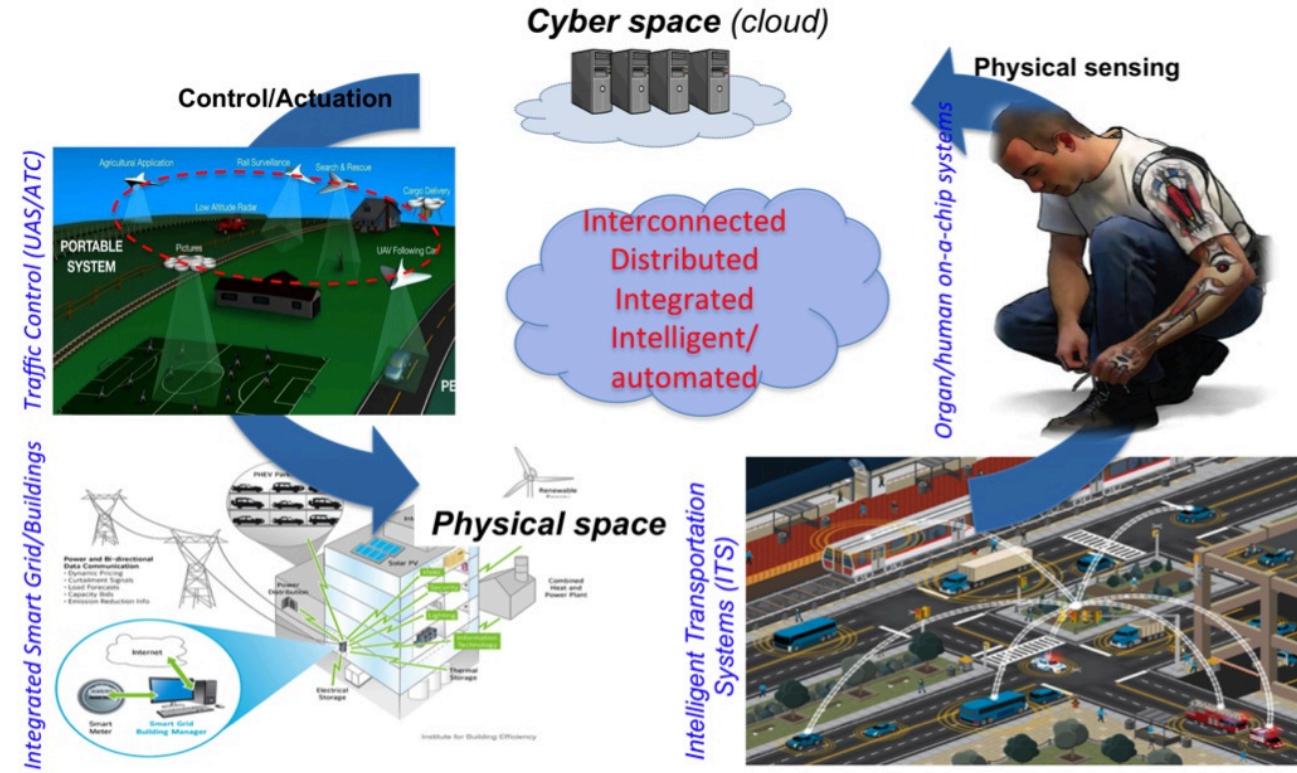
Acknowledgement: Financial support and collaborations with NAVAIR and NIST.



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 systems** (CPSs) operating in a **networked environment**.

Network of Systems Backbone: CPS and SoS

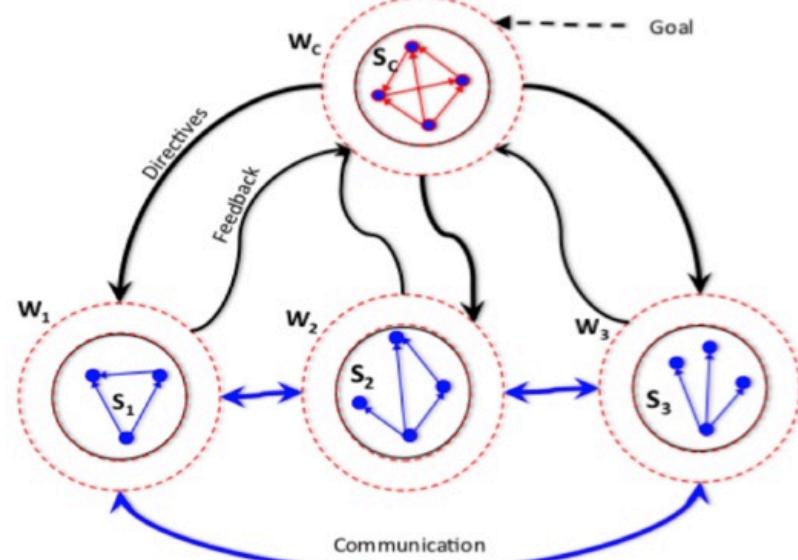
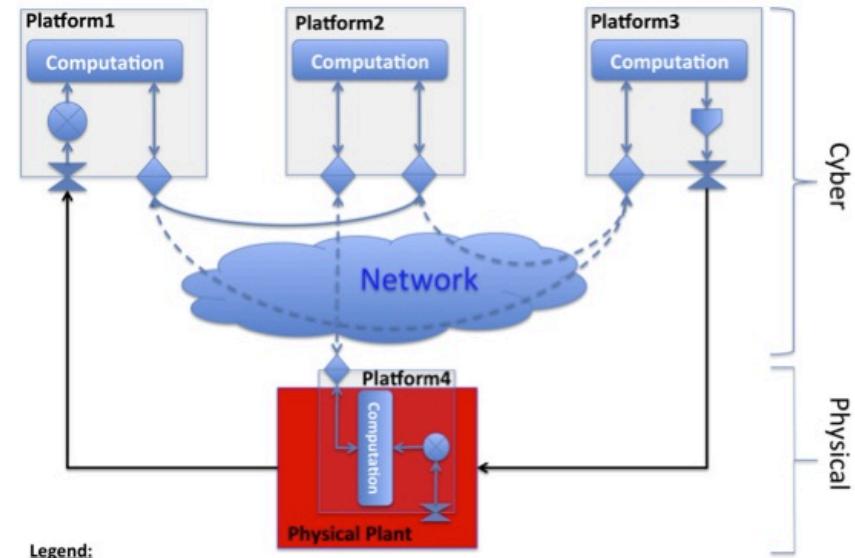


Local: Cyber-Physical Systems(CPS)

- 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

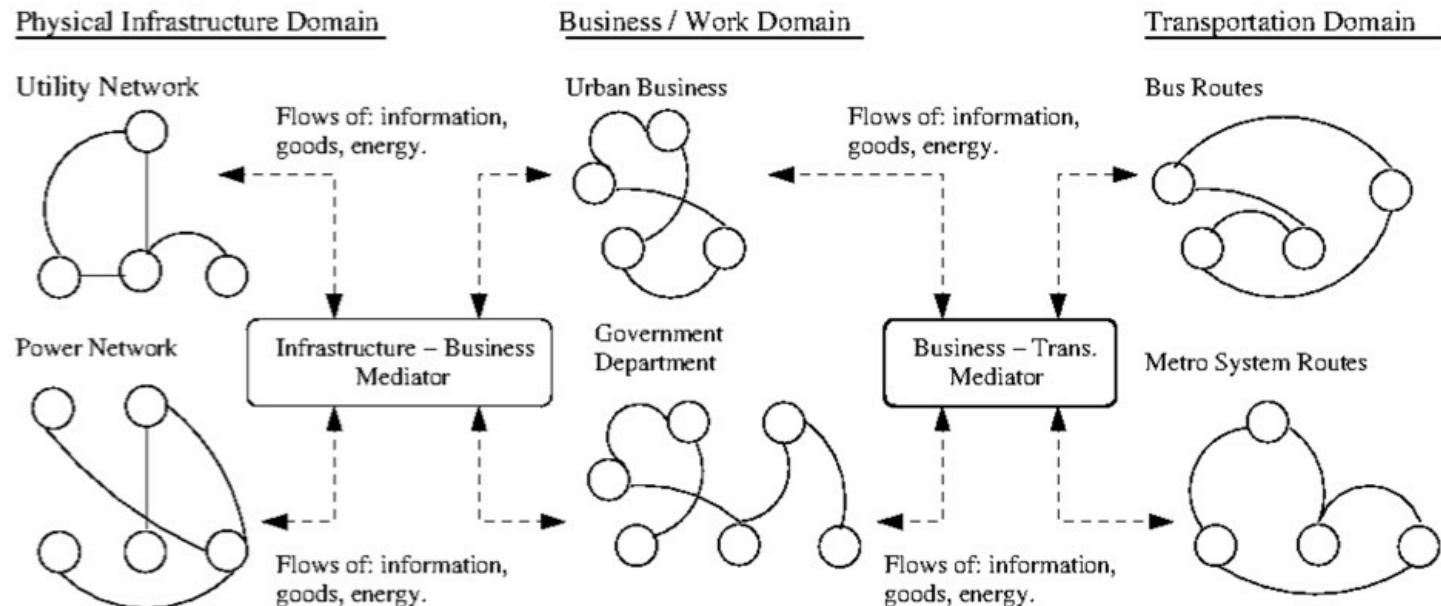


Distributed System Behavior Modeling for NoS



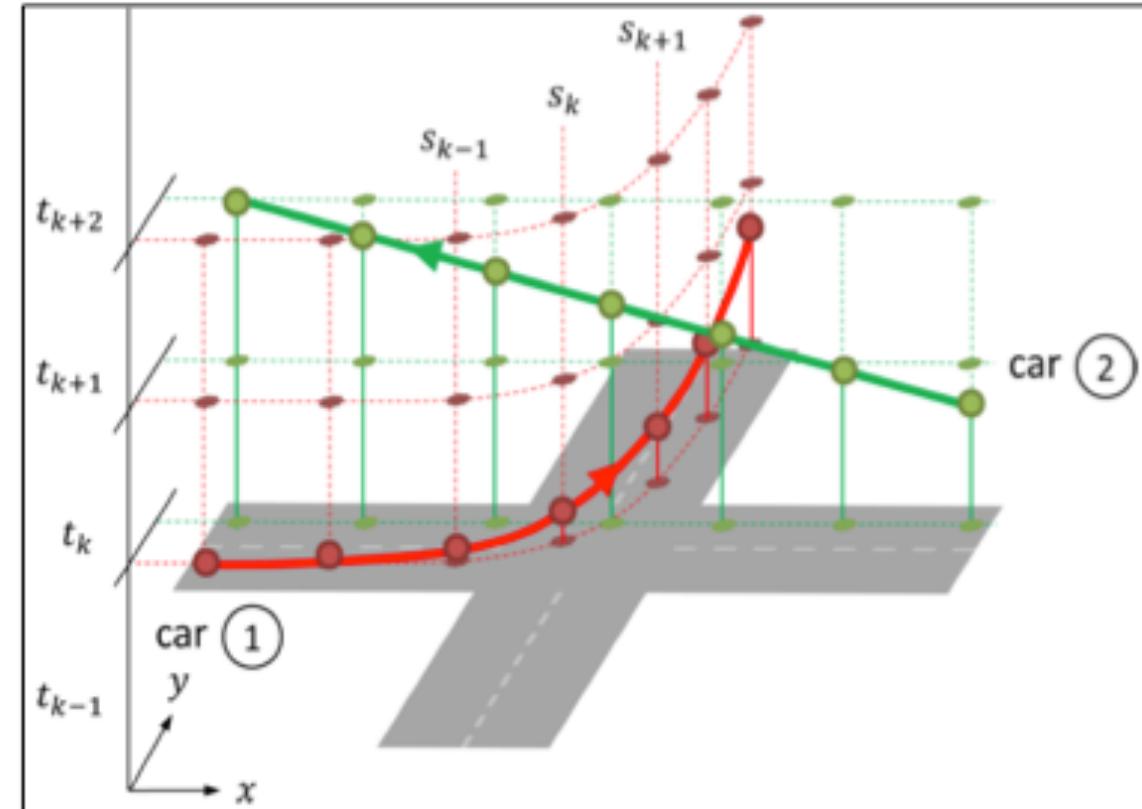
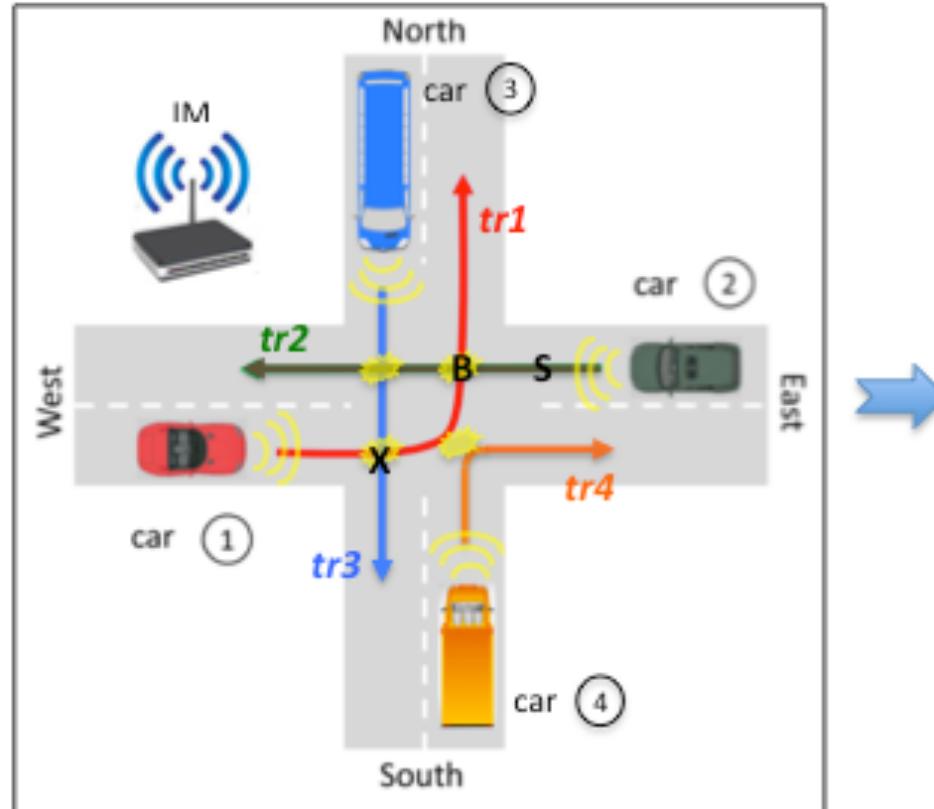
Enabling Distributed System Control

- **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]

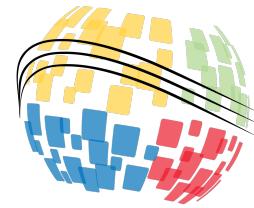


Source: Coelho, Austin and Blackburn, 2017.

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]

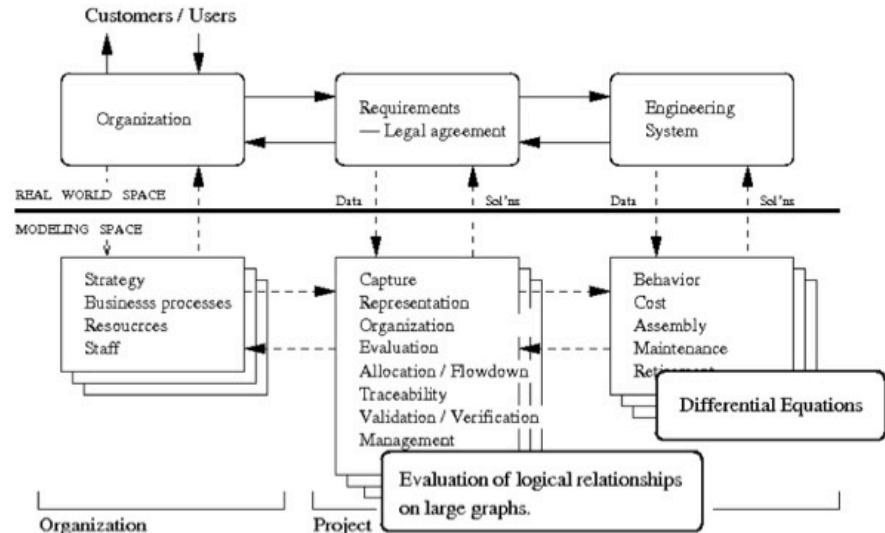
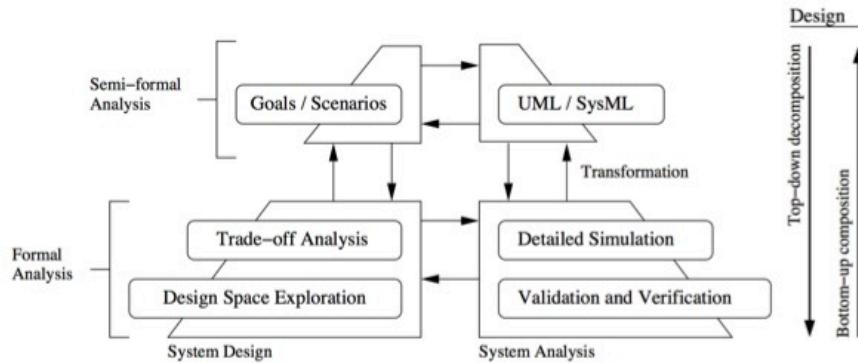


Figure: Multi-level approach [Mosteller, 2014]



Design correctness \Rightarrow semantic-driven approach to modeling/integration

MBSE ill-equipped for decision making/reasoning

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



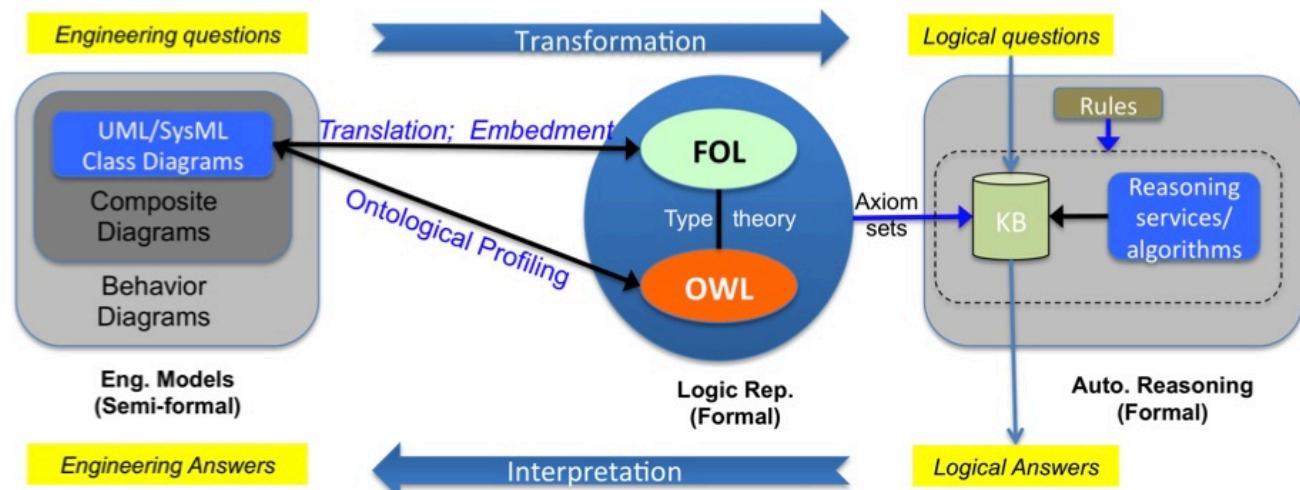
Semantics in MBSE

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]



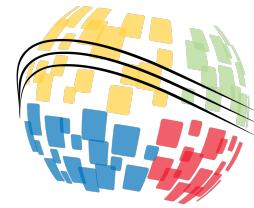
Ans.: Model inconsistencies, redundancies.

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

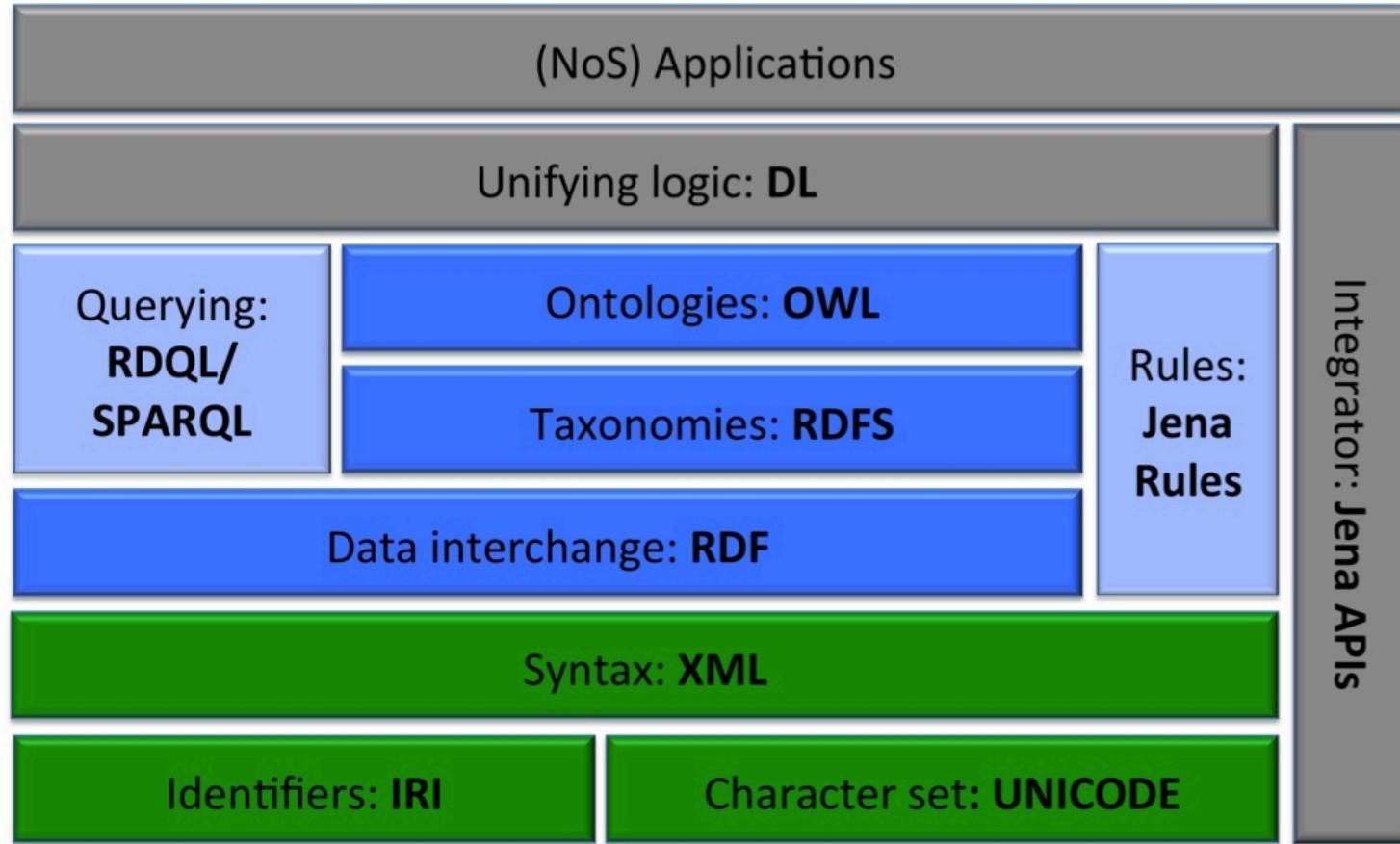
Tenet 1: NoS should be designed and managed through the use of models, as opposed to documents

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

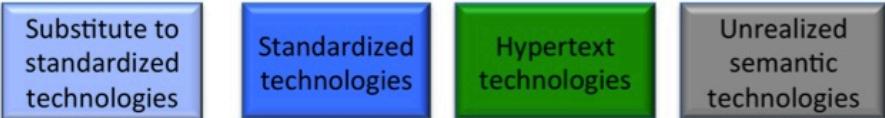
Tenet 2: NoS design methodologies need to employ semantic descriptions of domains and formal reasoning

- 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



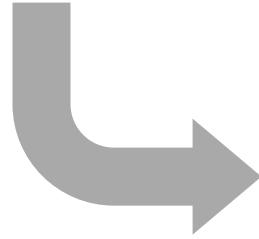
Legend:



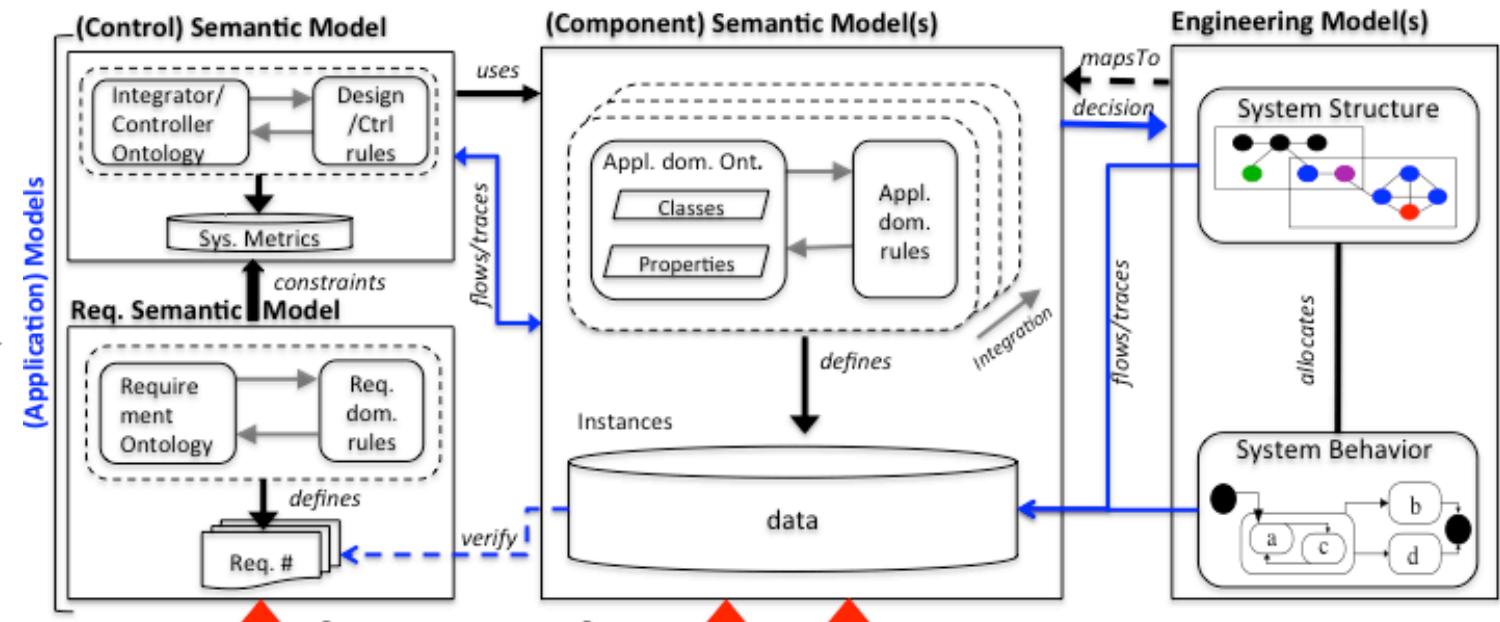
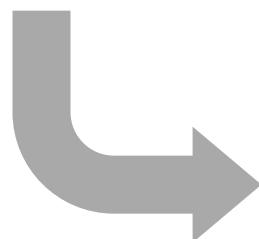
System Architecture (Work in Progress)



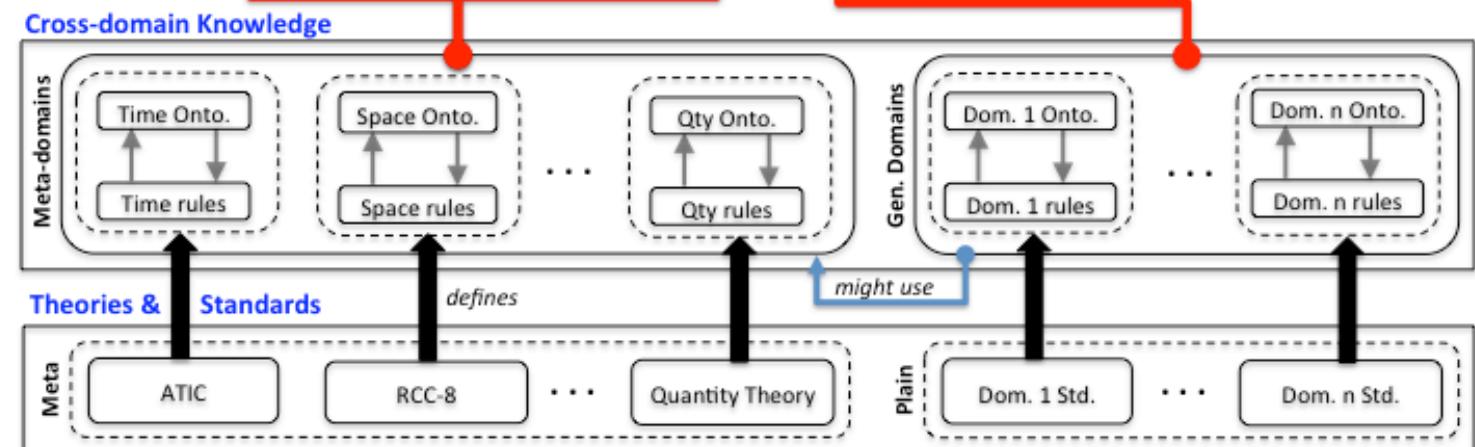
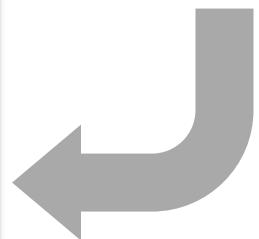
Semantic Model



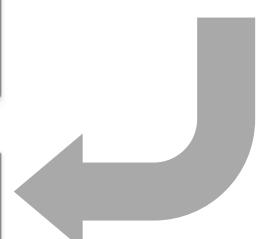
Cross-domain knowledge



Engineering Models



Theories and Standards





Simple Example



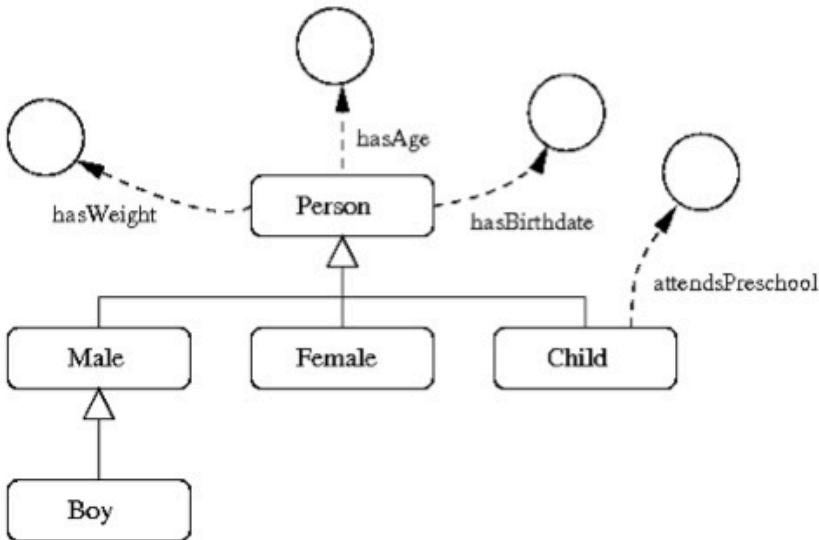
Simplified Semantic Modeling of a Family

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

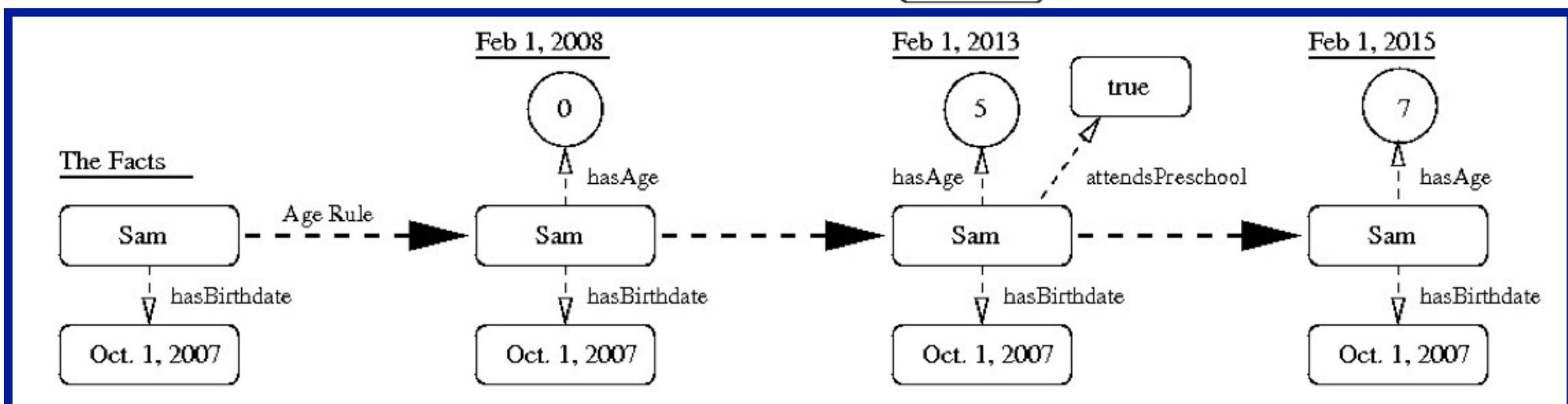
Rule 1: For a given date of birth, a built-in function `getAge()` computes a person's age.

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

Rule 3: Children who are age 5 attend preschool.



Ontology



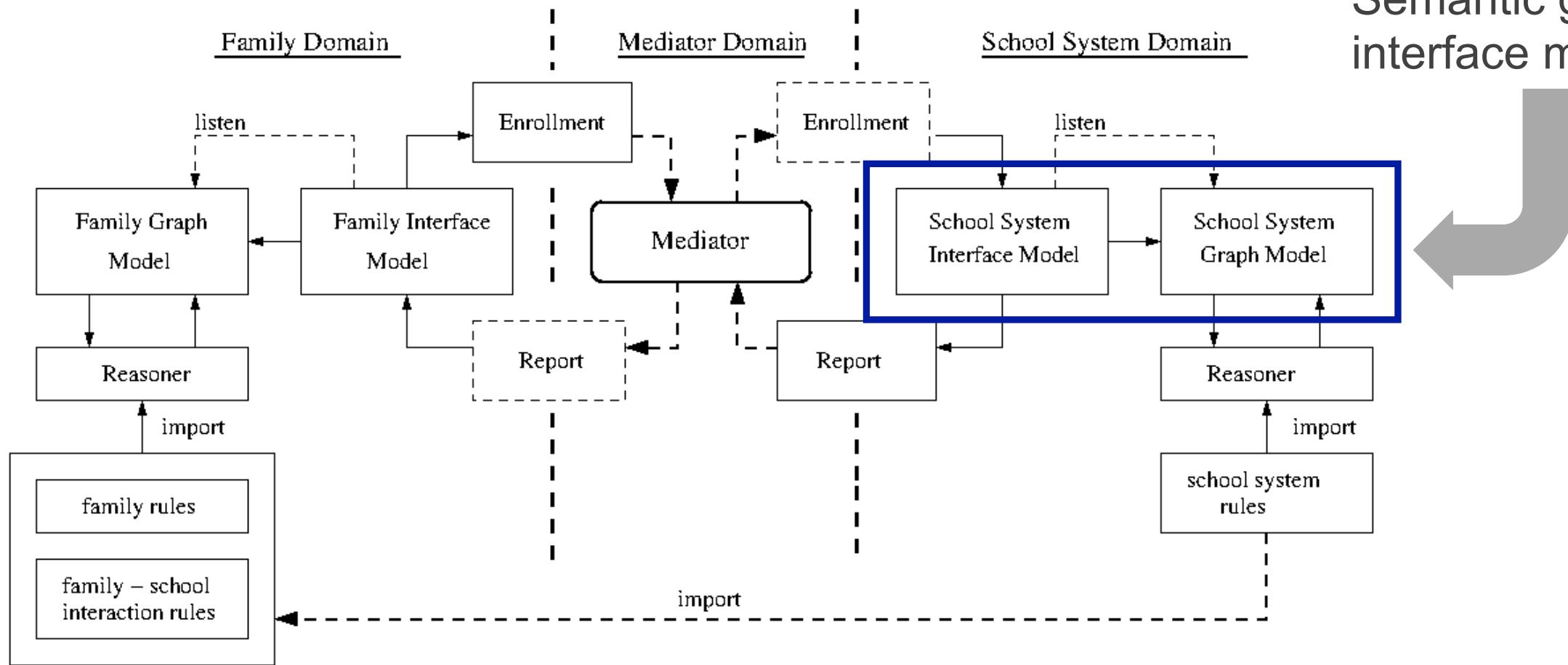
Event-driven evolution of semantic graph.

Source: Delgoshaei, Austin, Pertzbom 2014.

Behavior Modeling of Family-School Interactions

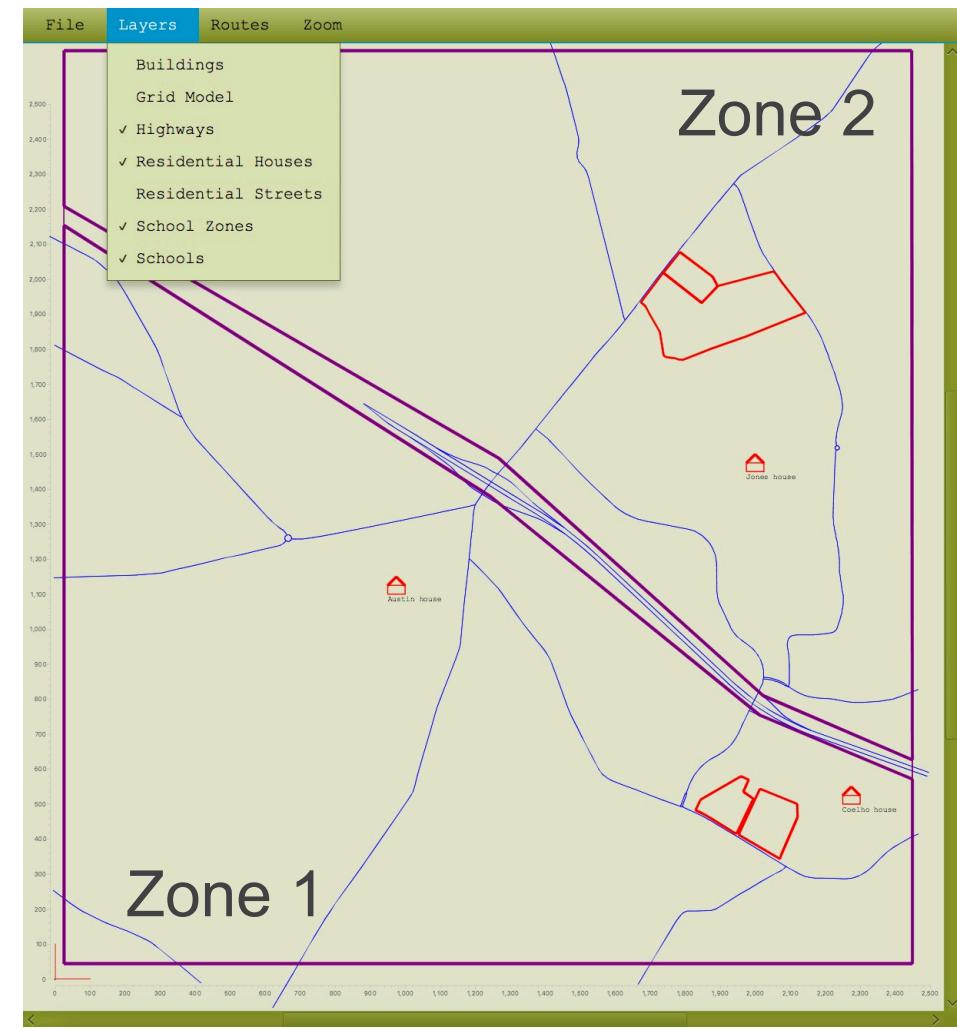
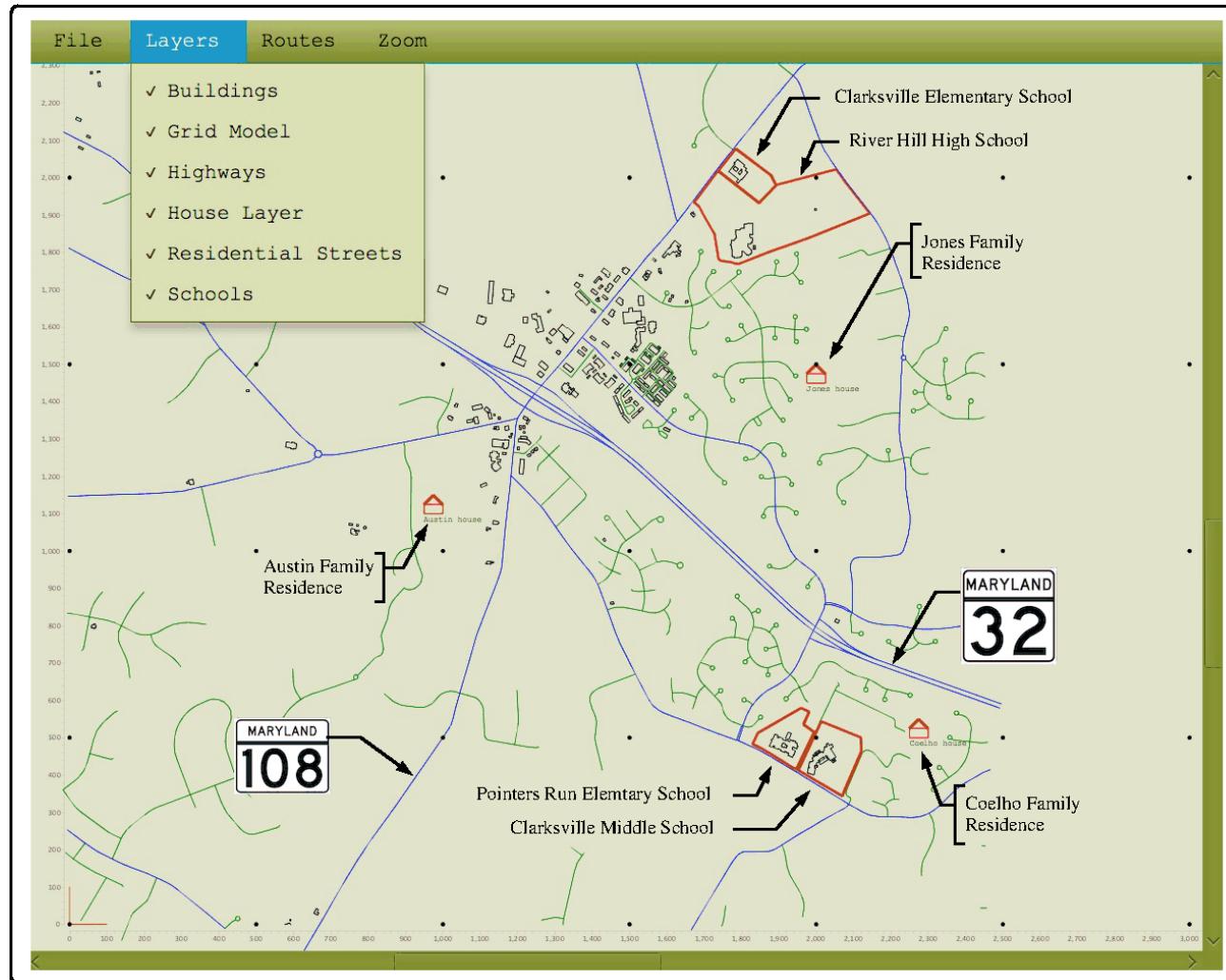


Semantic graph and interface model



Source: Coelho, Austin and Blackburn, 2017.

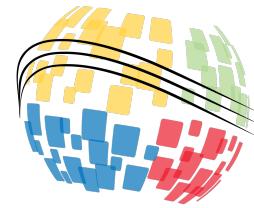
Family-School-Urban System Dynamics





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:

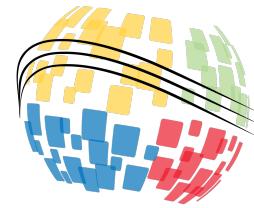
We want to know what is true, and when?

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?

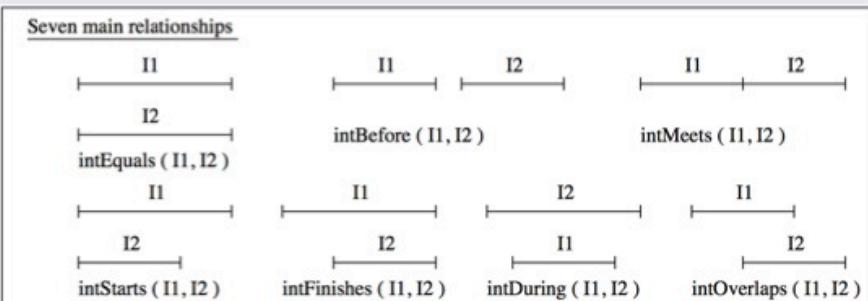


Allen's Temporal Interval Calculus (ATIC)

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)

$$\begin{aligned} \text{intOverlaps}(I_1, I_2) \equiv & [\text{ProperInterval}(I_1) \wedge \text{ProperInterval}(I_2)] \\ & \wedge (\exists t_2, t_3)[\text{ends}(t_2, I_1) \wedge \text{begins}(t_3, I_2) \wedge \text{before}(t_3, t_2)] \\ & \wedge (\forall t_1)[\text{begins}(t_1, I_1) \Rightarrow \text{before}(t_1, t_3)] \\ & \wedge (\forall t_4)[\text{ends}(t_4, I_2) \Rightarrow \text{before}(t_2, t_4)] \end{aligned}$$



Illustration: ATIC-based Time Ontology and Reasoning

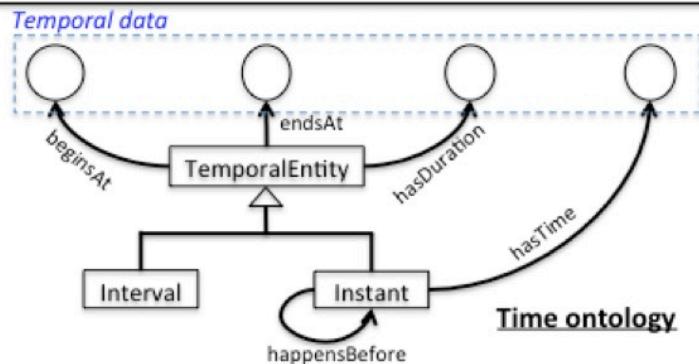
Facts: Car 1 is at location X at time tX and at time tB at location B. Similarly, Car 2 is at location S at tS and at B at tB. Interval tXB starts and ends at the same time respectively as tX and tB. Idem for interval tSB and tS and tB.

Sample rules(literal):

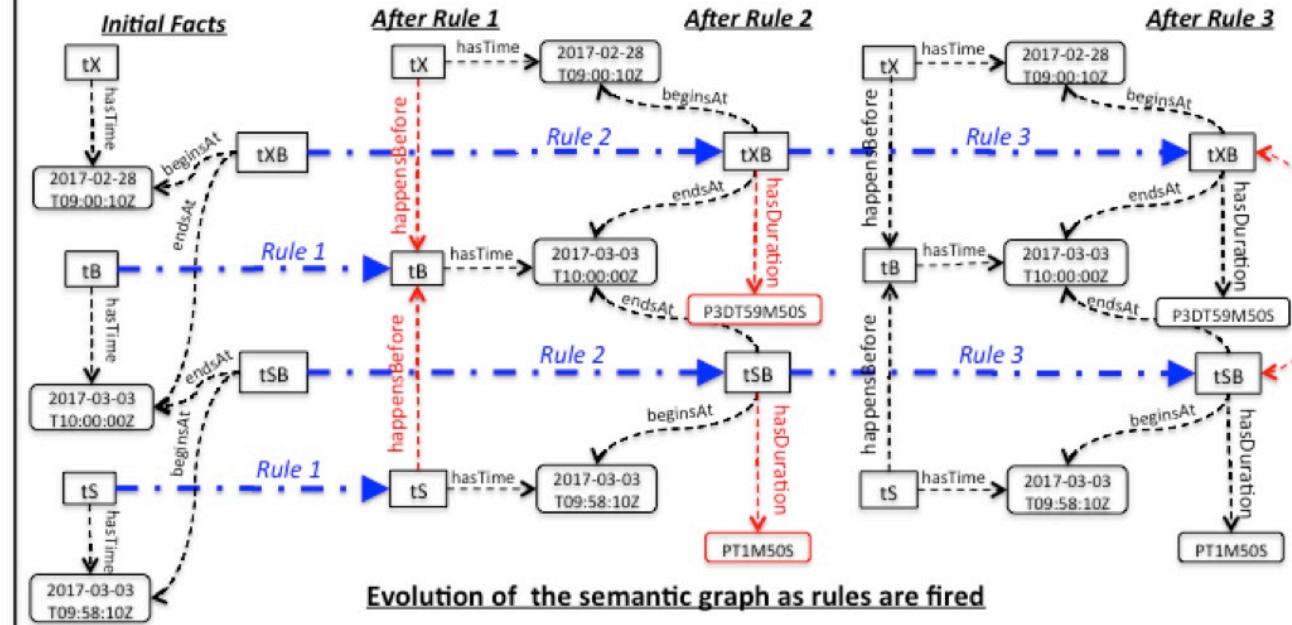
Rule 1: Time instants are partially ordered

Rule 2: For a given proper time interval, a built-in function getDuration() computes an interval duration

Rule 3: Two time intervals finish at the same time if they share the same end instant (intFinishes)

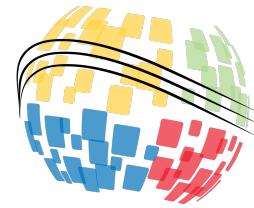


Time Ontology

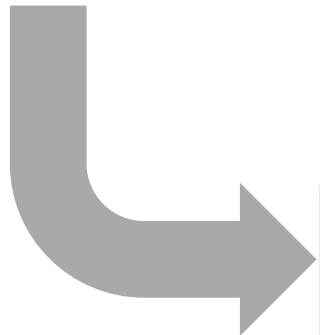


Event-driven
evolution of the
Semantic Graph

Reusable Semantic Block (Time)

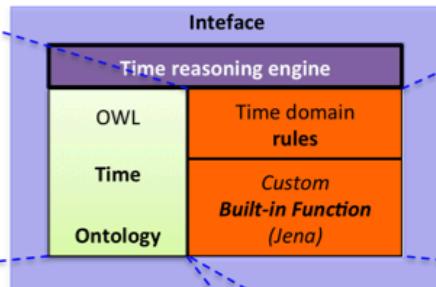


Ontology (OWL)



```
time.rules <>
12
13 // Rule Def01: Definition of an BegDur Interval .... greaterThan(?d,P)
14
15 [ BegDurIntervDef: (?x rdf:type af:TemporalEntity) (?x af:hasDuration ?d) (?x
16
17 // Rule Def02: Definition of an EndDuration Interval .... greaterThan(?d,P)
18
19 [ EndDurIntervDef: (?x rdf:type af:TemporalEntity) (?x af:hasDuration ?d) (?x
20
21 // Rule Def03: Definition of an BegEnd Interval ....
22
23 [ BegEndIntervDef: (?x rdf:type af:TemporalEntity) (?x af:beginsAt ?t1) (?x a
24
25 // Rule Def04: Definition of an open Interval ....
```

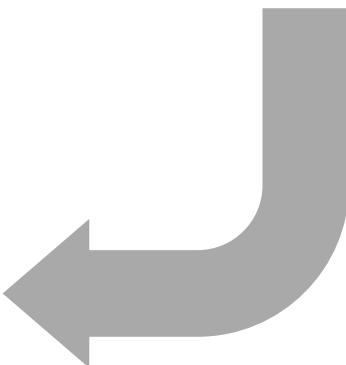
Jena Rules



```
myTimeOntology.owl <>
91
92 // Object Properties
93
94 -->
95 <!-- http://www.isi.edu/~pan/damltime/time-entry.owl#happensBefore -->
96
97 <rdf:Description rdf:about="#time-entry;happensBefore">
98   <rdf:type rdf:resource="#owl;AsymmetricProperty"/>
99 </rdf:Description>
100
101 <!-- http://www.isi.edu/~pan/damltime/time-entry.owl#hasDuration -->
102
103 <rdf:Description rdf:about="#time-entry;hasDuration">
104   <rdf:type rdf:resource="#owl;FunctionalProperty"/>
105 </rdf:Description>
```

```
GetGreaterThanOrUnit.java <>
85
86   @Override
87   public boolean bodyCall(Node[] args, int length, RuleContext context) {
88     checkArgs(length, context);
89     BindingEnvironment env = context.getEnv();
90     Node n1 = getArg(0, args, context);
91     Node n2 = getArg(1, args, context);
92     Node n3 = getArg(2, args, context);
93     String incompatibleUnits = "";
94
95     System.out.println("");
96     System.out.println("In GetGREATER_THAN_UNIT.bodyCall()....");
97
98     if (n1.isLiteral() == true && n2.isLiteral() == true && n3.isLiteral() == true) {
99       Object v1 = n1.getLiteralValue();
100      Object v2 = n2.getLiteralValue();
101      Object v3 = n3.getLiteralValue();
102
103      Node leBoolean = null;
104
105      if (v1 instanceof String && v2 instanceof String && v3 instanceof String) {
```

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	

Diagram below the table:

Figure: Composition table(excerpt)

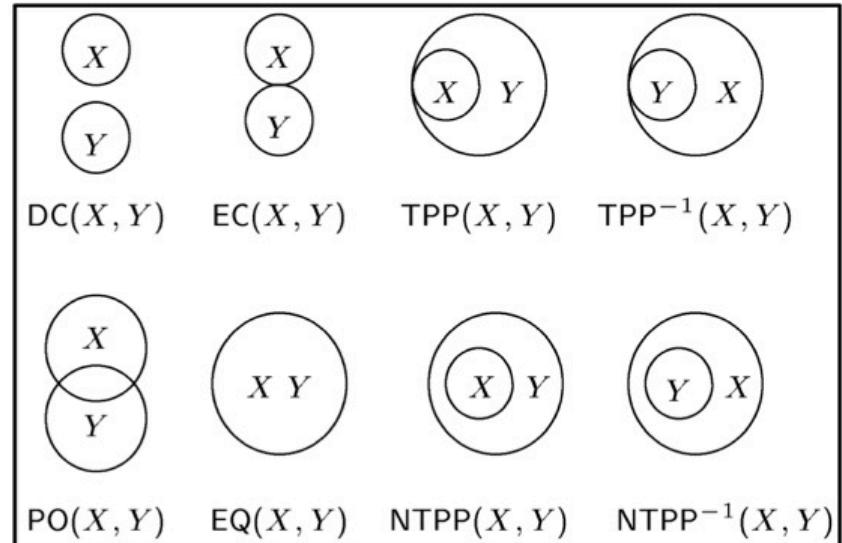


Figure: RCC-8, possibly -5 relations

Example (Restrictions - for decidability)

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

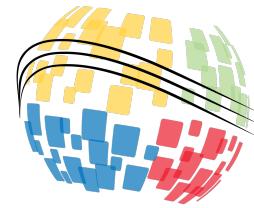


Illustration: RCC8-based Ontology and Rules

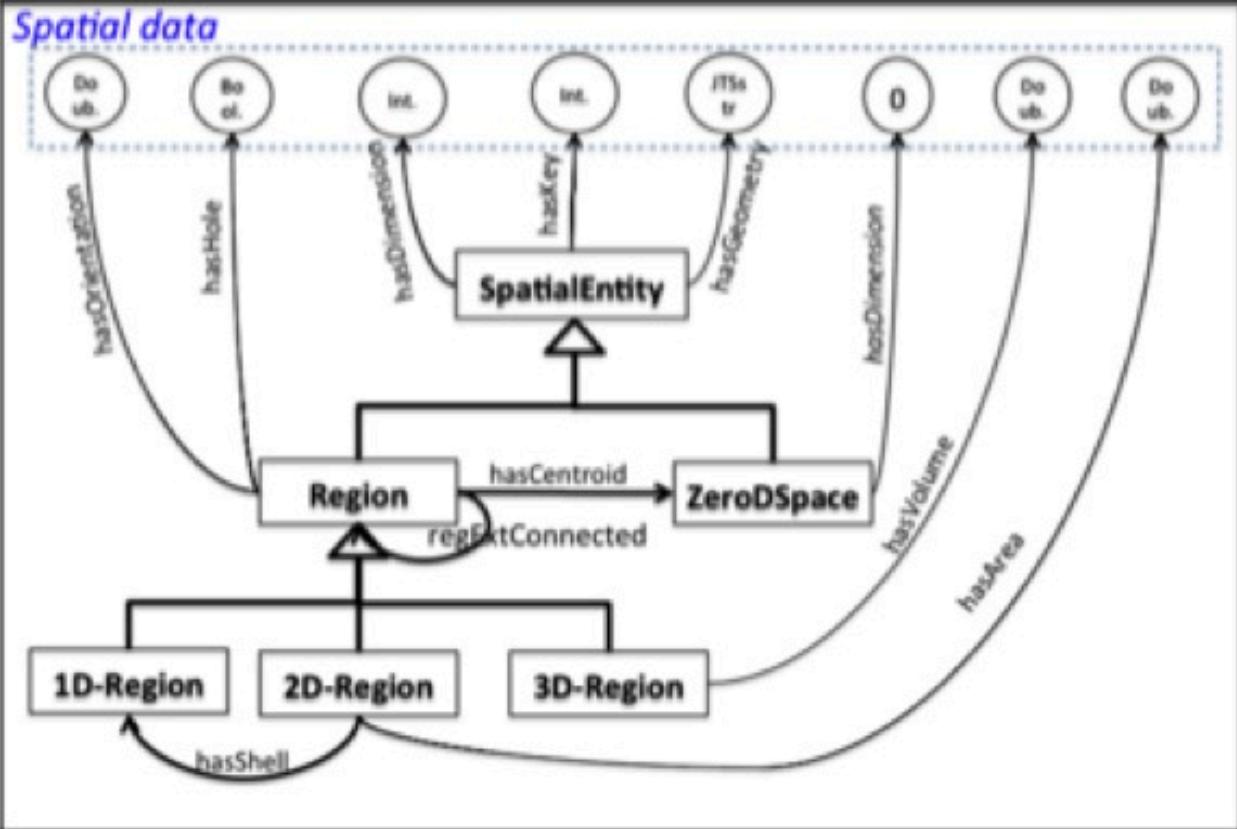
Facts: At a given instant t , cars, as spatial entities c_1, \dots, c_4 are traveling through a subset of the intersection as spatial entities s_1, \dots, s_4 respectively along trajectories tr_1, \dots, tr_4 . Spatial entities types and (JTS) geometries - e.g., Point, LineString, Polygon - are known

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

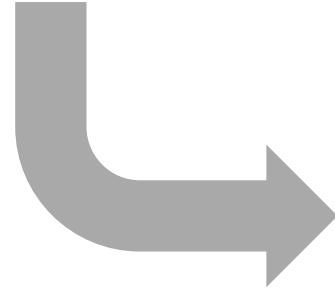
Rule 3: Two spatial entities are disconnected if their geometry are disjoint



Spatial Reasoning with Jena and Jena Rules



Excerpt of
Region Class



spaceOnto01.txt (a)

```
[java] Named Class(4): Region
[java] --- Full Name: http://petnga.org/ontologies/space#Region
[java] --- Superclass: Resource ...
[java] --- Superclass: SpatialEntity ...
[java] --- Superclass: Thing ...
[java] --- Subclass: ThreeDRegion ...
[java] --- Subclass: TwoDRegion ...
[java] --- Subclass: OneDRegion ...
[java] --- Disjoint with: ZeroDSpace ...
[java] --- Data Property Name: hasGeometryType ...
[java] --- Domain: SpatialEntity ...
[java] --- Data Property Name: hasDimension ...
[java] --- Domain: SpatialEntity ...
[java] --- Data Property Name: hasGeometry ...
[java] --- Domain: SpatialEntity ...
[java] --- Data Property Name: hasLength ...
[java] --- Domain: Region ...
[java] --- Data Property Name: hasName ...
[java] --- Domain: SpatialEntity ...
[java] --- Object Property Name: regTangPropPartInv ...
[java] --- Domain: Region ...
[java] --- Object Property Name: regNonTangPropPart ...
[java] --- Domain: Region ...
[java] --- Object Property Name: on ...
[java] --- Domain: SpatialEntity ...
[java] --- Object Property Name: regEquals ...
[java] --- Domain: Region ...
[java] --- Object Property Name: regNonTangPropPartInv ...
[java] --- Domain: Region ...
[java] --- Object Property Name: regPartialOverlaps ...
[java] --- Domain: Region ...
[java] --- Object Property Name: inside ...
[java] --- Domain: SpatialEntity ...
[java] --- Object Property Name: hasShell ...
[java] --- Domain: Region ...
[java] --- Object Property Name: regTangPropPart ...
[java] --- Domain: Region ...
[java] --- Object Property Name: regDisConnected ...
[java] --- Domain: Region ...
[java] --- Object Property Name: outside ...
[java] --- Domain: SpatialEntity ...
[java] --- Object Property Name: regExtConnected ...
[java] --- Domain: Region ...
[java] --- Object Property Name: hasCentroid ...
[java] --- Domain: Region ...
```

spacaeOnto01.txt (b)

```
Statements: Statements for space s1 ...
=====
Statement[ 1]
Subject : http://petnga.org/ontologies/space#S1
Predicate: http://petnga.org/ontologies/space#regEquals
Object : http://petnga.org/ontologies/space#S1
Statement[ 2]
Subject : http://petnga.org/ontologies/space#S1
Predicate: http://petnga.org/ontologies/space#regDisConnected
Object : http://petnga.org/ontologies/space#S0
Statement[ 3]
Subject : http://petnga.org/ontologies/space#S1
Predicate: http://petnga.org/ontologies/space#regDisConnected
Object : http://petnga.org/ontologies/space#T0
Statement[ 4]
Subject : http://petnga.org/ontologies/space#S1
Predicate: http://petnga.org/ontologies/space#hasGeometryType
Object : "Polygon"
Statement[ 5]
Subject : http://petnga.org/ontologies/space#S1
Predicate: http://petnga.org/ontologies/space#outside
Object : http://petnga.org/ontologies/space#S0
Statement[ 6]
Subject : http://petnga.org/ontologies/space#S1
Predicate: http://petnga.org/ontologies/space#hasDimension
Object : "2^^http://www.w3.org/2001/XMLSchema#int"
Statement[ 7]
Subject : http://petnga.org/ontologies/space#S1
Predicate: http://petnga.org/ontologies/space#hasGeometry
Object : "POLYGON ((300 200, 300 400, 700 400, 700 200, 300 200))"
Statement[ 8]
Subject : http://petnga.org/ontologies/space#S1
Predicate: http://www.w3.org/1999/02/22-rdf-syntax-ns#type
Object : http://petnga.org/ontologies/space#TwoDRegion
Statement[ 9]
Subject : http://petnga.org/ontologies/space#S1
Predicate: http://www.w3.org/1999/02/22-rdf-syntax-ns#type
Object : http://petnga.org/ontologies/space#Region
Statement[ 10]
Subject : http://petnga.org/ontologies/space#S1
Predicate: http://www.w3.org/1999/02/22-rdf-syntax-ns#type
Object : http://petnga.org/ontologies/space#SpatialEntity
Statement[ 11]
Subject : http://petnga.org/ontologies/space#S1
Predicate: http://www.w3.org/1999/02/22-rdf-syntax-ns#type
Object : http://www.w3.org/2000/01/rdf-schema#Resource
Statement[ 12]
Subject : http://petnga.org/ontologies/space#S1
Predicate: http://www.w3.org/1999/02/22-rdf-syntax-ns#type
Object : http://www.w3.org/2002/07/owl#Thing
```

Rule 3 (RCC-8)

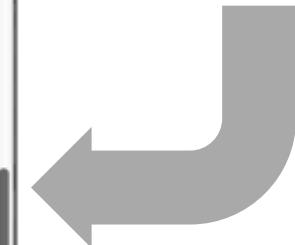
Rule 1

Rule 2

Initial Facts

Class propagation inferences

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



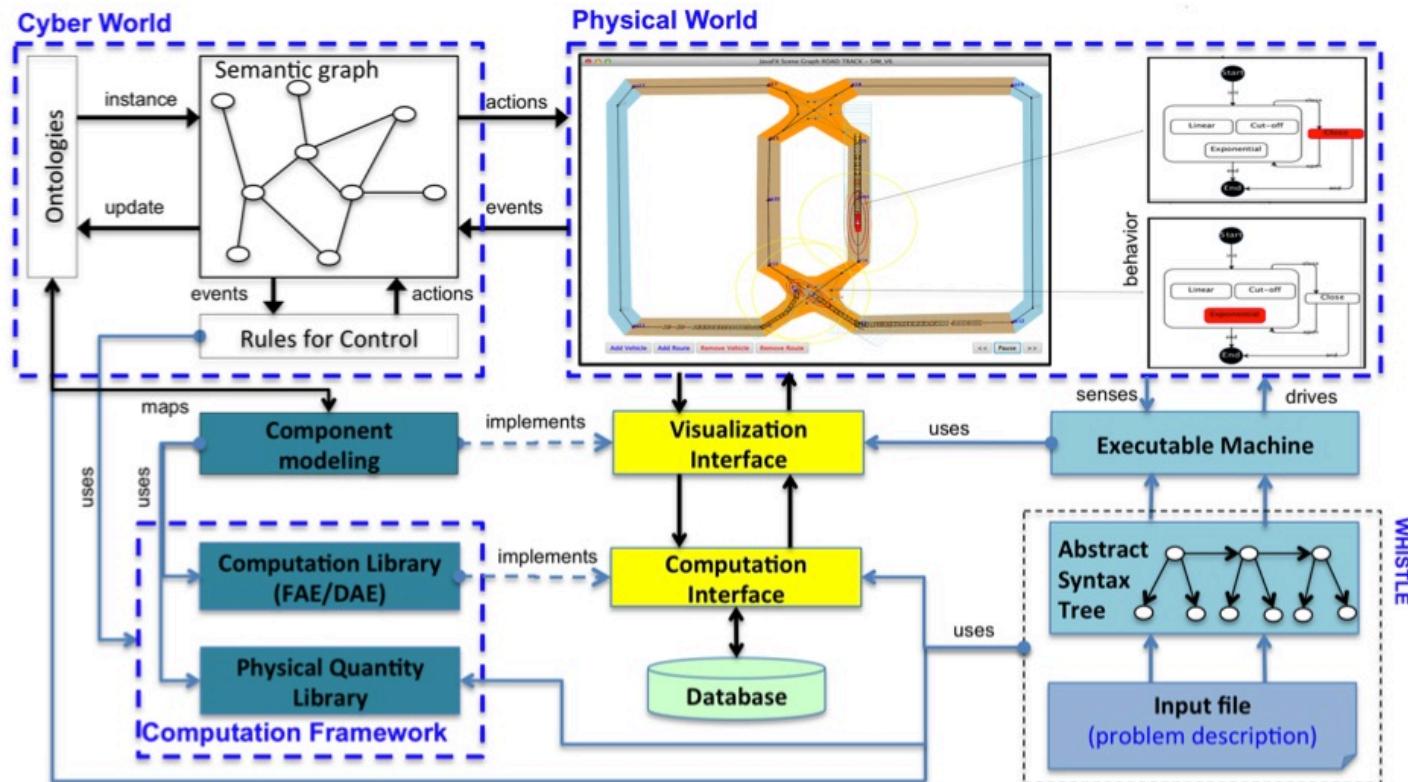
Language capabilities

- 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



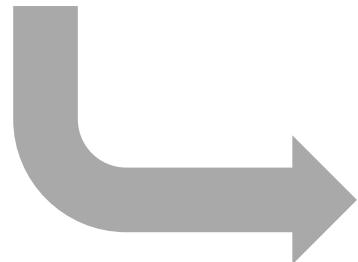
Systems Integration

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

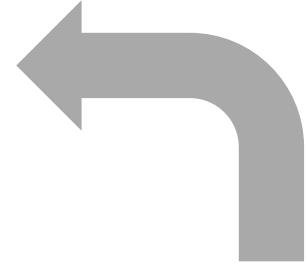
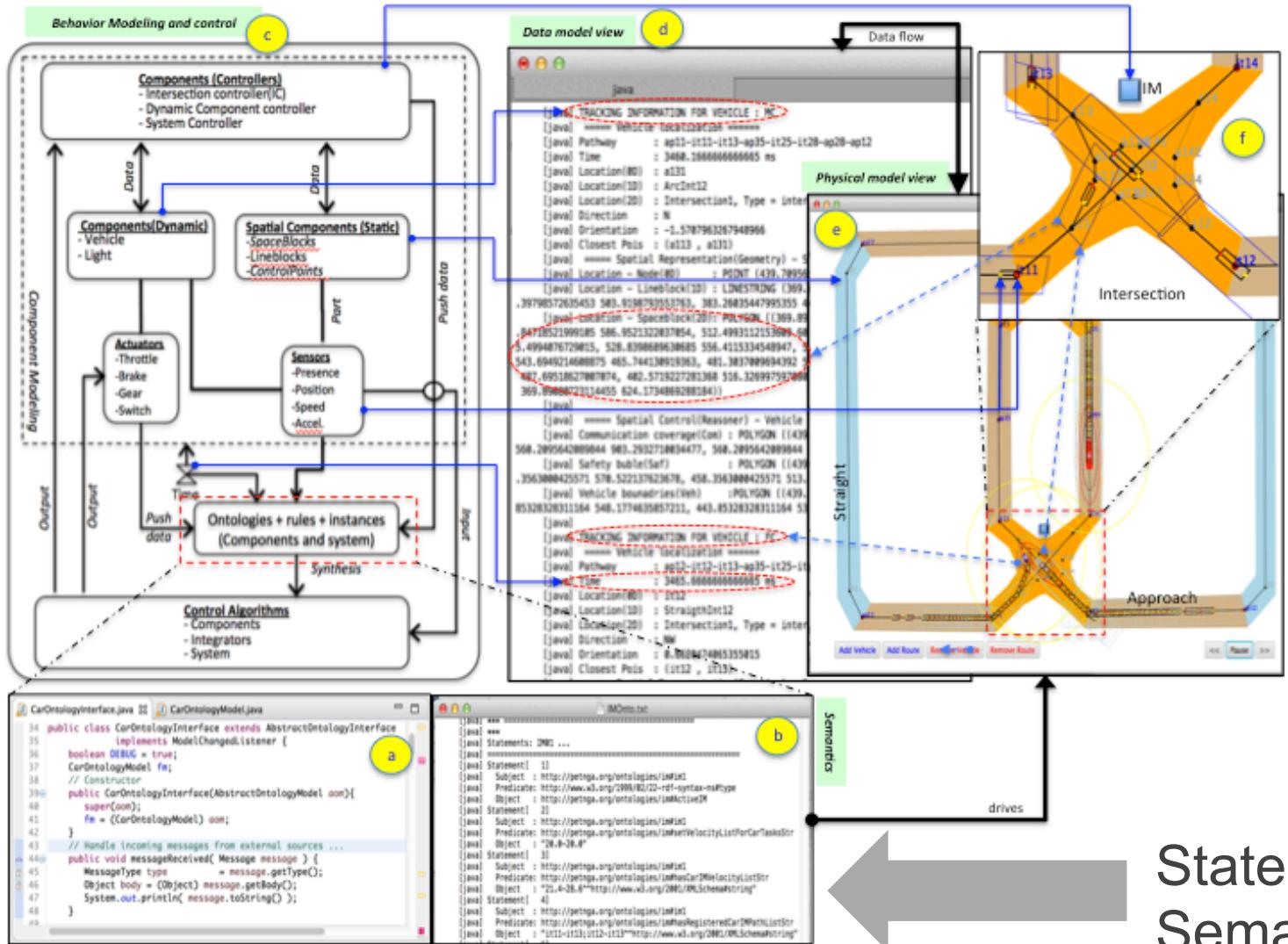
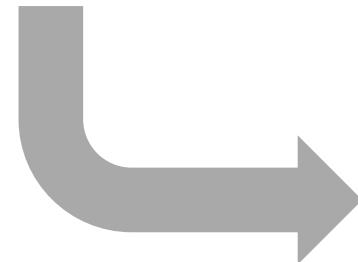
Application: Traffic Intersection with No Traffic Lights



Behavior modeling and control.



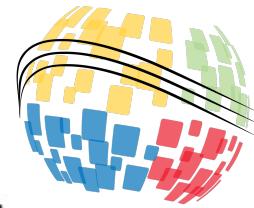
Car Ontology Interface



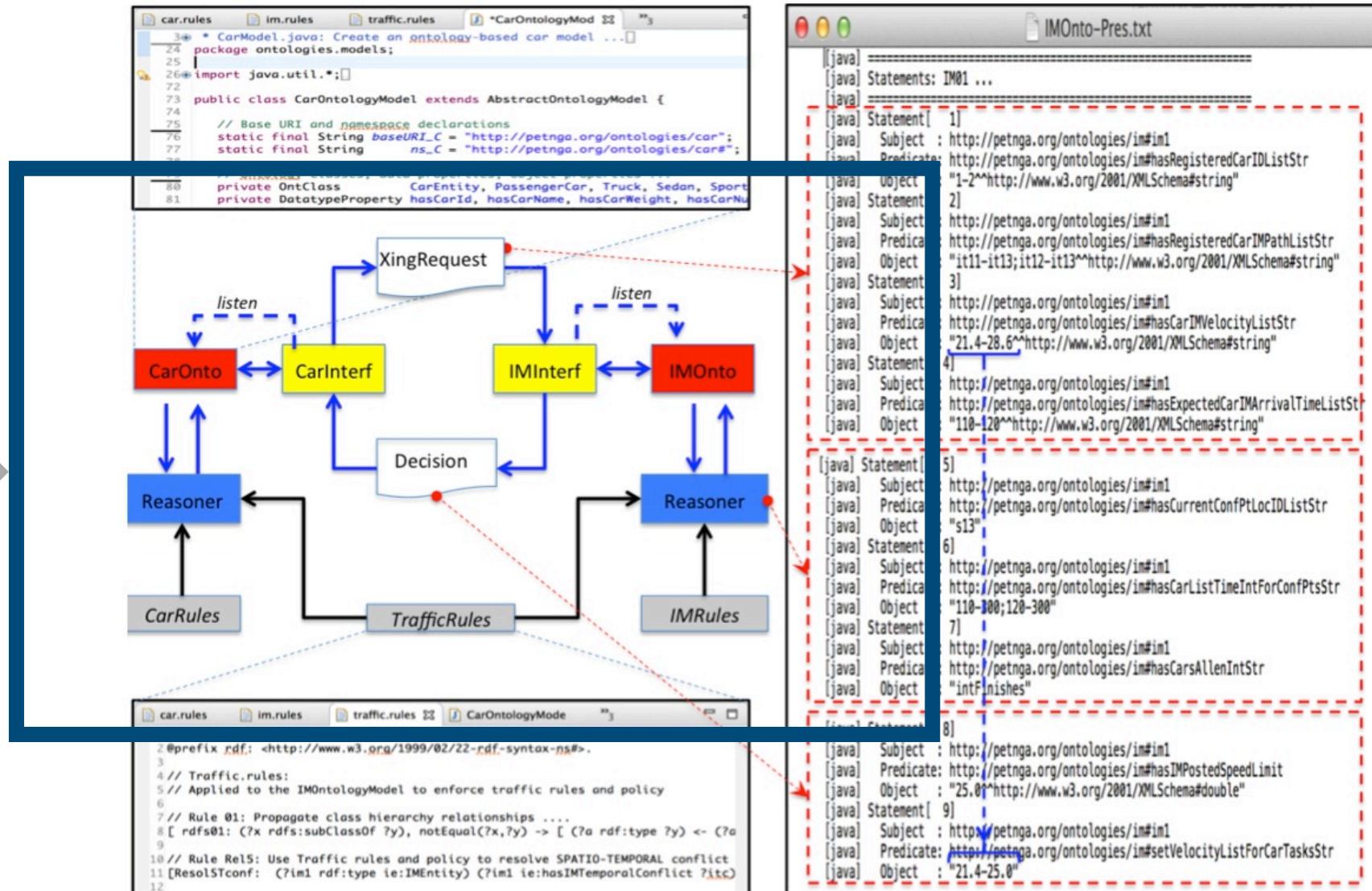
Visualization of race track pathways and geometry

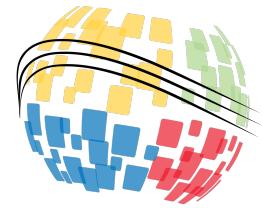
Statements in the Semantic Model

Spatio-Temporal: Reasoning, Communication and Control



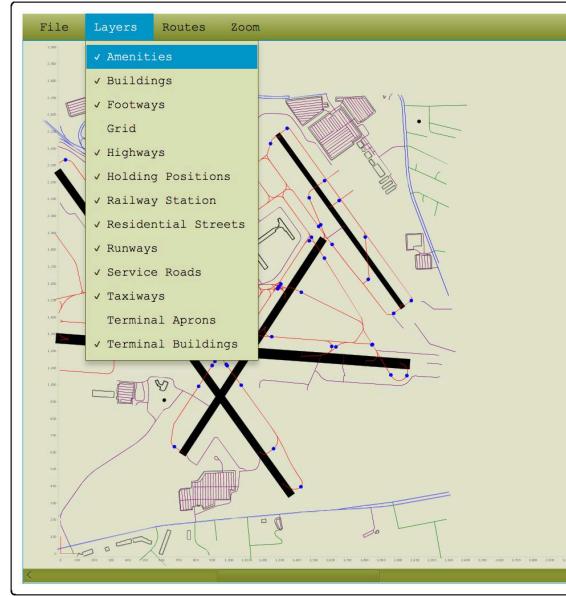
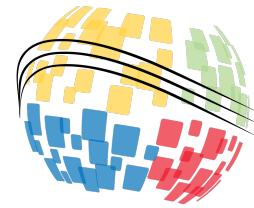
Intersection Manager / Vehicle Communication





Scaling Things Up

Work in Progress (2017-2018)



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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 2011), 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**.

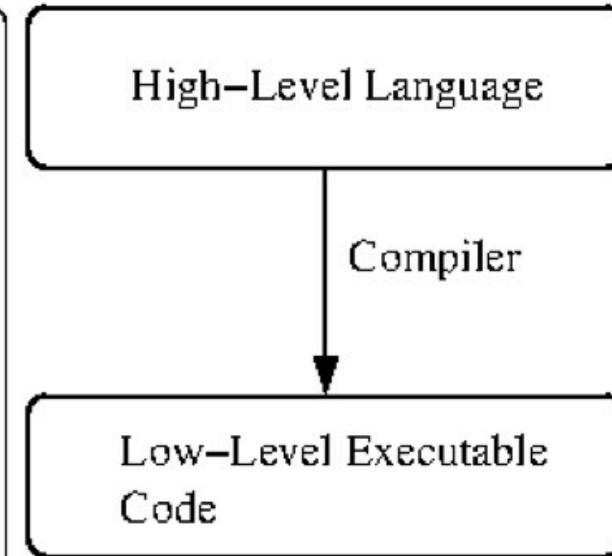
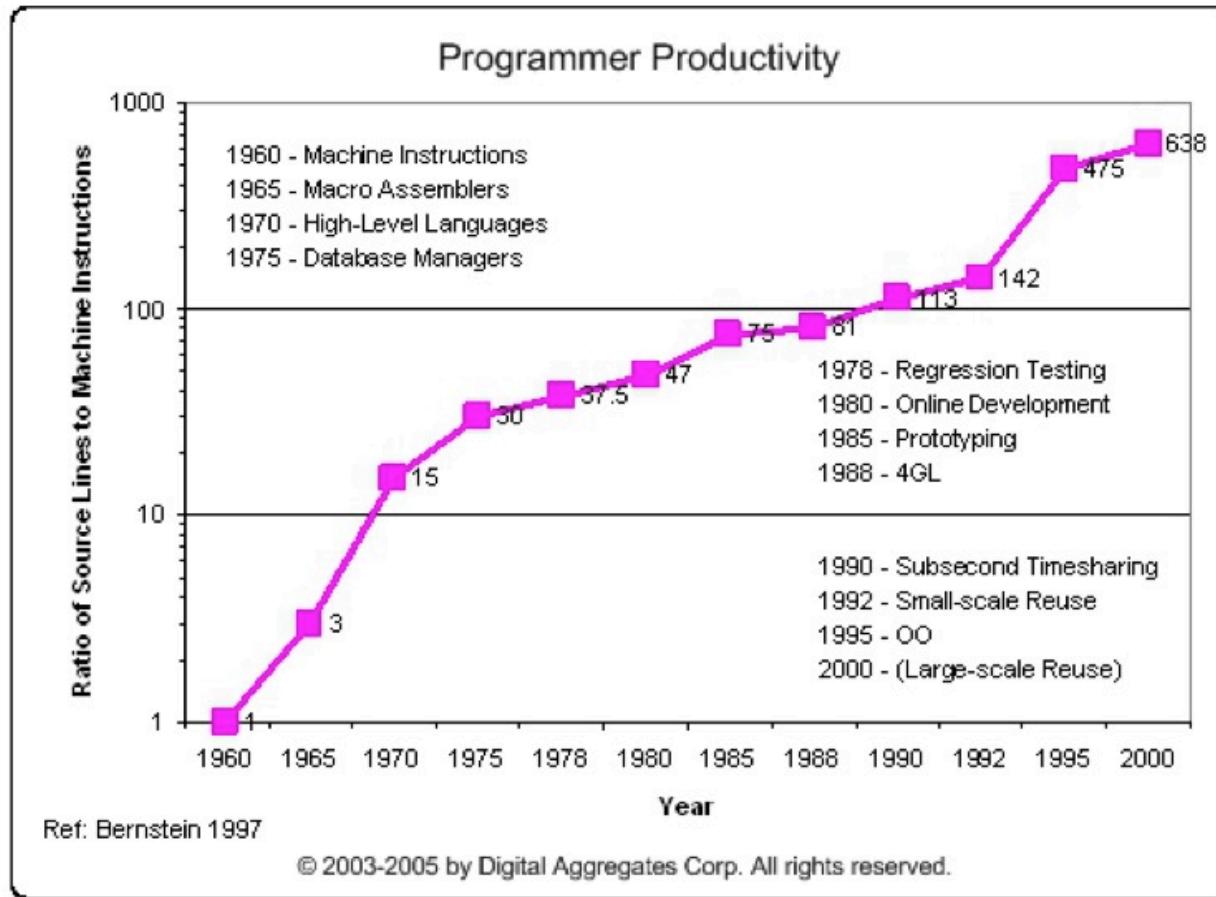


Backup Slides

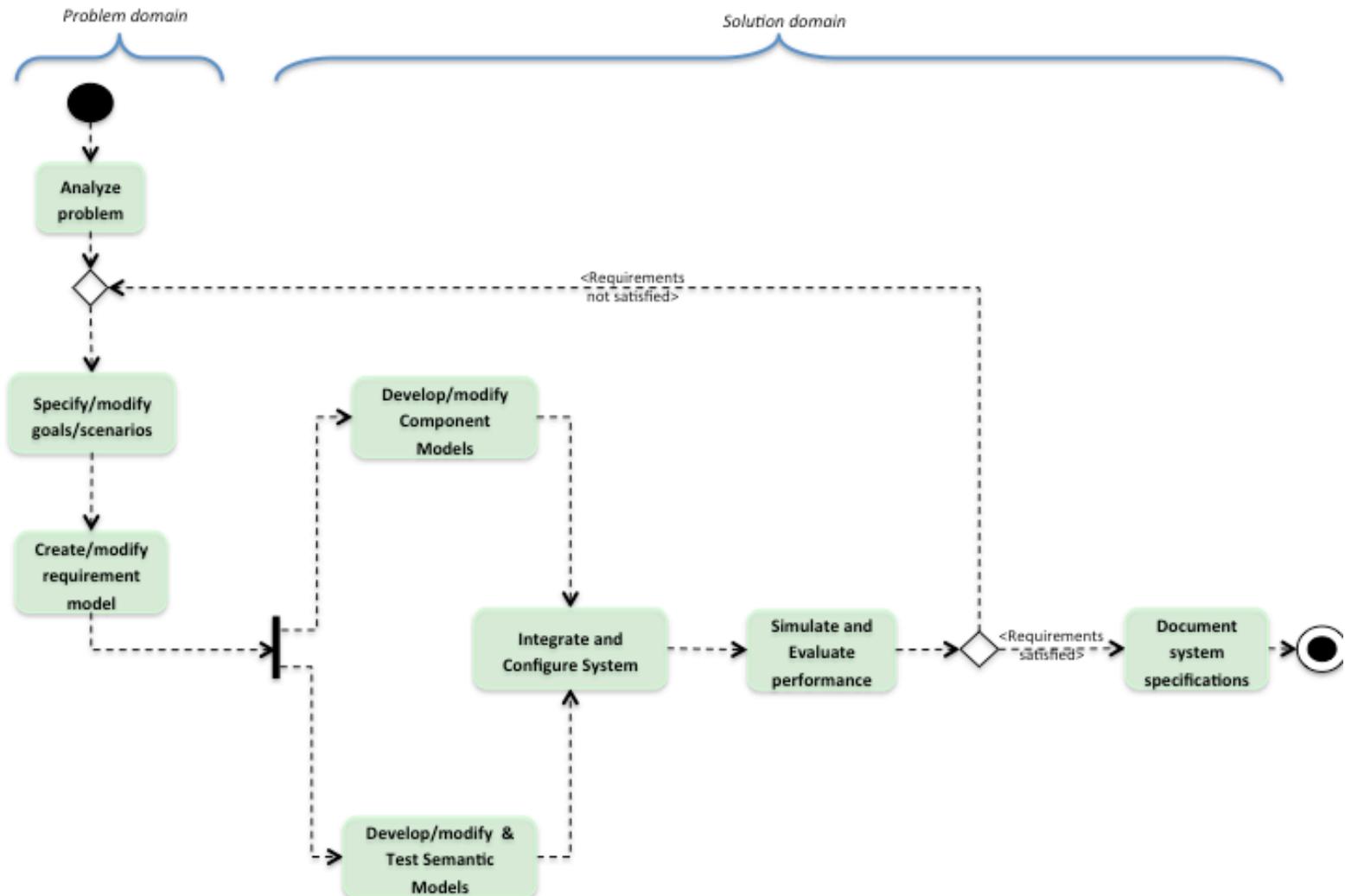
Management of Software Complexity



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



Proposed Implementation Process





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