MODEL-BASED SYSTEMS ENGINEERING FOR CYBER-PHYSICAL SYSTEMS

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OVERVIEW

Model-Based Systems Engineering at Maryland

- Pathway to University of Maryland
- Model-Based Systems Engineering (MBSE) at ISR
- Our view of MBSE and CPS.

Current Research on CPS

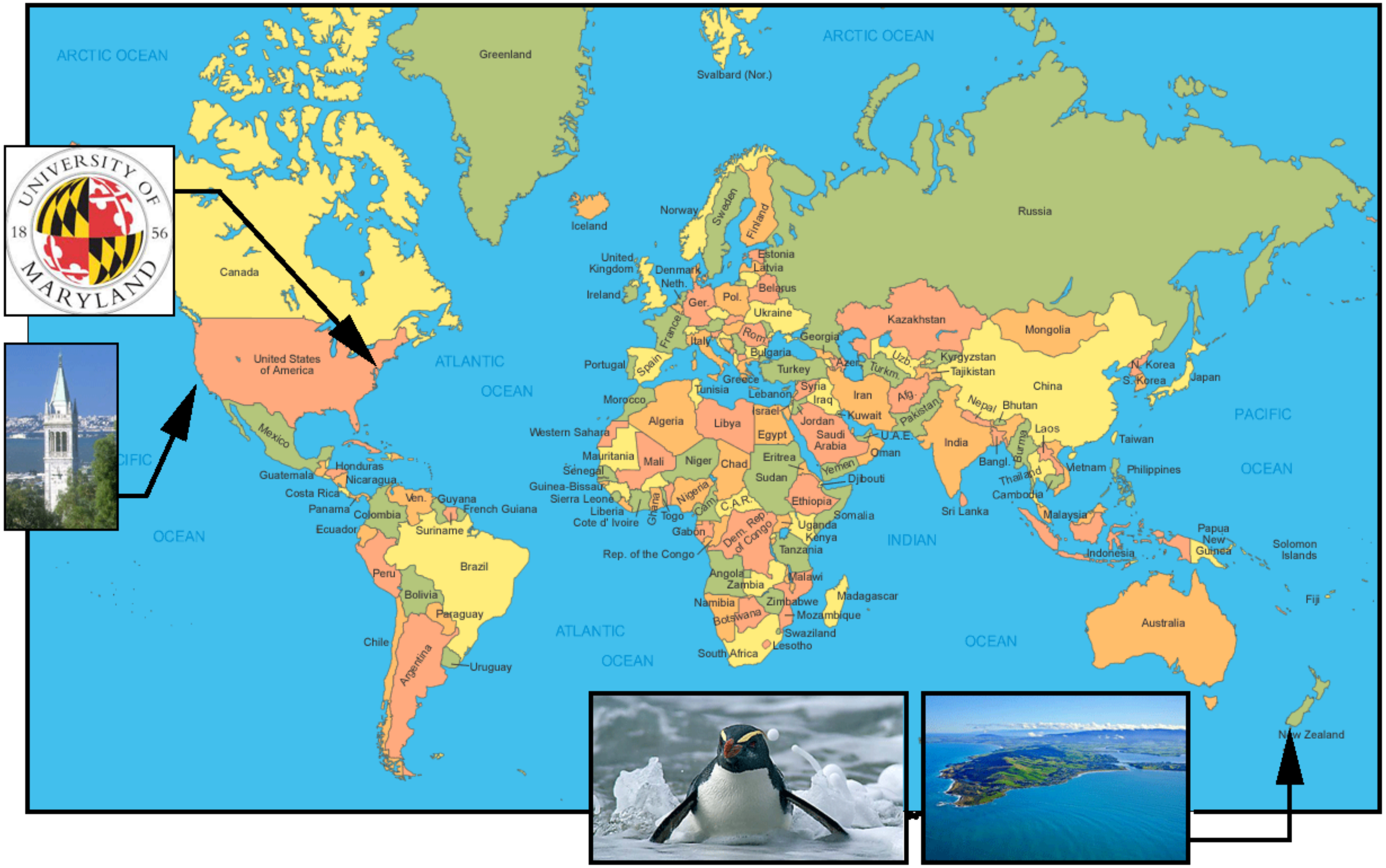
- Ontology-enabled traceability. Semantic platforms for simulation and control of trains and buildings.
- Ontologies of time and time-based reasoning. Ontologies of time and space, and spatio-temporal reasoning.

Acknowledgements / Co-Workers

- At UMD: Cari Wojcik, John Baras, Reza Ghodssi, Matt Mosteller, Karam Rajab, Nefretiti Nassar, Parastoo Delgoshaei, Eddie Tseng, and Leonard Petnga.
- At NIST: Conrad Bock, Daniel Veronica and Amanda Pertzborn.

BACKGROUND

Pathway to University of Maryland



INSTITUTE FOR SYSTEM RESEARCH

38 joint appointment faculty, **26** affiliated faculty, **7** research faculty, **1** Professor of the Practice in **4** colleges and **14** departments

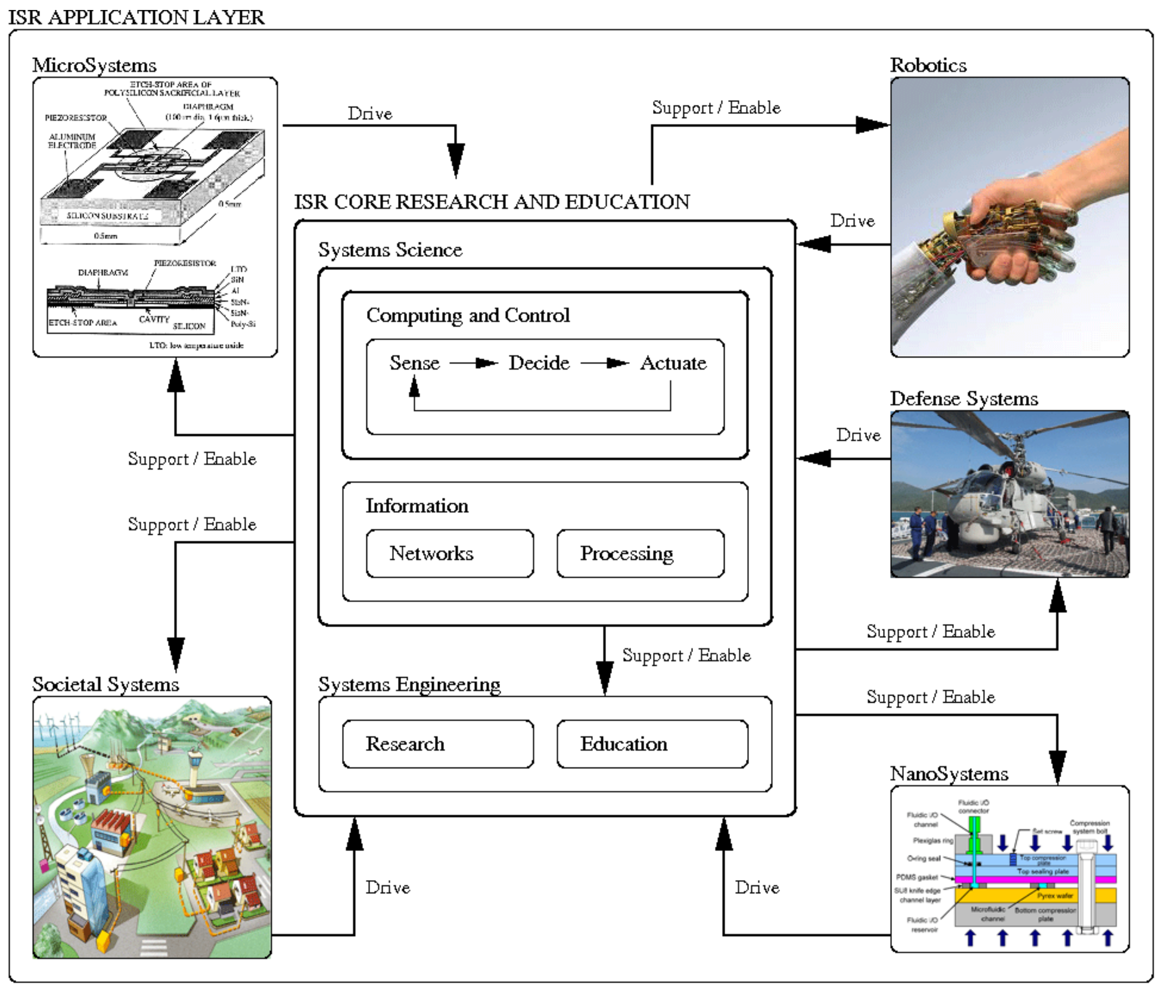
15 postdoctoral researchers leveraging research programs

200+ research graduate students

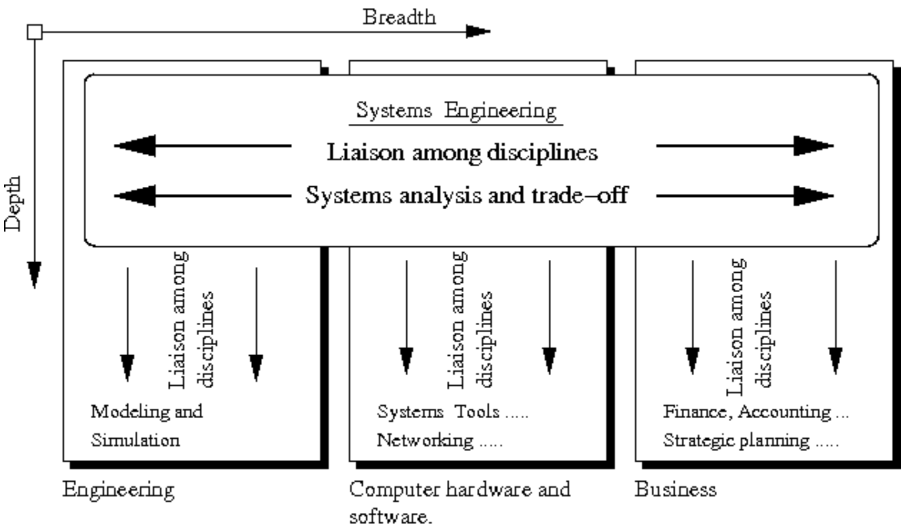
45 MS Systems Engineering/ ENPM graduate students

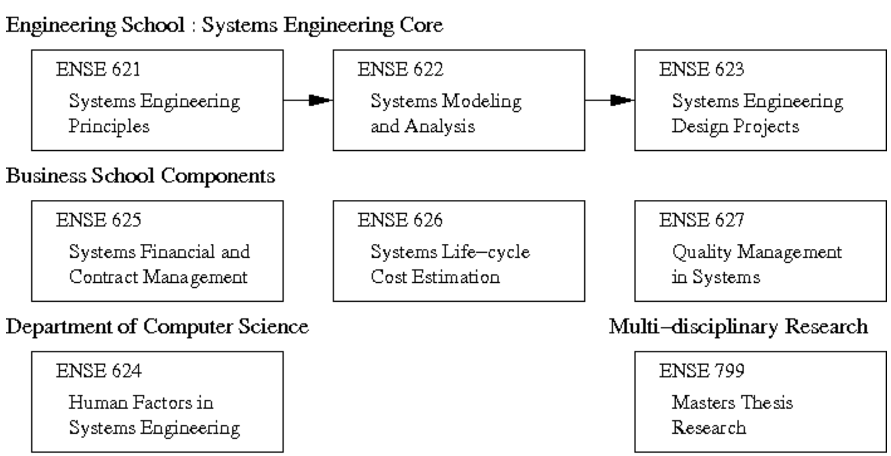
55 undergraduate students in SE Projects course

9 undergraduate students in research programs



SYSTEMS ENGINEERING EDUCATION AT ISR





MSSE PROGRAM

Model-Based Systems Engineering in a Systems Research Environment (30-credits)

MBSE Design Sequence (9-credits)

- Systems Concepts, Issues, and Processes
- Systems Requirements, Design, and Trade-off Analysis
- Systems Projects, Validation and Verification

SE Specialty Courses (9-credits)

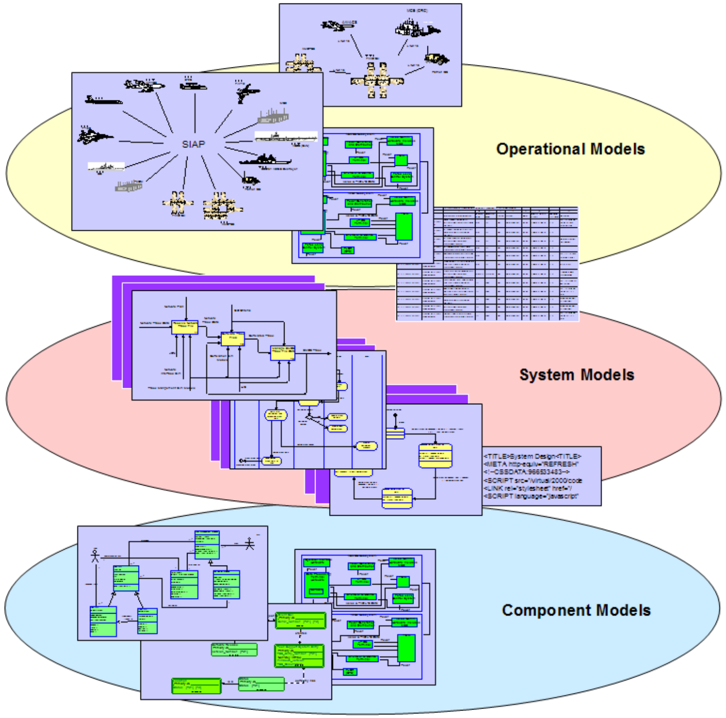
- Human Factors in SE
- Systems Life Cycle Analysis and Risk Management
- System Quality and Robustness Analysis

Thesis (6-credits)

MODEL-BASED SYSTEMS ENGINEERING

Definition and Scope

- Formalizes the development of systems through the use of models.
- Broad in scope, across multiple stages of system development and multiple physics.

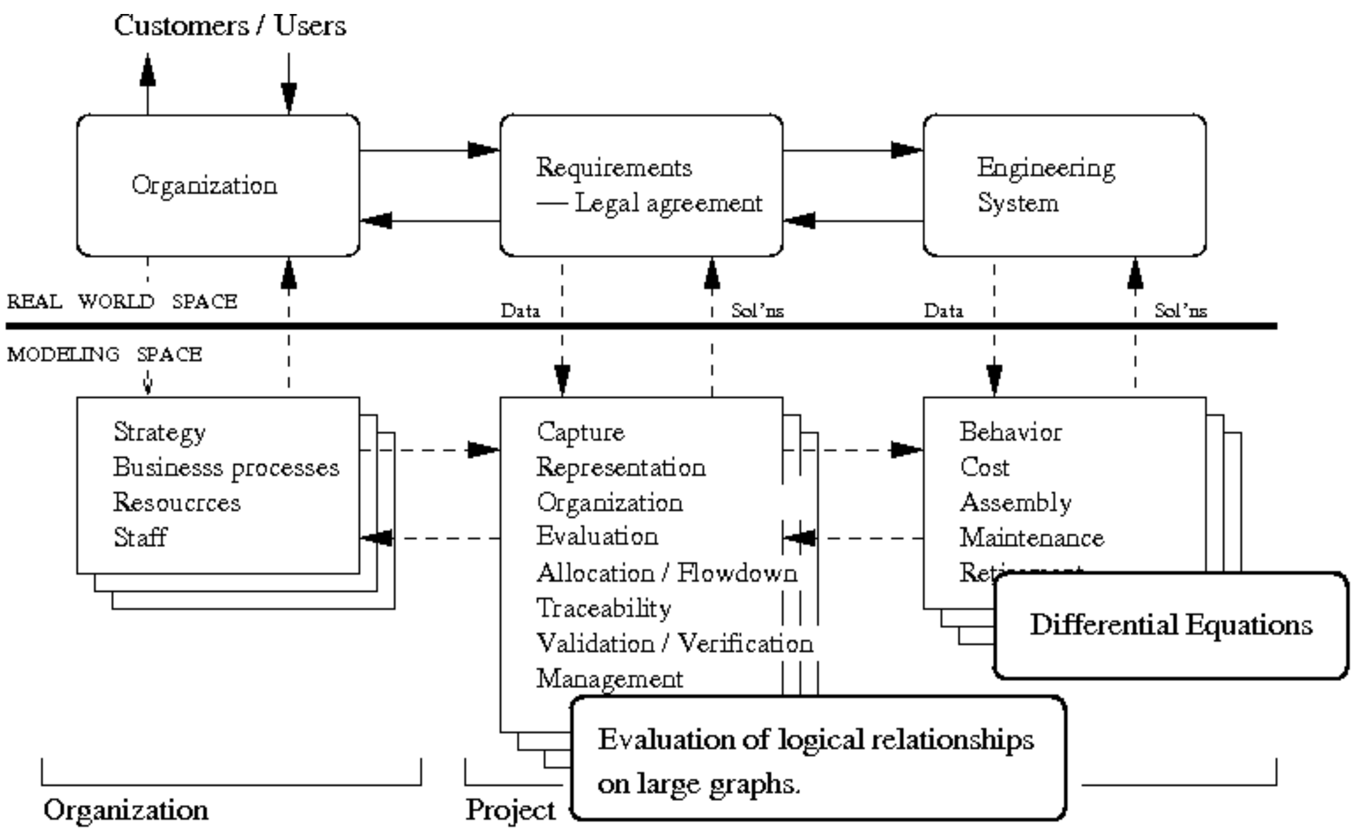


Benefits of MBSE

- Allows for the development of virtual prototypes.
- Facilitates communication among disciplines in team-based development.
- Enables semi-formal and formal approaches to system assessment.
- Management of system complexity.

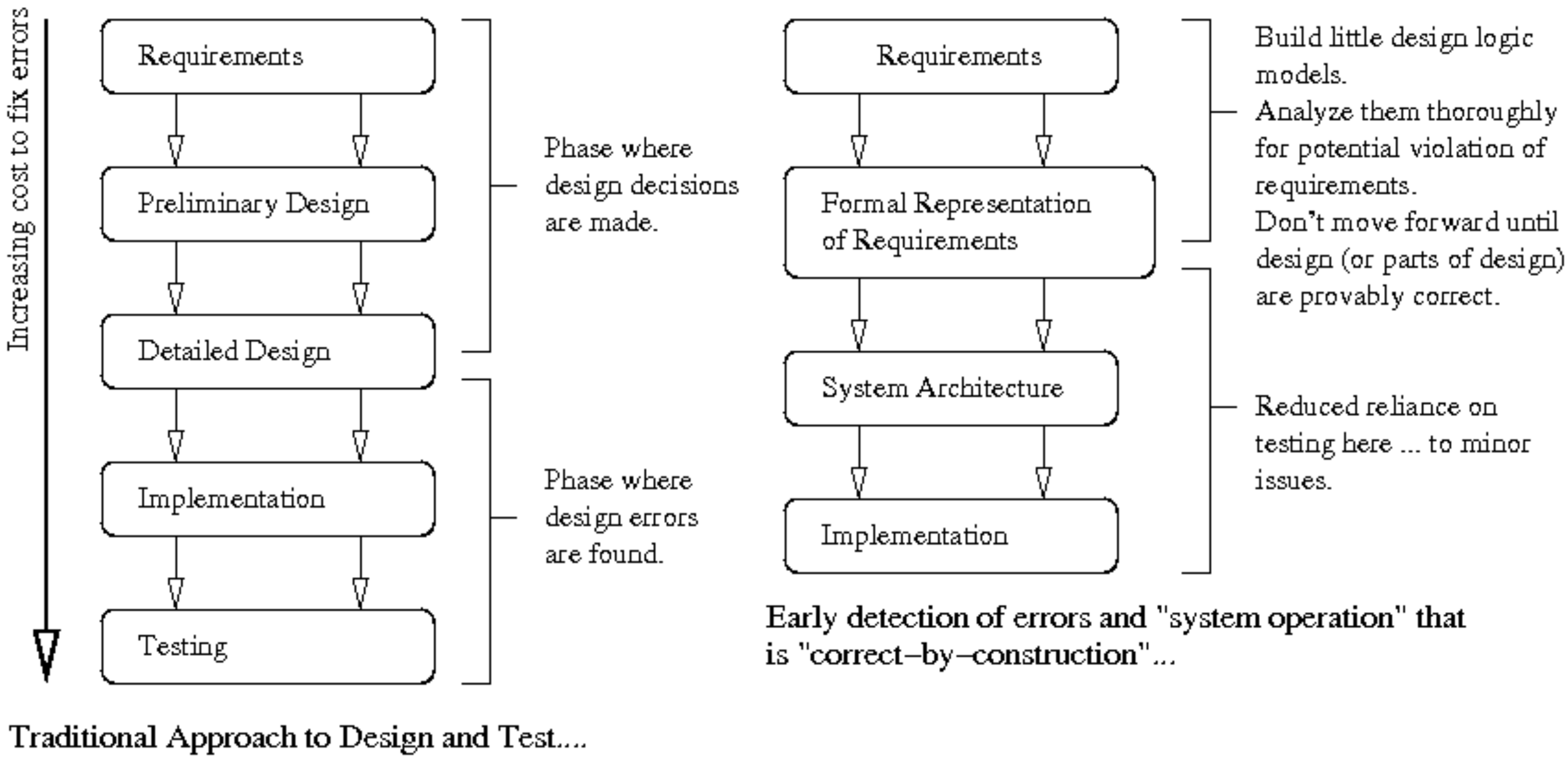
MODEL-BASED SYSTEMS ENGINEERING

Tenet 1: Create Big-Picture View and Emphasize Model-Based Systems Engineering. The mathematics needed for formal approaches to systems engineering is foreign to many engineers.



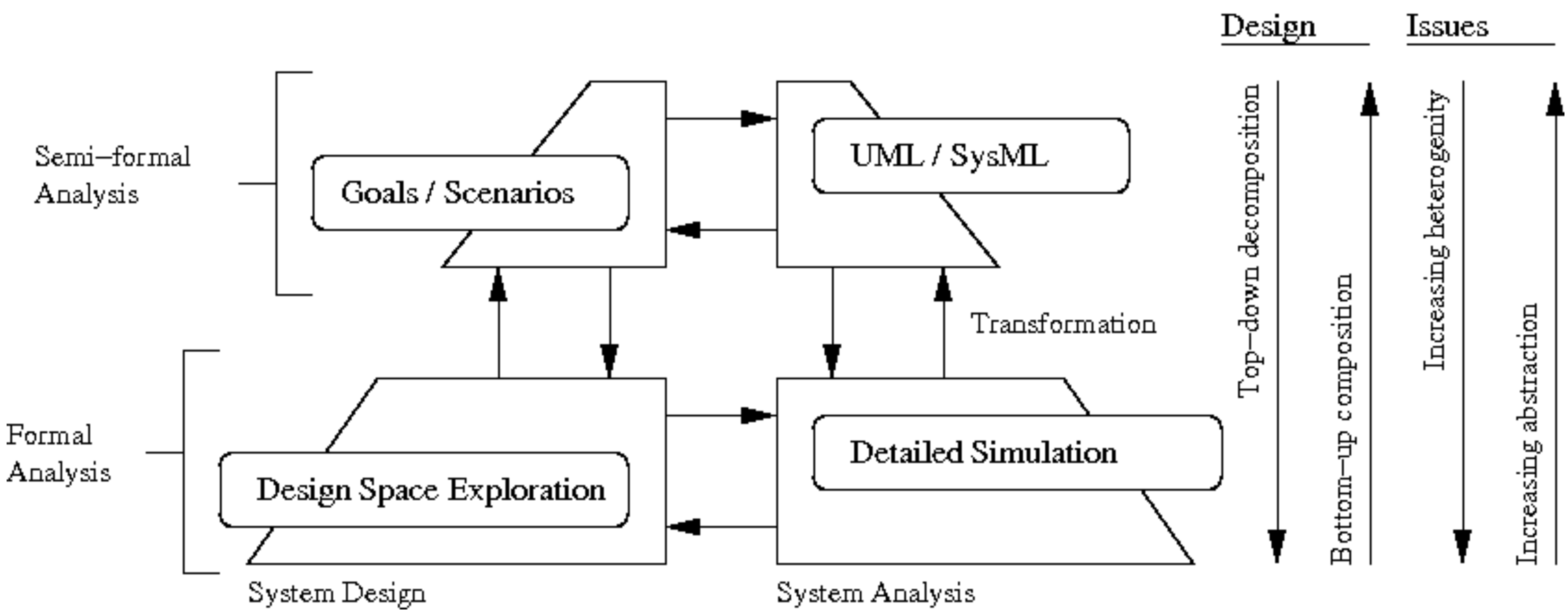
MODEL-BASED SYSTEMS ENGINEERING

Tenet 2: Emphasize Disciplined Approaches to Design. Techniques include decomposition, abstraction, and formal analysis.



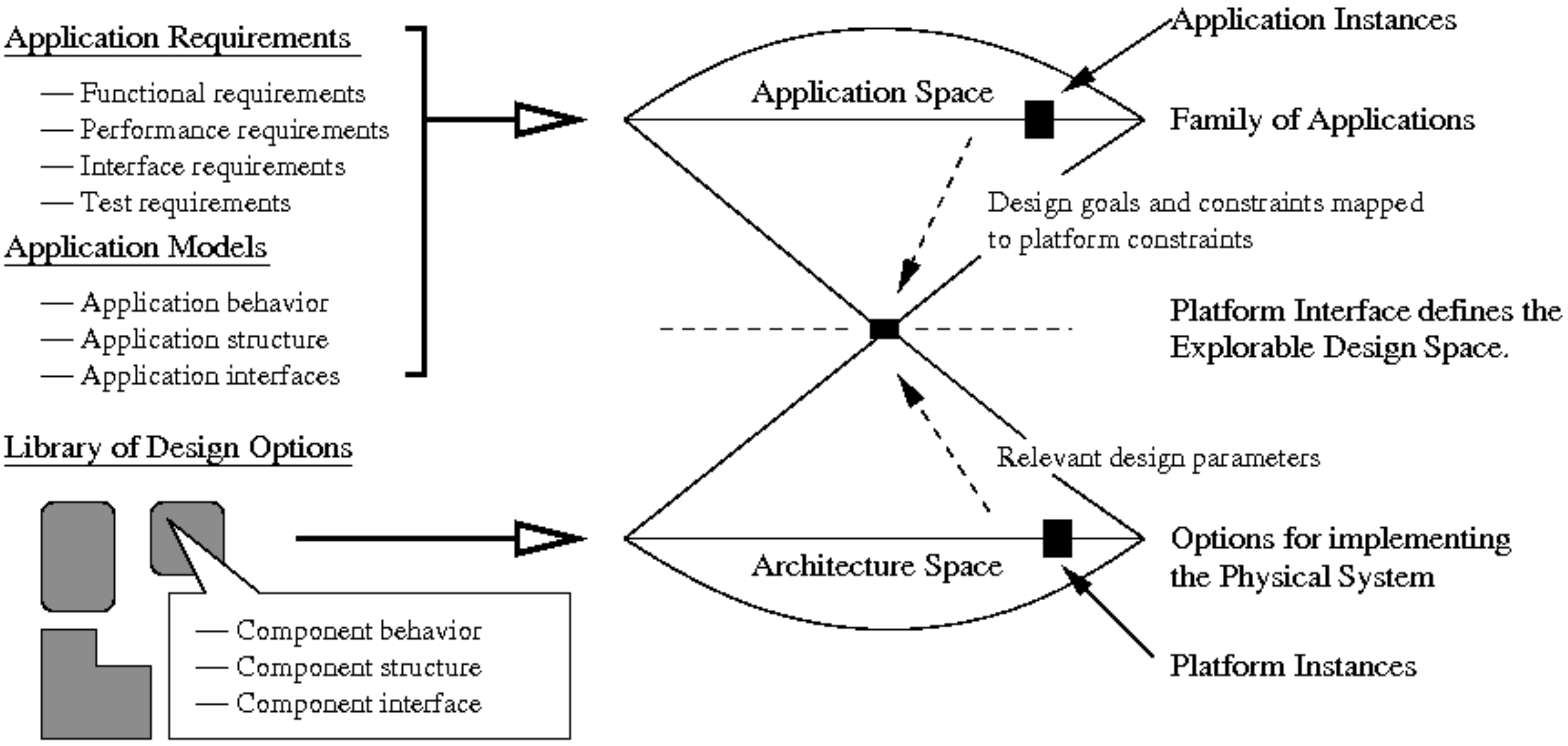
MODEL-BASED SYSTEMS ENGINEERING

Tenet 3: To keep the complexity of design activities in check, we need to employ mixtures of semi-formal and formal approaches to system development.



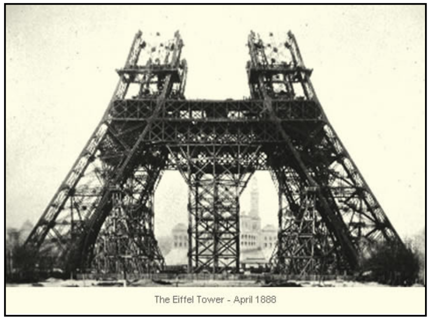
MODEL-BASED SYSTEMS ENGINEERING

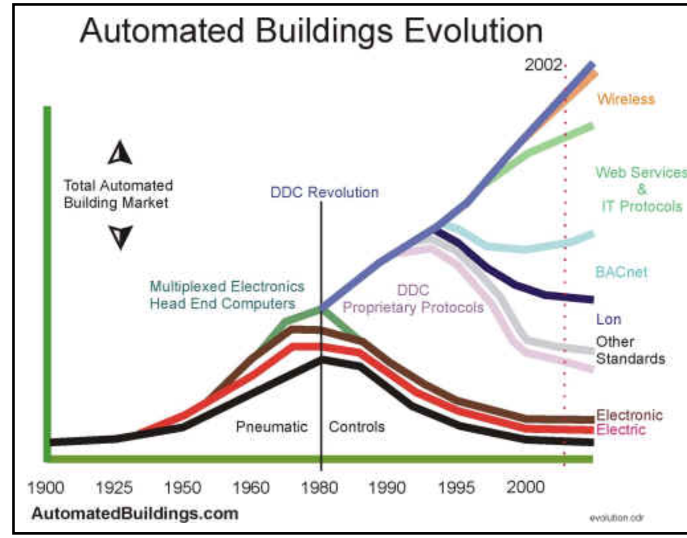
Tenet 4: Use platform abstractions for system-level design.



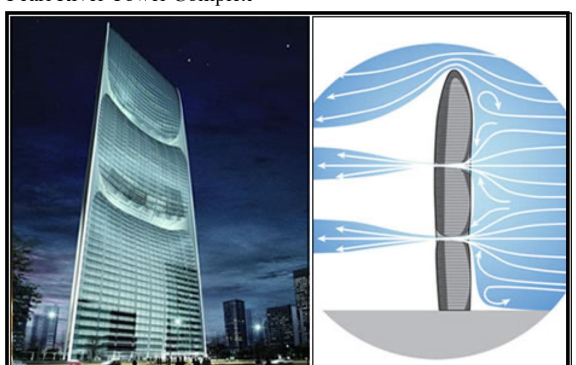
MODEL-BASED SYSTEMS ENGINEERING

Motivating Application Area 1: Buildings!

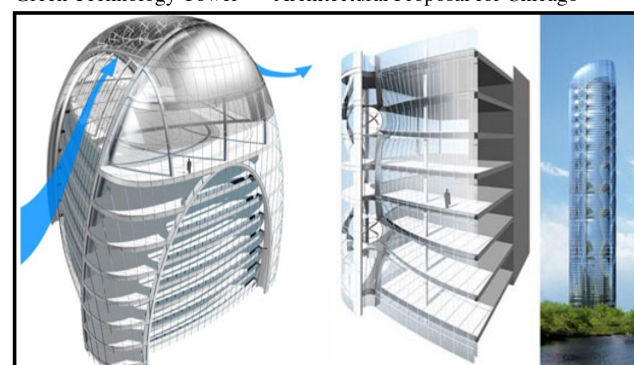




Pearl River Tower Complex

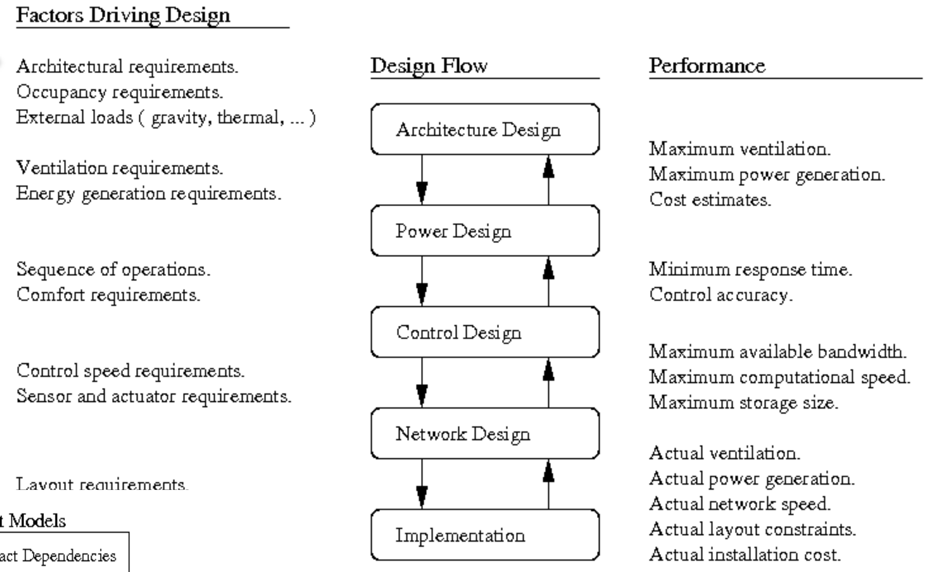


Green Technology Tower –– Architectural Proposal for Chicago

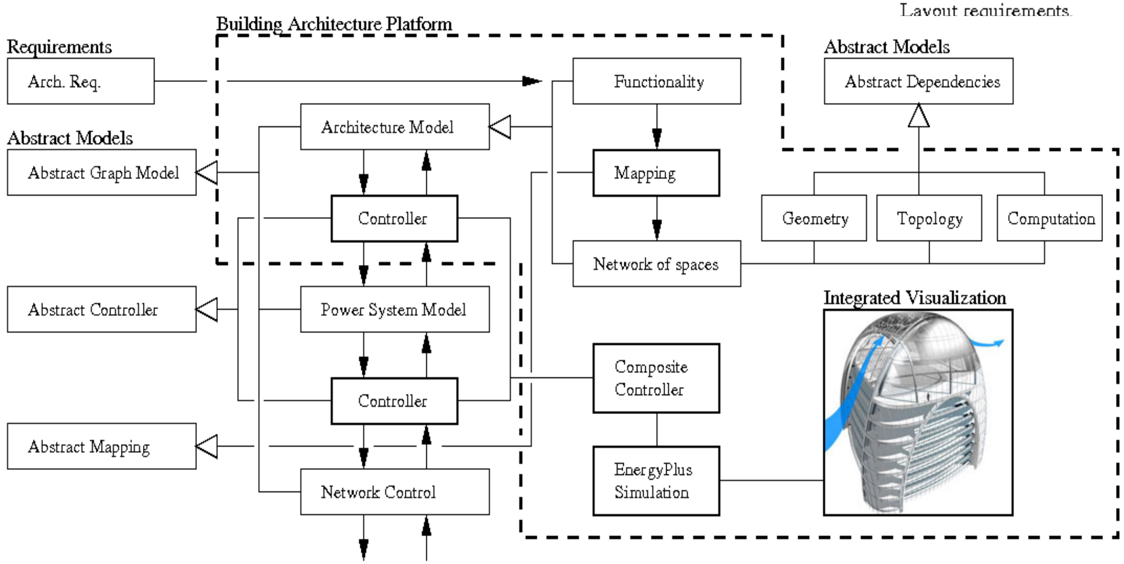


MODEL-BASED SYSTEMS ENGINEERING

Design Platform Stack

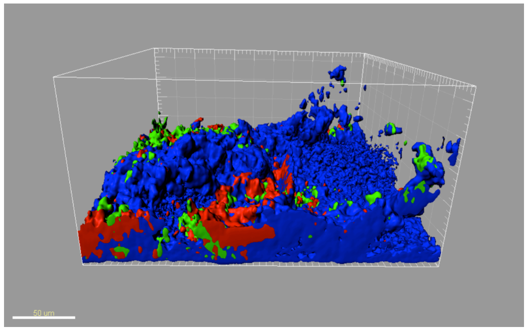


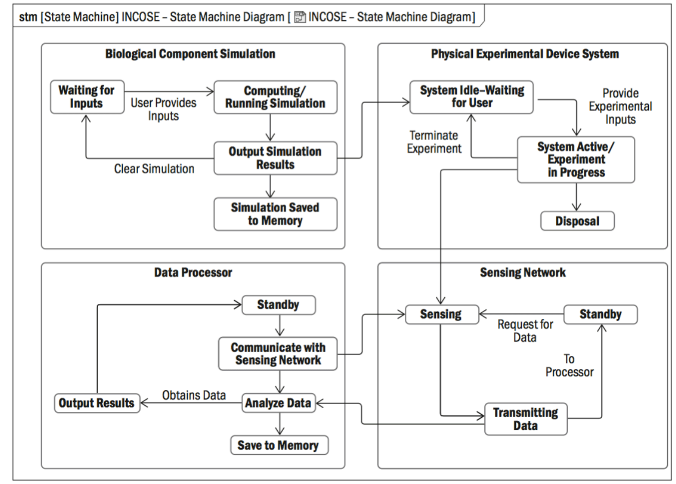
Research: Design of a scalable and extensible platform infrastructure

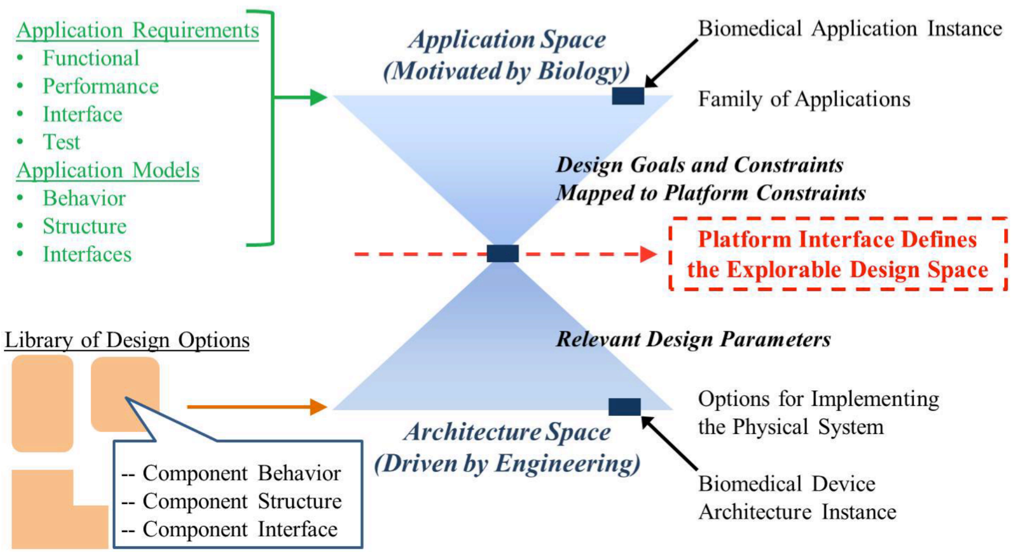


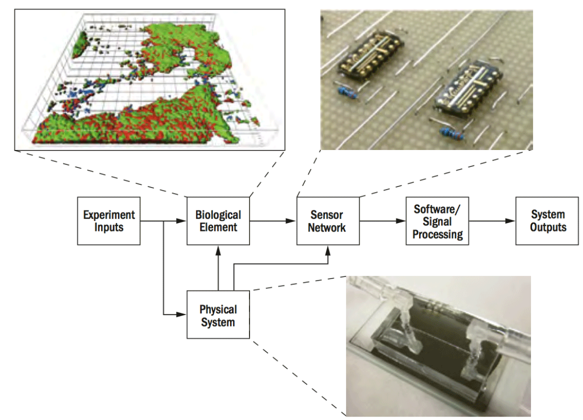
MODEL-BASED SYSTEMS ENGINEEERING

Motivating Application Area 2: Platforms for Biomedical Experimental Research









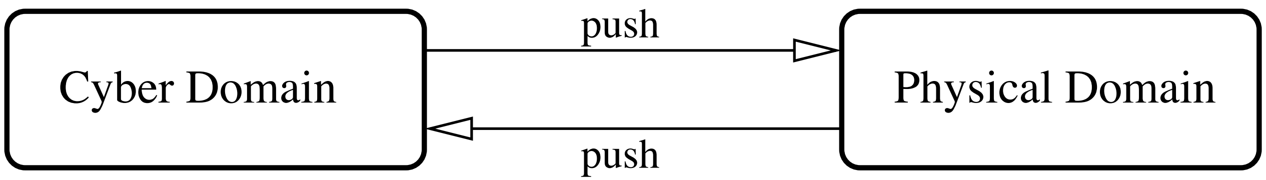
Source: Mosteller et al., 2012

PART 1

MODEL-BASED SYSTEMS ENGINEERING OF CYBER-PHYSICAL SYSTEMS AT MARYLAND

CYBER-PHYSICAL SYSTEMS

Our Definition of CPS



C–P Structure

Cyber capability in every physical component.
Executable code
Networks of computation
Heterogeneous implementations

Spatial and network abstractions
—— physical spaces
—— physical and social networks.
—— networks of networks
Sensors and actuators.

C–P Behavior

Dominated by logic
Control, communications
Stringent requirements on timing
Needs to be fault tolerant

Physics from multiple domains.
Combined logic and differential equations.
Not entirely predictable.
Multiple spatial– and temporal– resolutions.

PATHWAY TO RESEARCH IN CPS

Scientific and Technical Challenges

- Modeling: Lack of an integration science with needed mathematical foundations
- Design: Weak procedures for handing meta domains (time, space, ..).
- Operation and Decision: High dependence on embedded and local computational intelligence

Research Opportunities

- Design cyber that can reason with physical quantities (not just numbers), time and space.
- Design component hierarchies and networks, and component ports that work with physical quantities.
- Embed physical quantities, ontologies, and reasoning capability deeply into scripting languages. Script and solve practical applications.

ENCE 688R: CIVIL INFORMATION SYSTEMS

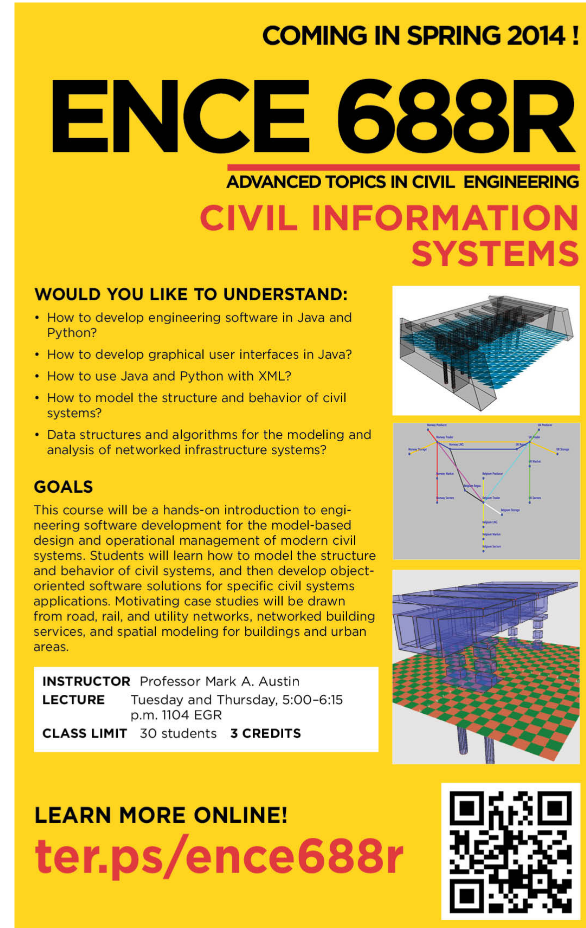
Pilot Course: Understand data structures and algorithms for modeling and analysis of networked infrastructure systems. Focus on object-oriented solutions and use of software design patterns.

Hands-On: Software development in Java, Python, Jython and XML.

Mechanism: Mixtures of Civil Engineering and Systems Engineering graduate students.

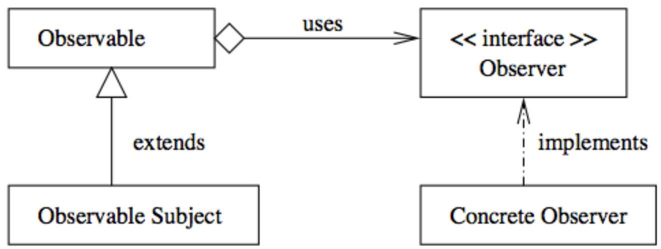
Class projects:

- Component based modeling of networked systems.
- Transportation route selection.
- Network-based modeling of cities.
- Dam modeling and visualization.
- European Gas Network Modeling.
- Ontology modeling and rule-based reasoning.

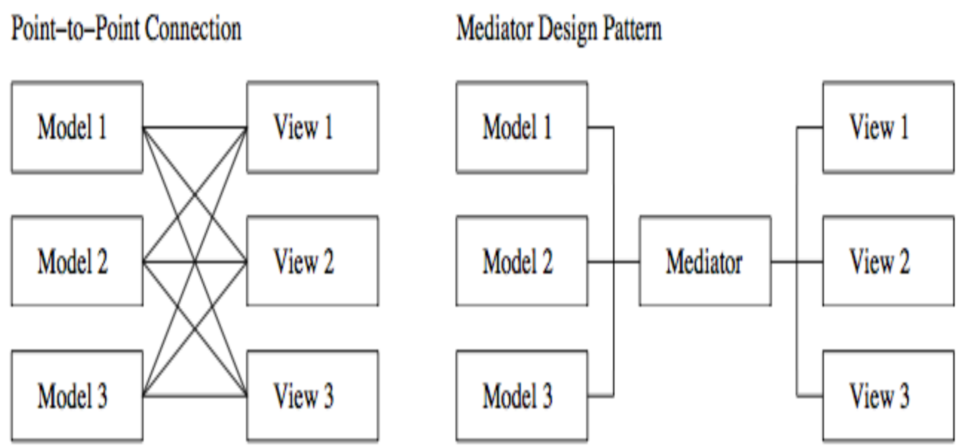


SOFTWARE DESIGN PATTERNS (NETWORKS)

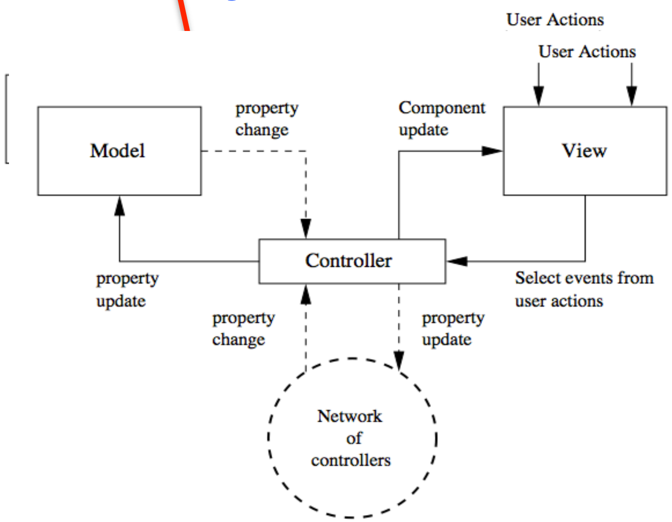
Observer Pattern



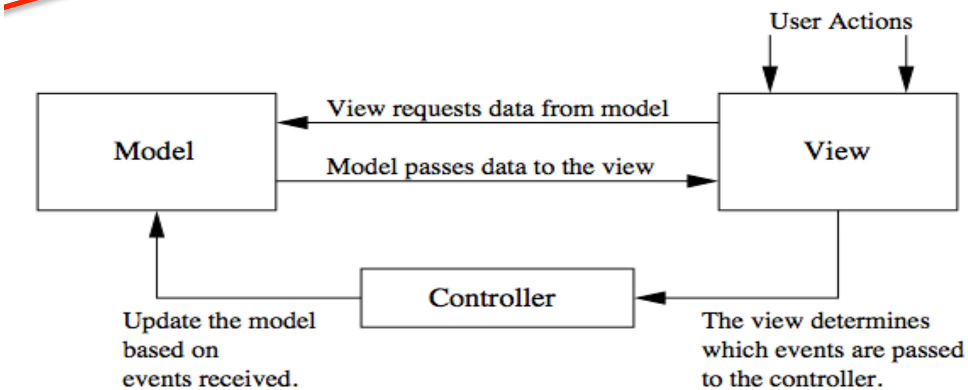
Mediator



Hybrid MVC Pattern

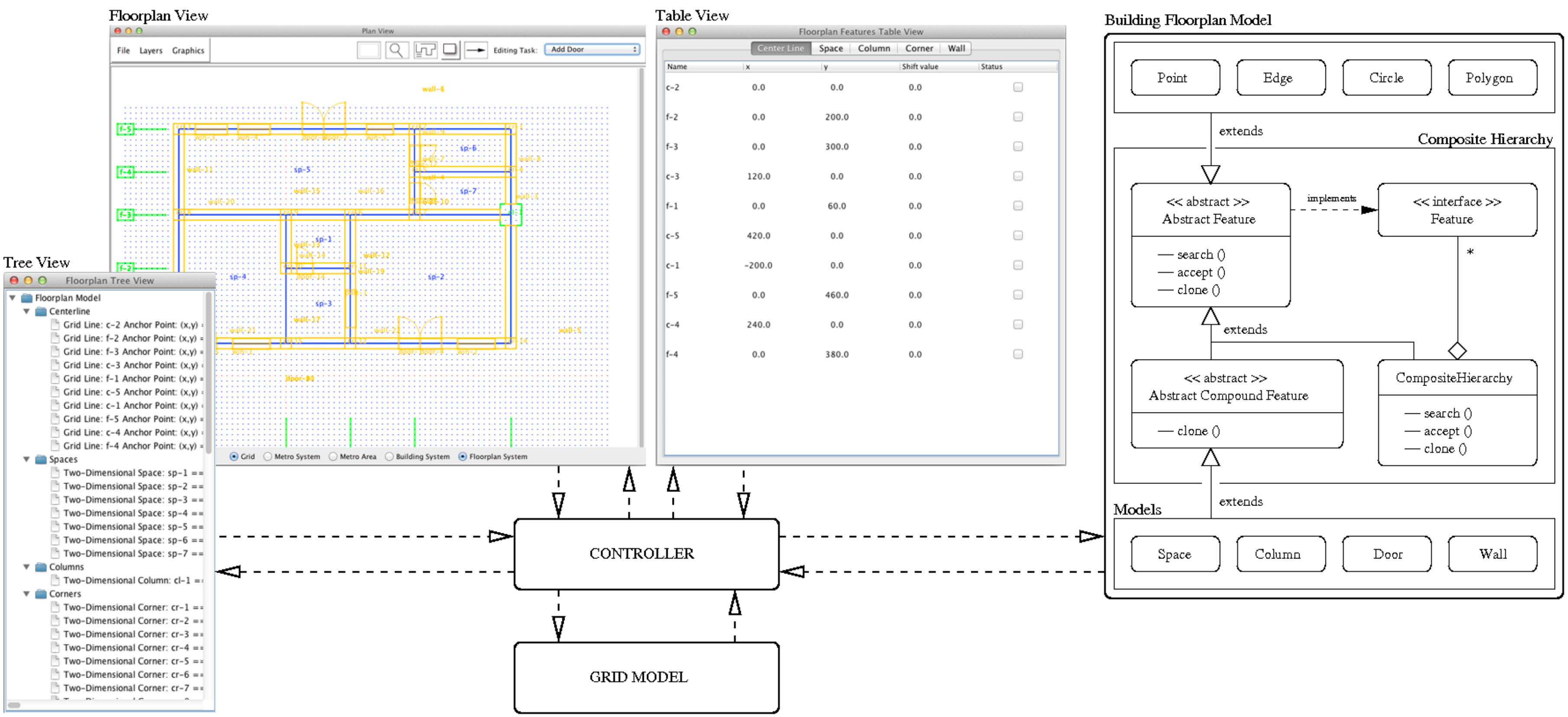


Model-View-Controller (MVC)



ENCE 688R / MSSE PROJECT WORK

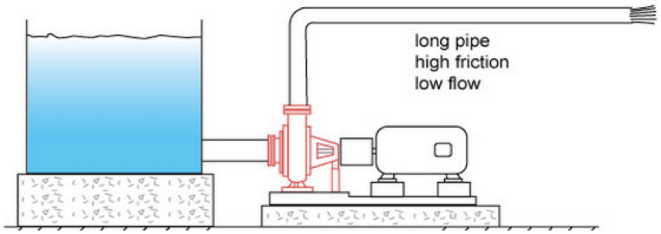
BUILDING FLOORPLAN EDITOR

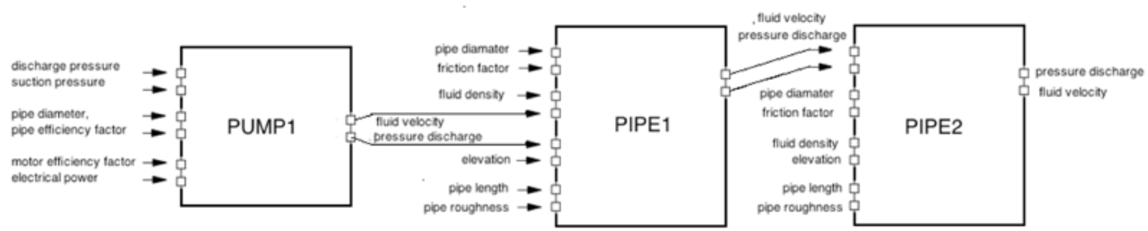


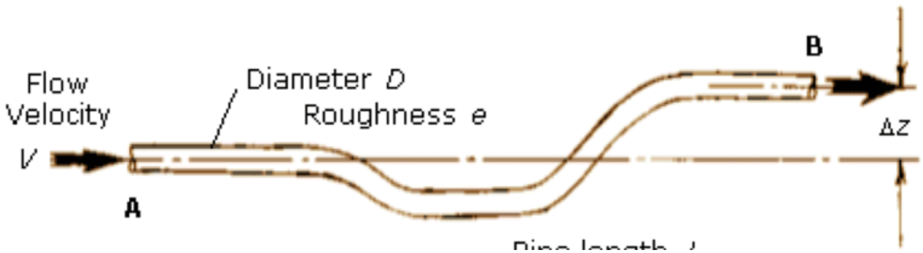
Source: Eddie Tseng, MSSE Graduate Student.

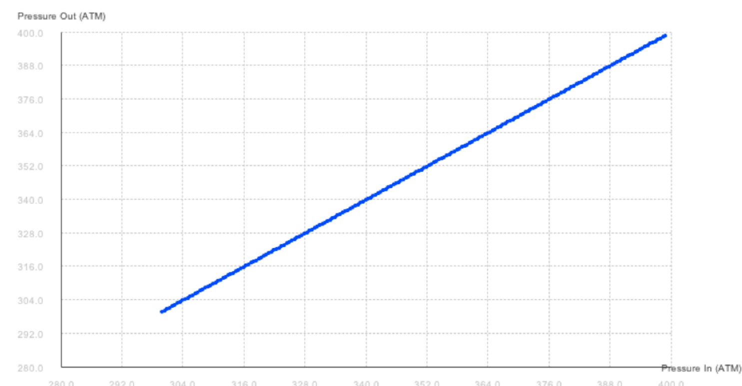
ENCE 688R / MSSE PROJECT WORK

COMPONENT-BASED MODELING OF PIPE NETWORKS









$$P_b[\mathrm{Pa}] = P_a[\mathrm{Pa}] - \rho[\mathrm{kg}/m^3] * g[\mathrm{m}/s^2] * \left(\Delta z[\mathrm{m}] + f[dimensionless]\frac{L[\mathrm{m}]}{D[\mathrm{m}]}\frac{V^2[m^2/s^2]}{2g[\mathrm{m}/s^2]}\right)$$

Source: Karam Rajab, MSSE Graduate Student.

ENCE 688R / MSSE PROJECT WORK

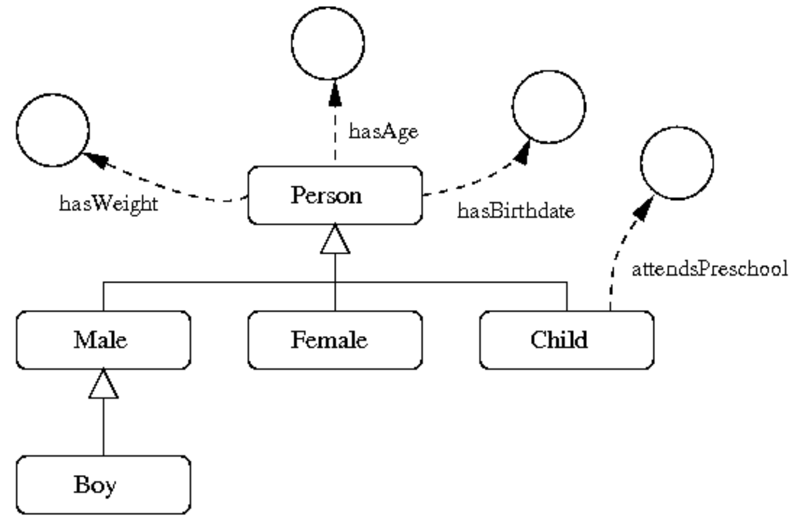
ONTOLOGY MODELING AND RULE-BASED REASONING

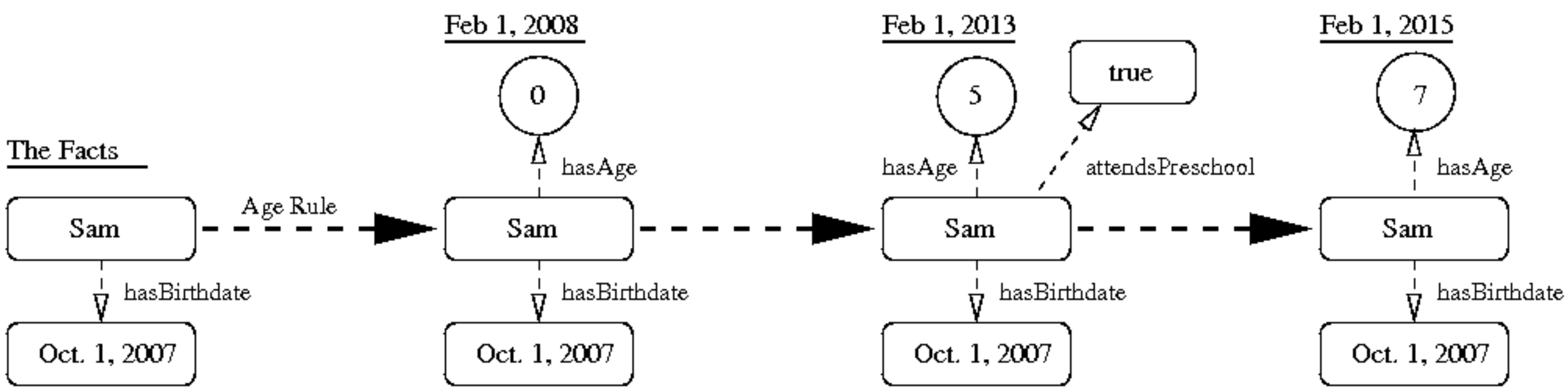
Fact. Sam is a boy. He was born October 1, 2007.

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.

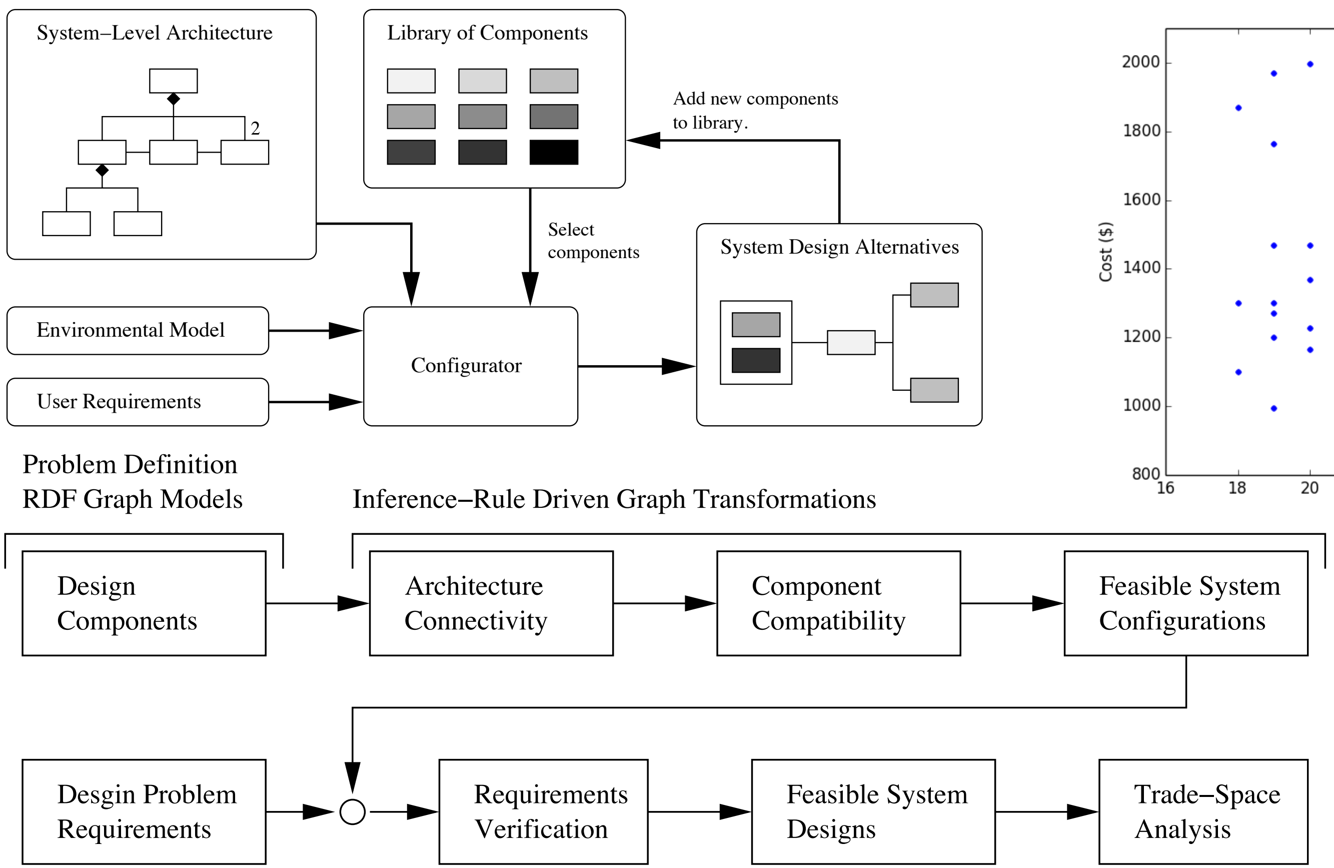
Rule 3: Children who are age 5 attend preschool.

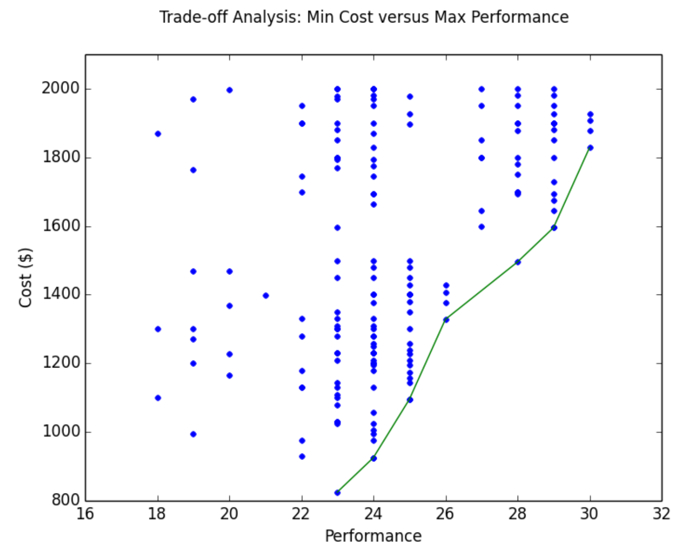


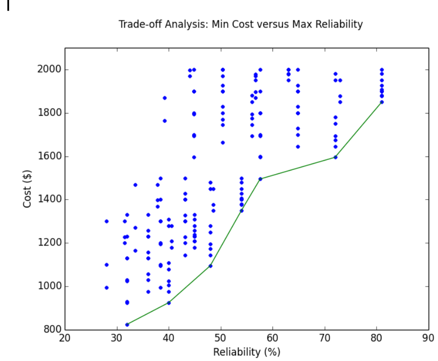


ENCE 688R / MSSE PROJECT WORK

DESIGN AND TRADE-OFF ANALYSIS WITH RDF GRAPHS







Source: Nefretiti Nassar, MSSE Graduate Student.

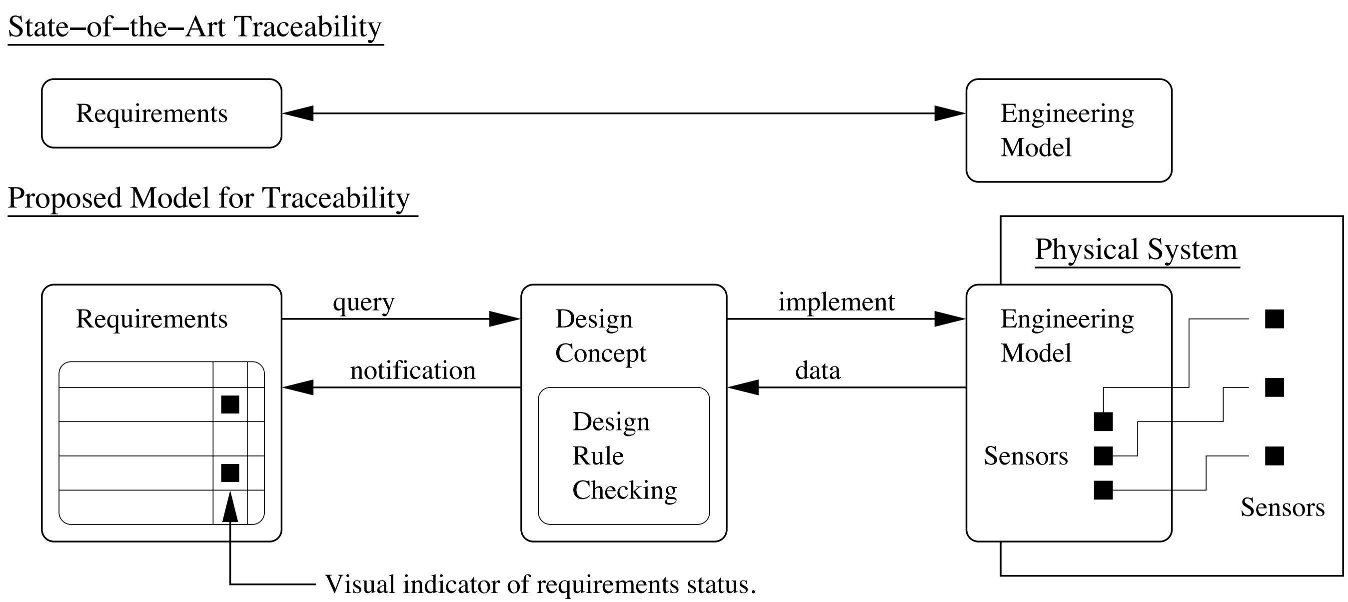
CURRENT RESEARCH ON CPS

Semantic Platforms for Design and Management of Trains and Buildings

Civil Systems Ph.D. Student: Parastoo Delgoshaei (2010-present)

TRACEABILITY MECHANISMS

New idea (2005): Ontology-enabled Traceability Mechanisms

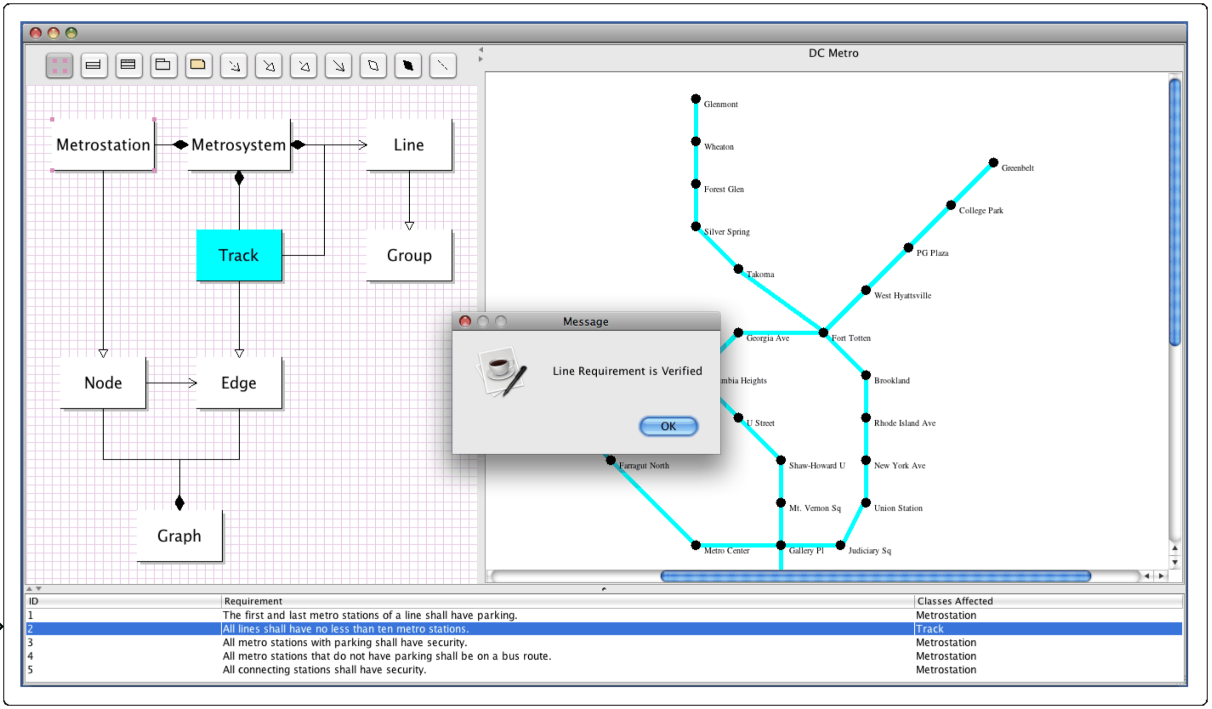


Approach: Requirements are satisfied through implementation of design concepts. Now traceability pathways are threaded through design concepts.

Key Benefit: Rule checking can be attached to “design concepts” (ontology), therefore, we have a pathway for early validation.

ONTOLOGY – ENABLED TRACEABILITY (WITH VERY BASIC RULE CHECKING)

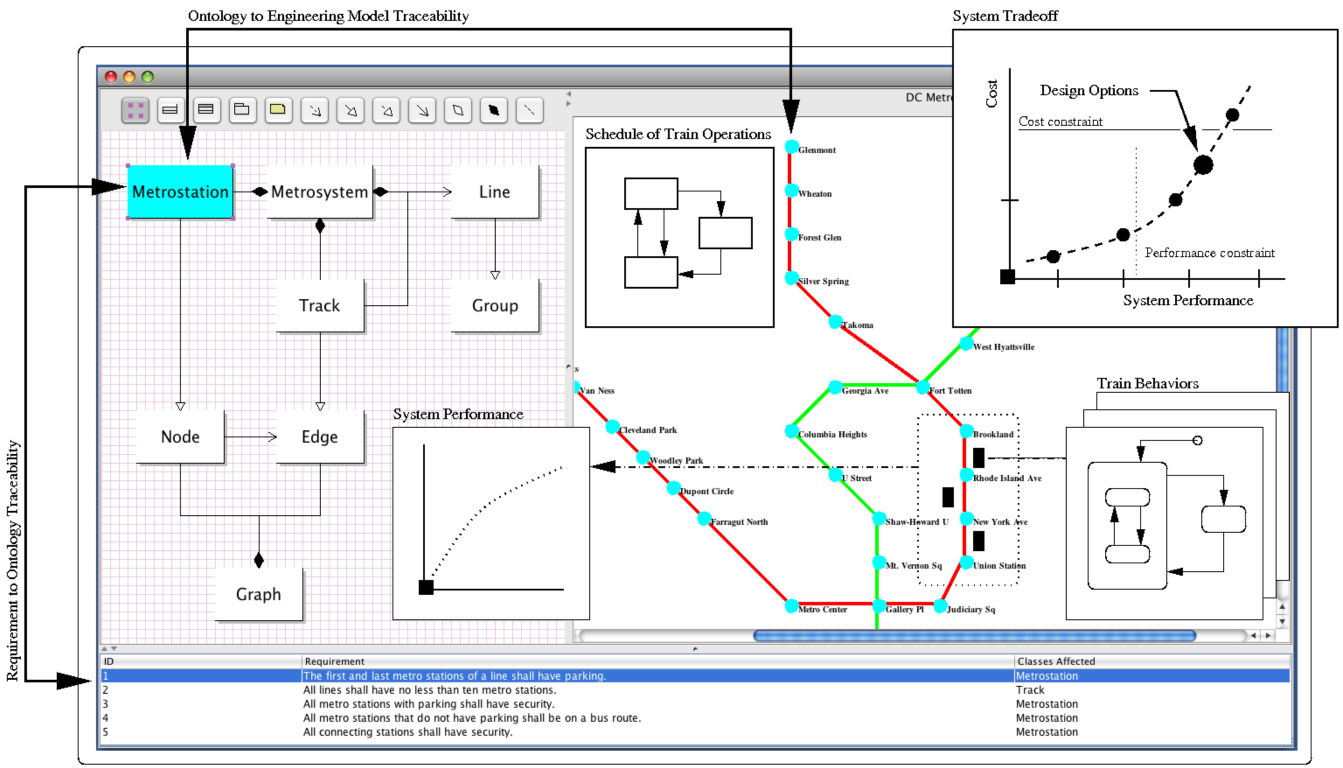
Key Advantage: Design rules and procedures for design rule checking can be attached to ontologies

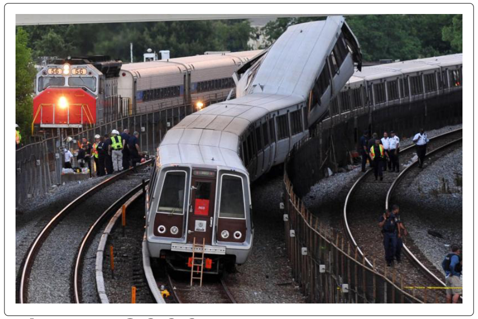


Design rule checking is triggered by double clicking on a requirement. Visualization shows the extent of ontologies and engineering entities involved in the rule checking.

Source: Cari Wojcik, 2006.

VISION FOR VERSION II (2010)



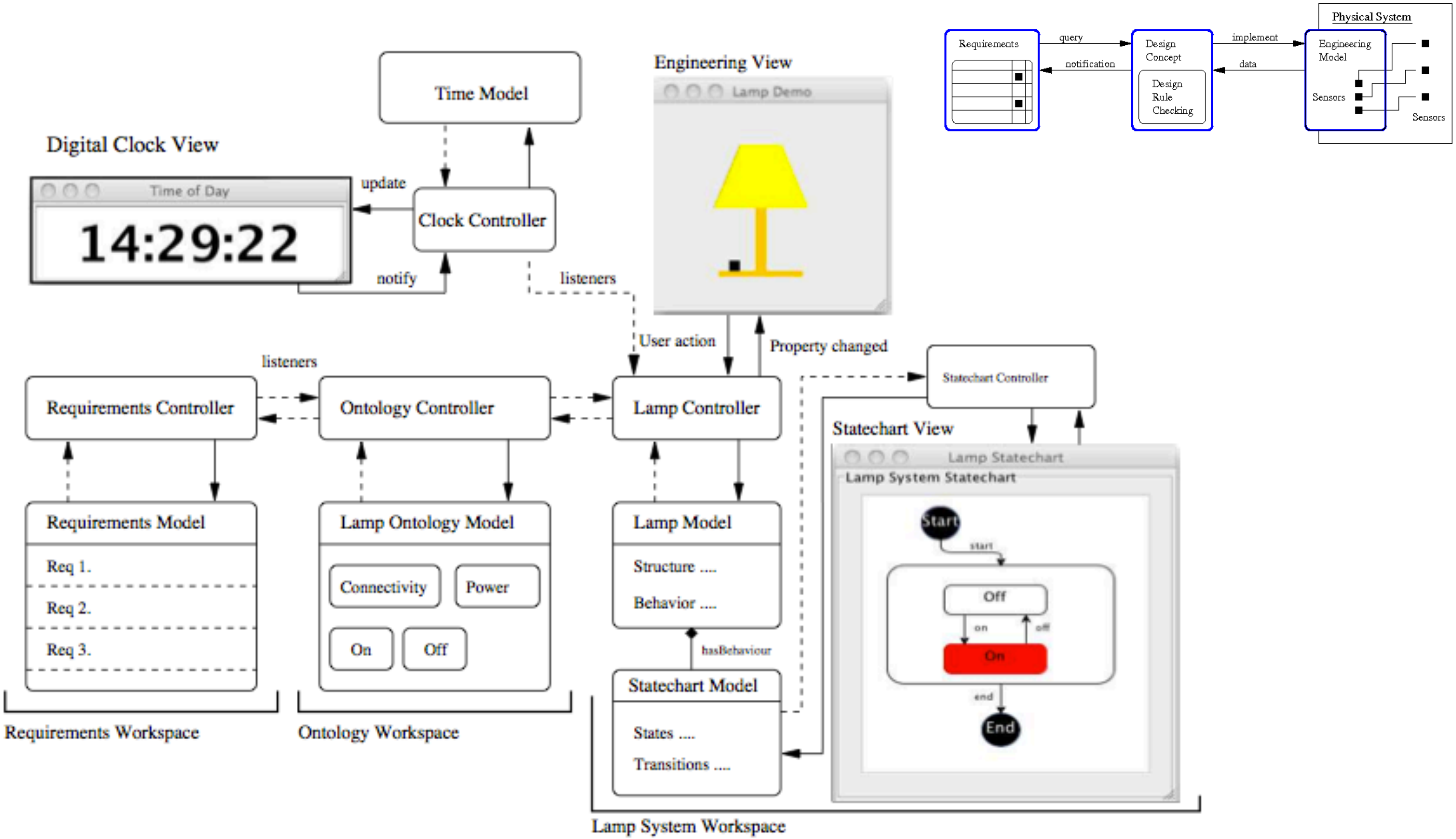


June, 2009.

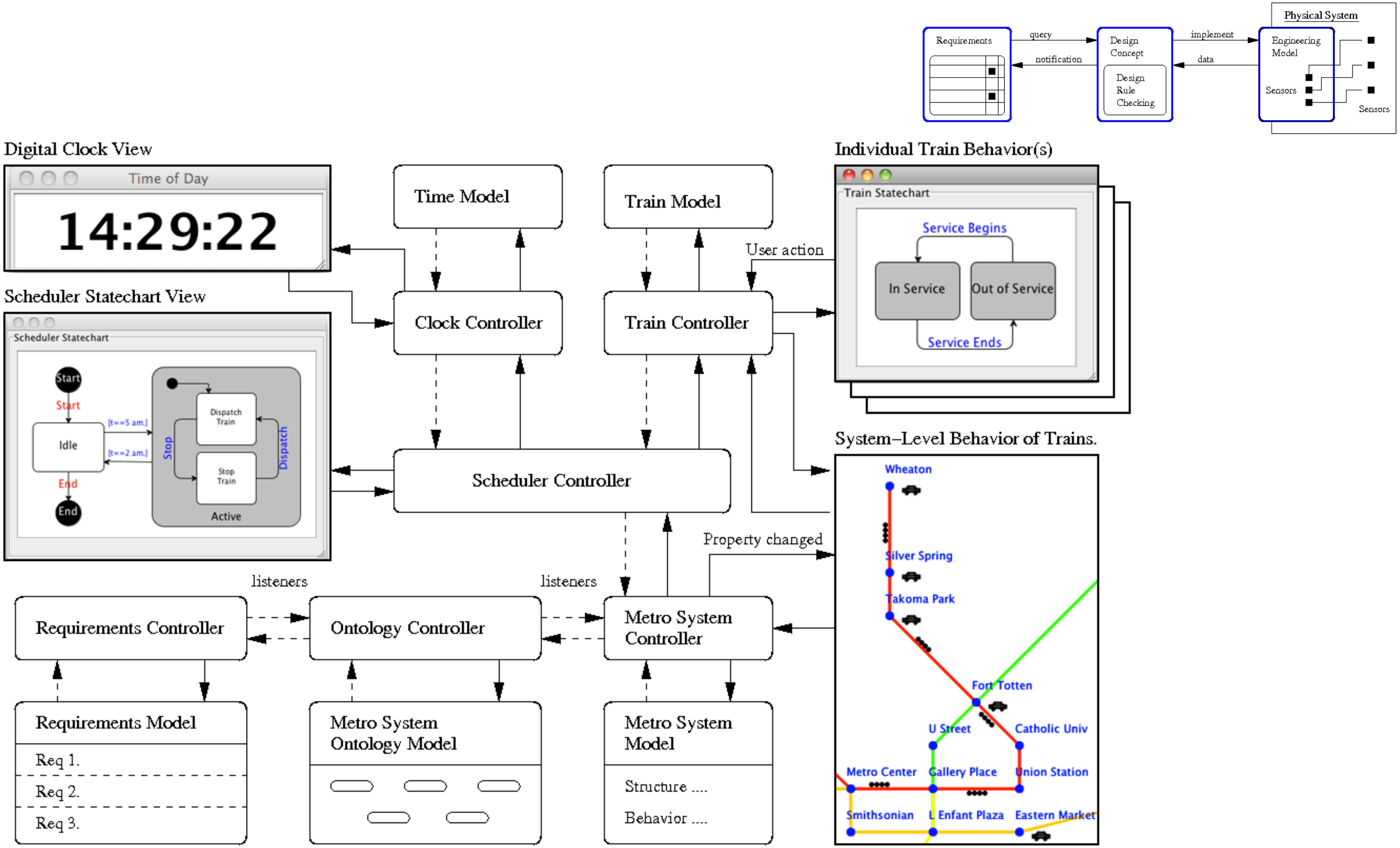
Re-design implementation to maximize use of software design patterns.
Model system schedules and train behavior with finite state machines.

System-level behavior will correspond to a network of communicating finite state machines.

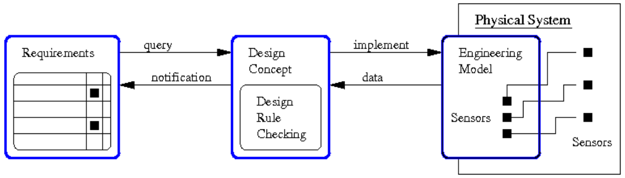
SIMPLE LAMP ARCHITECTURE



RAILWAY SYSTEM ARCHITECTURE



REQUIREMENTS-TO-STATECHART TRACEABILITY



Requirement level (textual representation)

The metro system will start working at 5 am.

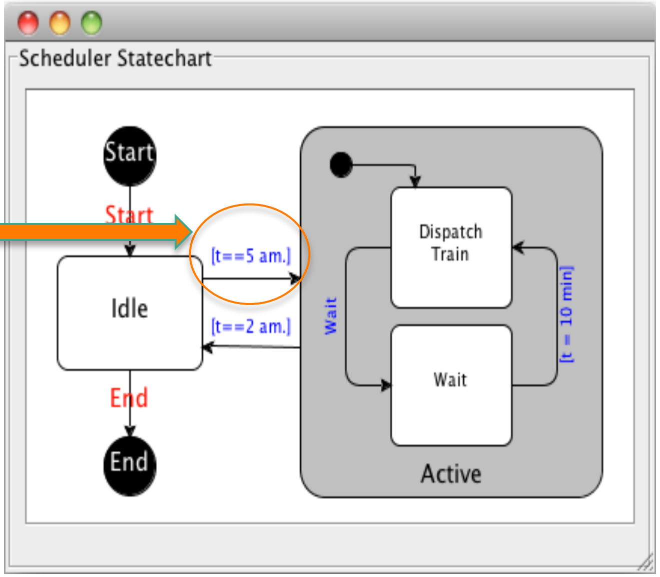
Rule level (SWRL)

scheduler(?s)^ hasTime(?s,?t) ^ swrlb:greaterThan(?t,5) ^ train(?tr)

^ isAvailable(?tr,true)=>sendTrain(?s,?tr)

Guard Statement

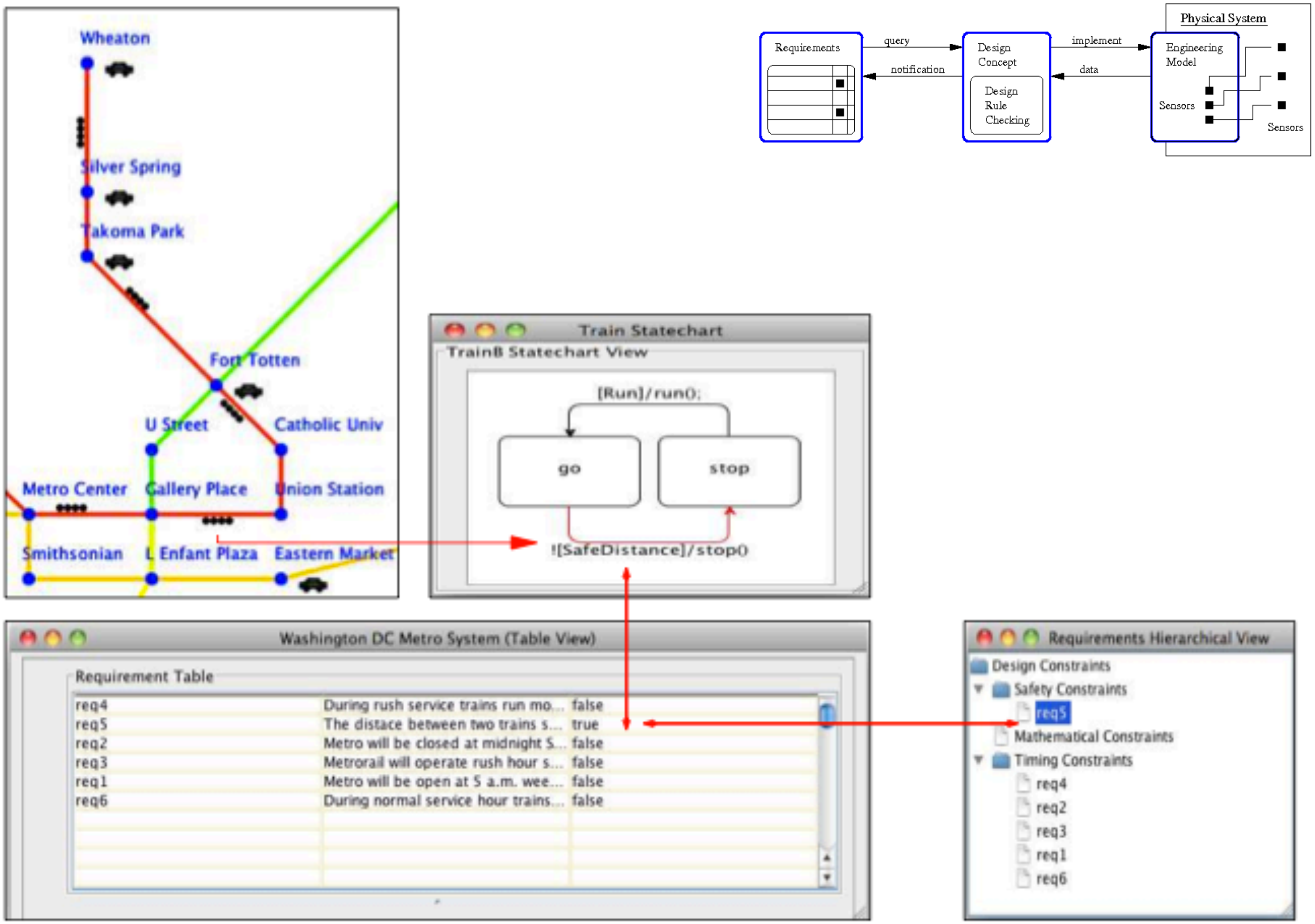
The transition from idle to active is conditional on "[t == 5 am.]" evaluation results.



Expected Behavior

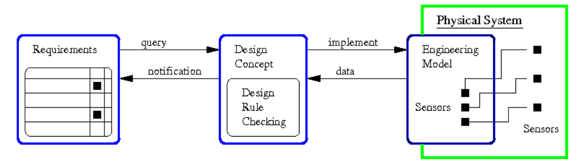
- The scheduler statechart will transition from idle to active at 5:00 am.
- The statechart of at least one train will transition to the "At Station" state.

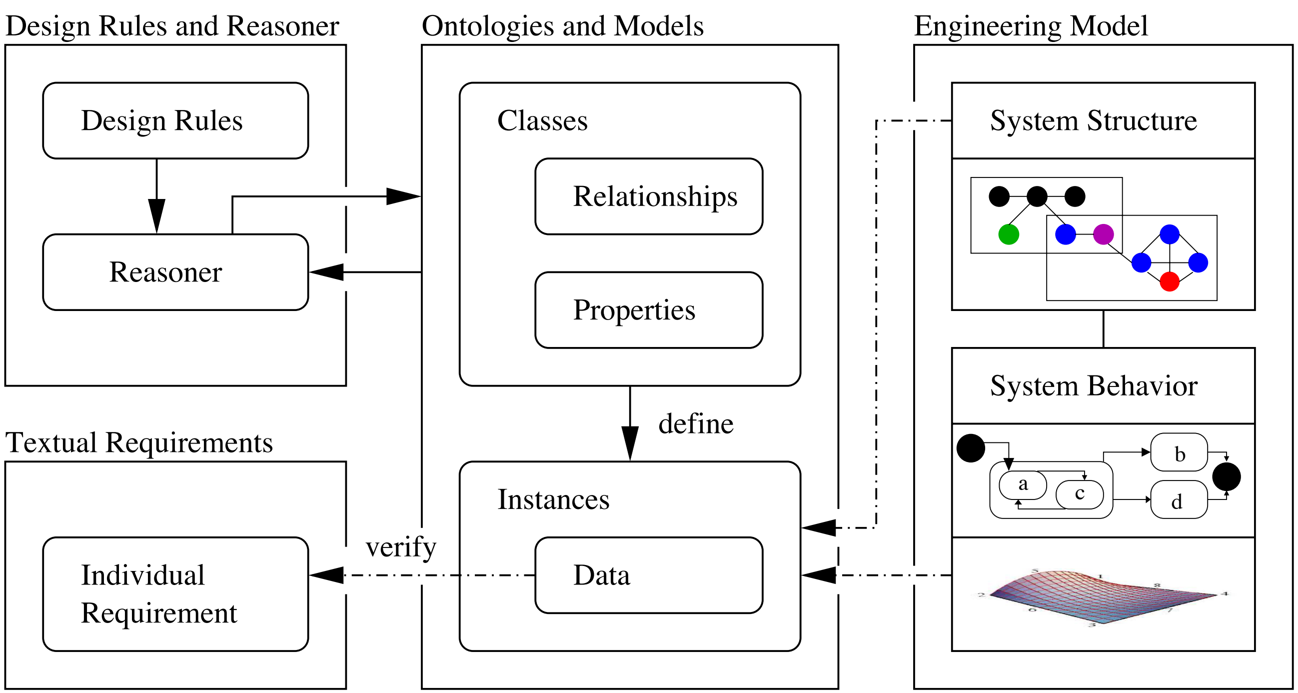
STATECHART TO REQUIREMENT TRACEABILITY



FROM TRAINS TO BUILDINGS (2013-2014)

Parastoo finishes MSSE Degree in Dec. 2012.
Matriculates to Ph.D. in Civil Systems in Jan. 2013.





Remarks

System structures are modeled as networks and composite hierarchies of components.

Behaviors will be associated with components.

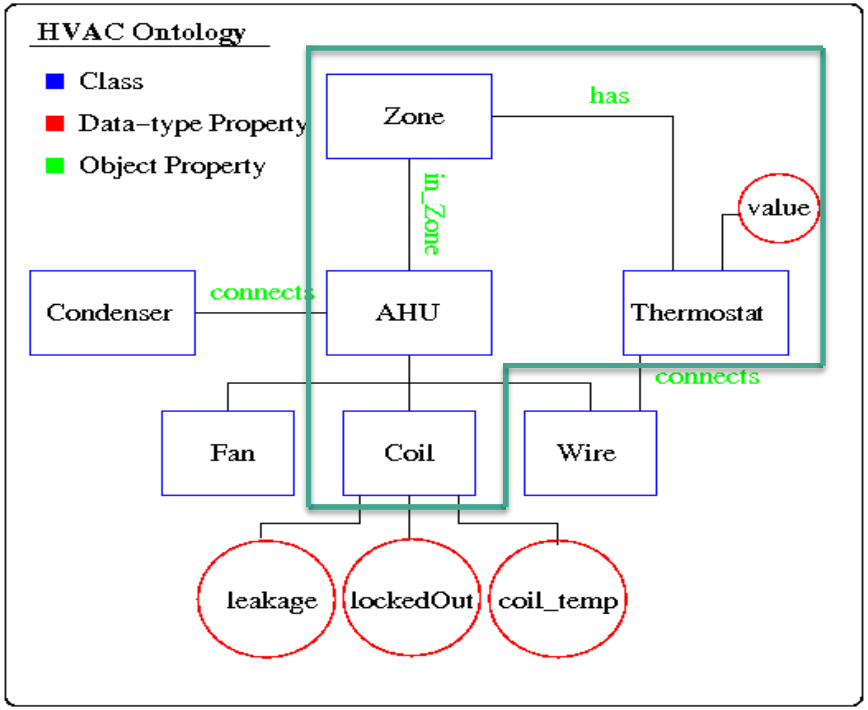
Discrete behavior will be modeled with finite state machines.

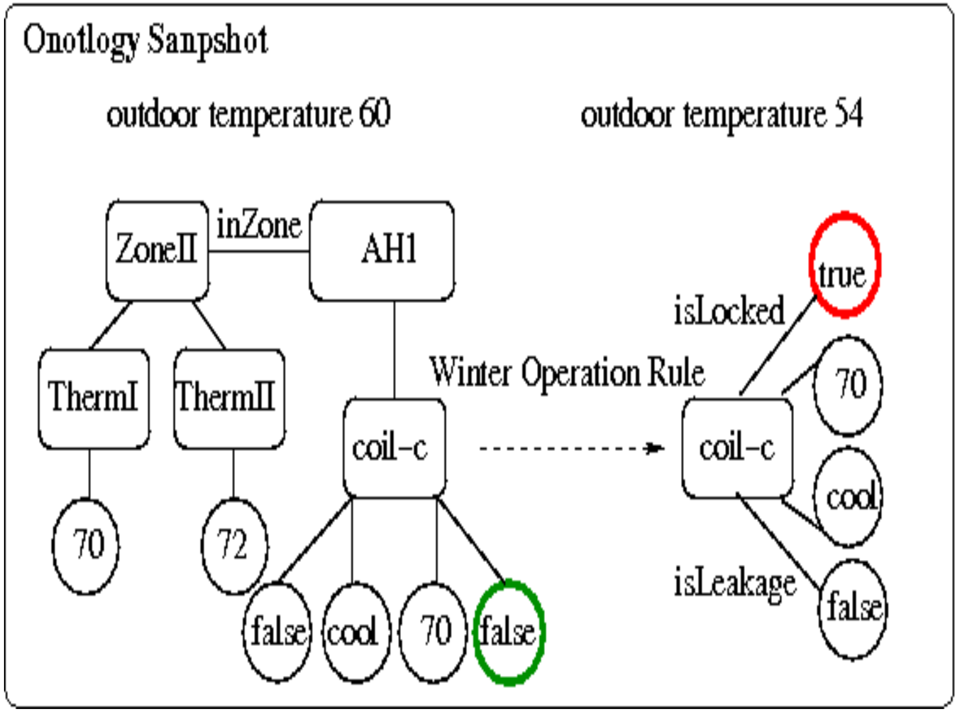
Continuous behavior will be represented by partial differential equations.

INFERENCE RULES FOR HVAC ONTOLOGY

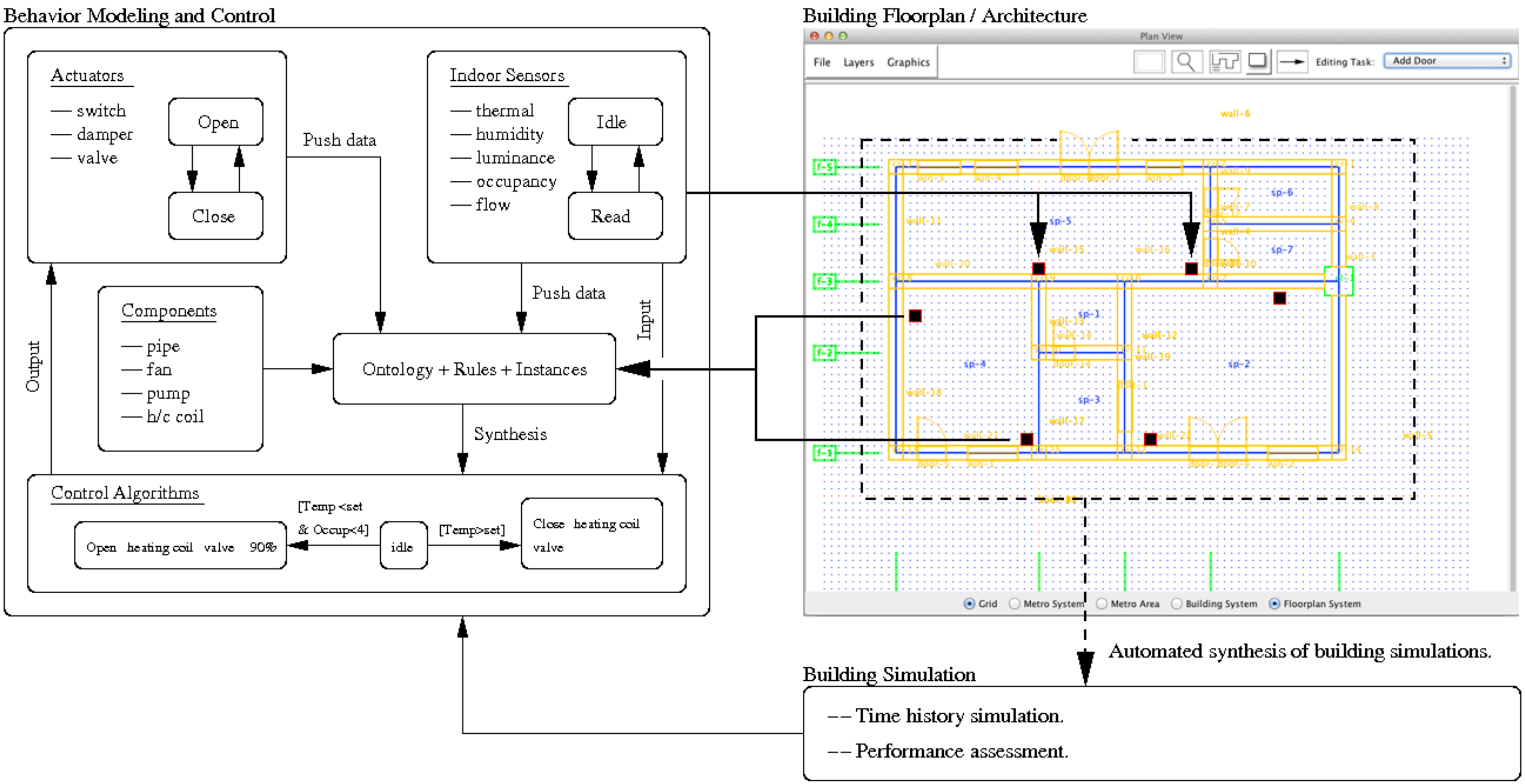
Requirement: Cooling coil will be locked out for winter operation (55 F)

Rule: (?cc RDF:type Cooling) (?cc ont:isLocked? ?l) (?out_temp ont:hasValue ?v) lessThan(?v,55) ->(?l, true)





SYSTEM-LEVEL DESIGN / SIMULATION / CONTROL



SCRIPTING LANGUAGE DESIGN (2013)

Problem Statement and Approach

- Support the integration of physical components and computation of discrete and continuous behaviors.
- Units are embedded within the basic data types, physical quantities, matrices of physical quantities, and branching and looping control.

Assignment Statements

```
// Setup parameters for tank 02 ....

area02 = 5 m^2;
h02    = 1 m;

// Setup parameters for pipe connecting tanks 01 and 02 ....

pipeRadius    = 10 cm;
pipeArea      = PI*pipeRadius^2;
pipeLength    = 5 m;
pipeRoughness = 0.005;

// Setup parameters for fluid contained in the pipe and tanks ....

rho = 1000.0 kg/m^3;  // density of water ...
g   = 9.81 m/sec^2;   // acceleration due to gravity ...
```

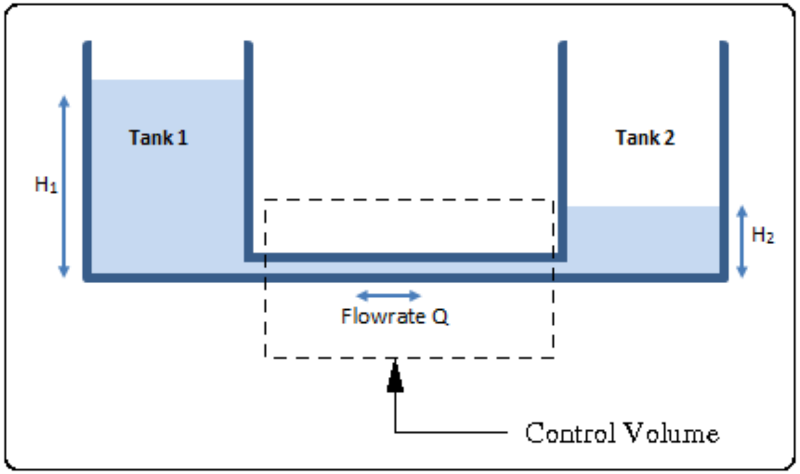
Looping Constructs

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

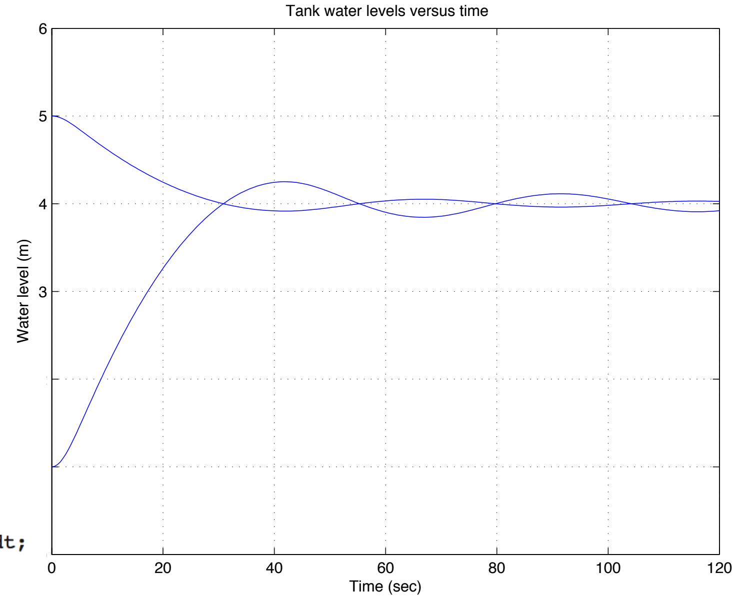
Matrices

```
Force    = [ 2 N, 3 N, 4 N ];
Distance = [ 1 m; 2 m; 3 m ];
Work     = Force*Distance;


Matrix: Force
row/col                  1             2             3
        units            N             N             N
   1           2.00000e+00   3.00000e+00   4.00000e+00

Matrix: Distance
row/col                  1
        units            m
   1           1.00000e+00
   2           2.00000e+00
   3           3.00000e+00

Matrix: Work
row/col                  1
        units          Jou
   1           2.00000e+01
```

A SIMPLE PROBLEM – FLOW BETWEEN TANKS




```
[java]
[java] Matrix: response01
[java] row/col                  1           2           3           4
[java]          units         sec           m           m     m^3/sec
[java]    1           0.00000e+00 5.00000e+00 1.00000e+00 0.00000e+00
[java]    2           5.00000e-01 4.99795e+00 1.00616e+00 1.23276e-01
[java]    3           1.00000e+00 4.99184e+00 1.02449e+00 2.43276e-01
[java]    4           1.50000e+00 4.98189e+00 1.05434e+00 3.53771e-01

... lines of output removed ...
```

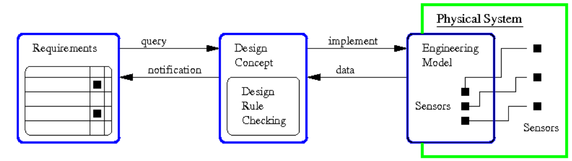


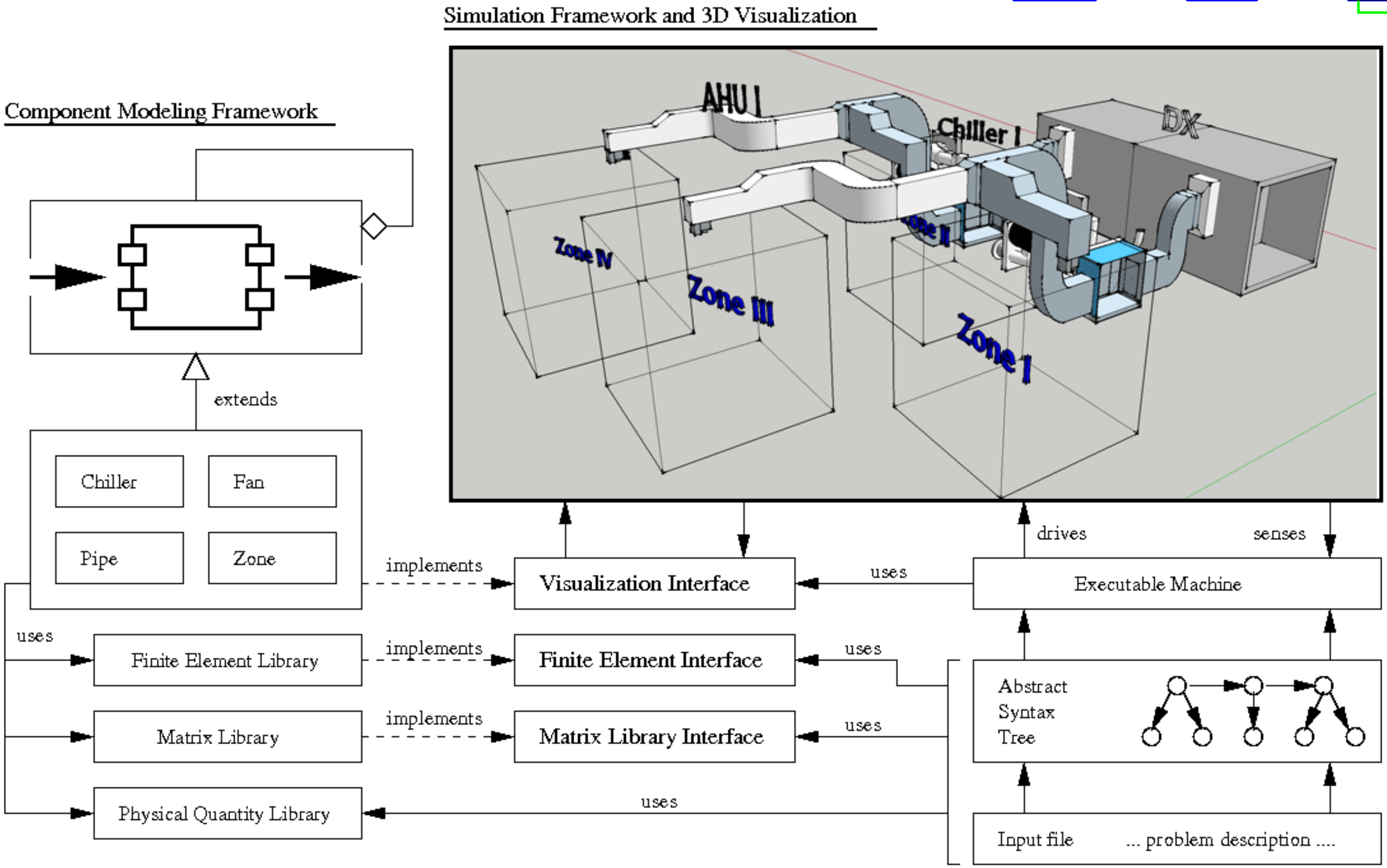
$$\left[\frac{dv(t)}{dt}\right] + \left[\frac{f_1}{2D}\right] v(t)|v(t)| = \left[\frac{g}{L}\right] \left[H_1(t) - H_2(t)\right].$$

```
// Compute simulation response ...

for (i = 1; i < nsteps; i = i + 1) {

    // Compute fluid velocity update ...

    velocityFluid  = pipeRoughness/(4.0*pipeRadius)*velocityOld*Abs(velocityOld)*dt;
    velocityUpdate = g/pipeLength*( h01Old - h02Old )*dt;
    velocityNew    = velocityOld + velocityUpdate - velocityFluid;

    // Update water depths in tanks 01 and 02 ...

    h01New = h01Old - (pipeArea/area01)*(velocityOld+velocityNew)*dt/2.0;
    h02New = h02Old + (pipeArea/area02)*(velocityOld+velocityNew)*dt/2.0;
```

Near-term goal: support for computational fluid dynamics.

FUTURE PLANS





Acknowledgement: Amanda Pertzborn

CURRENT RESEARCH ON CPS

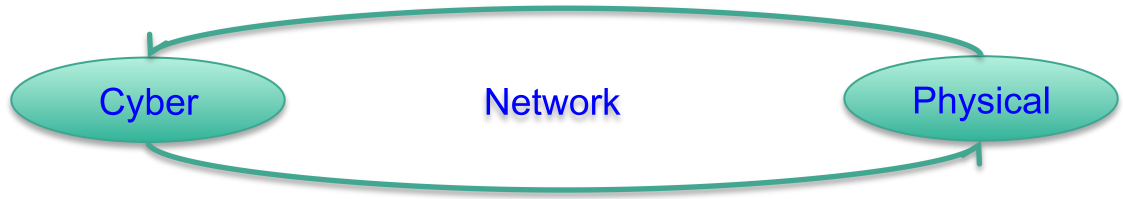
Ontologies of Time and Time-Based Reasoning. Spatio-Temporal Systems.

Civil Systems Ph.D. Student: Leonard Petnga (2012-present)

PROBLEM STATEMENT

What are Cyber-Physical Systems?

Systems with tight integration of *networked computational* and *physical* elements *(Lee, 2010)*



	Cyber	Network	Physical
Mathematical model:	**FSM**	**Graph**	**ODE**
Time model:	**Discrete**	**Discrete**	**Continuous**
Space model:	**Discrete**	**Discrete**	**Discrete/Continuous**
Role:	**Decision/Computation/Reasoning**	**Communication**	**Sensing/Actuation**

Scientific and Technical Challenges :

- **Modeling:** **Lack of "Integration science"** with needed mathematical foundations
- **Design:** Weak "procedures" for handing **meta domains** (time, space, ..) critical to system "ity"
- **Operation/Decision :** High **dependence on embedded/local computational intelligence**

➔ **Right physical action at the right time and right place are critical to … safety!**

➔ **How to embed physical semantics in cyber models for smartness**

OBJECTIVE AND SCOPE

Investigate and understand

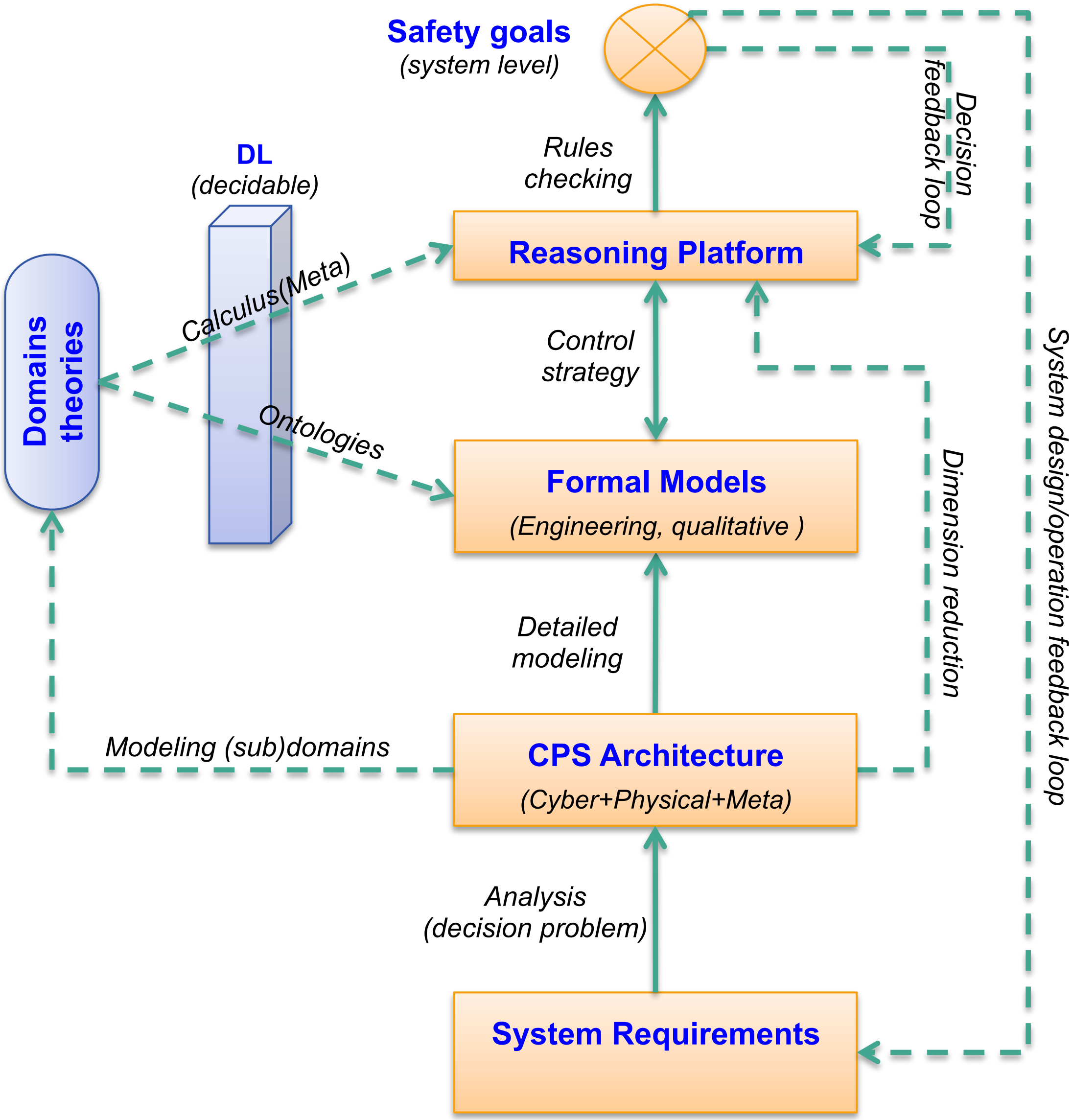
- Meta domains especially **temporal** and **spatial theories**
- **Ontologies** roles in deriving formal, precise models and **architecting CPS**
- **DL-based semantics Reasoning** for achieving **System level safety** in CPS
- **Allen's Temporal Interval Calculus** and **Region Connection Calculus (RCC)**
- **Semantic web technologies**

To conceptualize formal procedures and reasoning framework enabling HW-SW co-design, system-level safety study and domain-specific semantics in MBSE of CPS.

Implement: integration mechanisms between temporal and non-temporal domains in safety-critical systems in general and CPS in particular.

Applications: Civil Systems (traffic system, connected vehicles, automated aircraft taxing), robots (automated warehouse), aeronautic (UAV fleet), energy (wind farm).

OUR APPROACH: What's New?



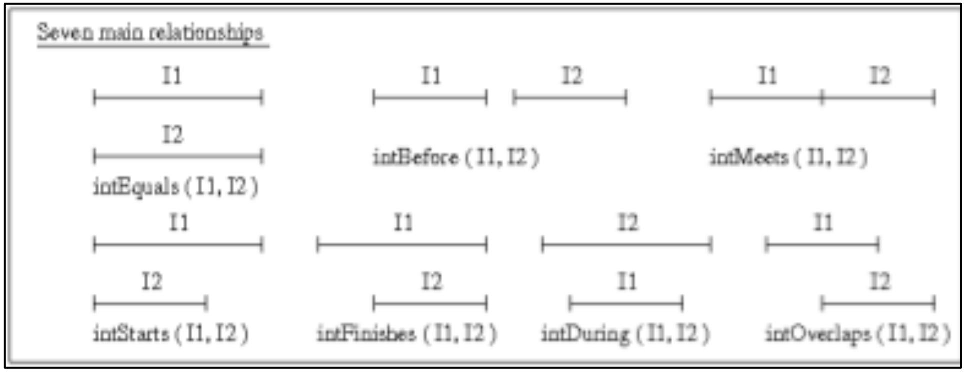
- ✓ ***Modular framework*** *:* domains and rules (theories) formally defined; Ontologies integrity .
- ✓ ***Reasoning-enabled*** *:* DL-semantics for decision making; Handling of physical quantities.
- ✓ ***Interface ontologies*** *:* define and link primitive-domains.
- ✓ ***Formal analysis of system's safety properties***: decision trees for safety requirements (hard constraints) checked;

OUR APPROACH: Scope

CPS for which safety and performance depend on correct time/space-based prediction of the future state of the system.

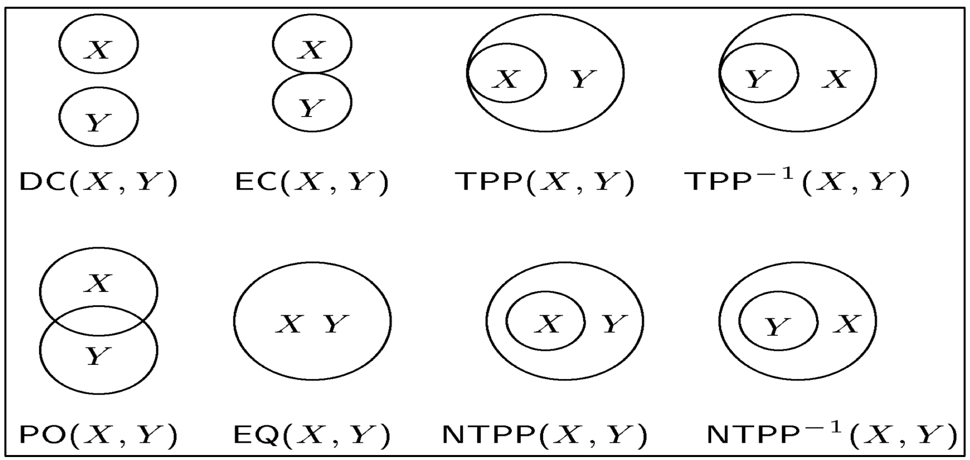
SUPPORTIVE SEMANTICS : TEMPORAL AND SPATIAL CALCULUS

◆ Allen's Temporal Interval Calculus



- **Interval-based theory**: proper time intervals defined from time instants
- **Restricted axioms** ensuring time reasoning **decidability** (OWL DL)
- *Ex. intOverlaps (FOL)*

◆ Region Connection Calculus(RCC)

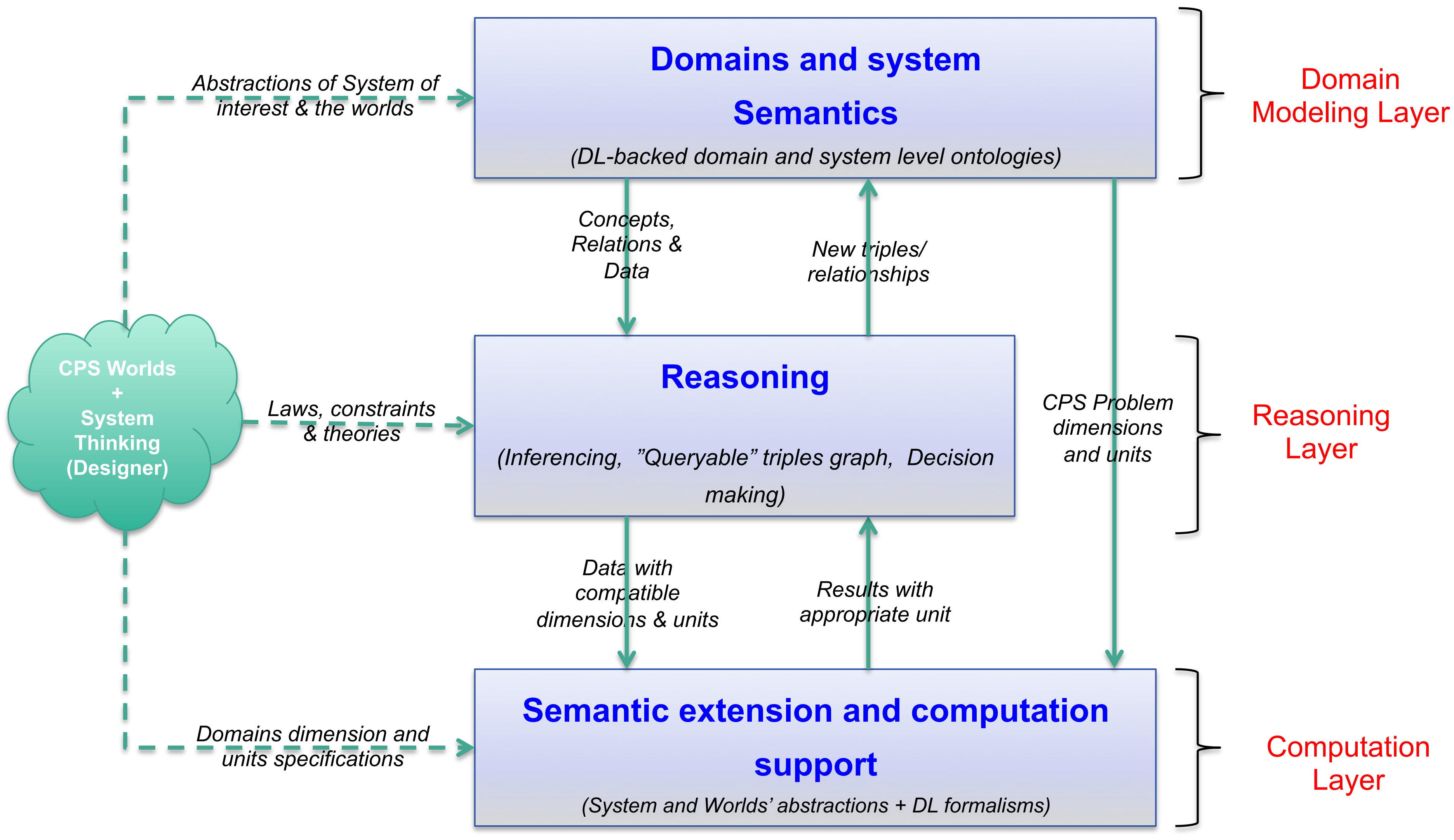


- **Region-based spatial model**: Regular 2D spaces, convex shapes
- **"Maximal fragment" satisfiable in polynomial time** *(Renz 1999)*
- *Ex. disjoint (DC)*

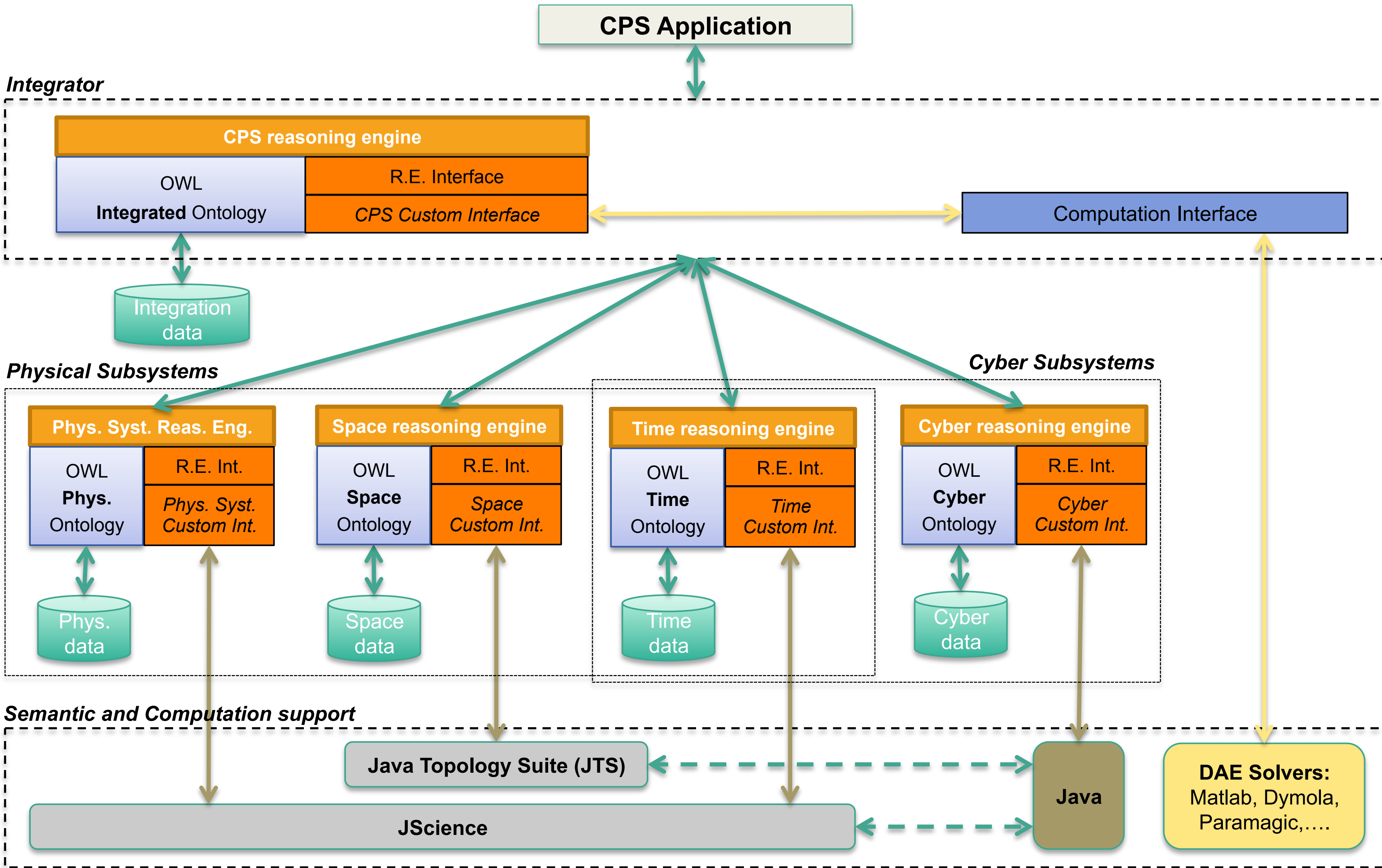
  ($\forall x \forall y (DC(x, y) \leftrightarrow \neg C(x, y))$)

➔ Trade-off between expressiveness and computability …….. for satisfiability!

SYSTEM ARCHITECTURE - HIGH-LEVEL

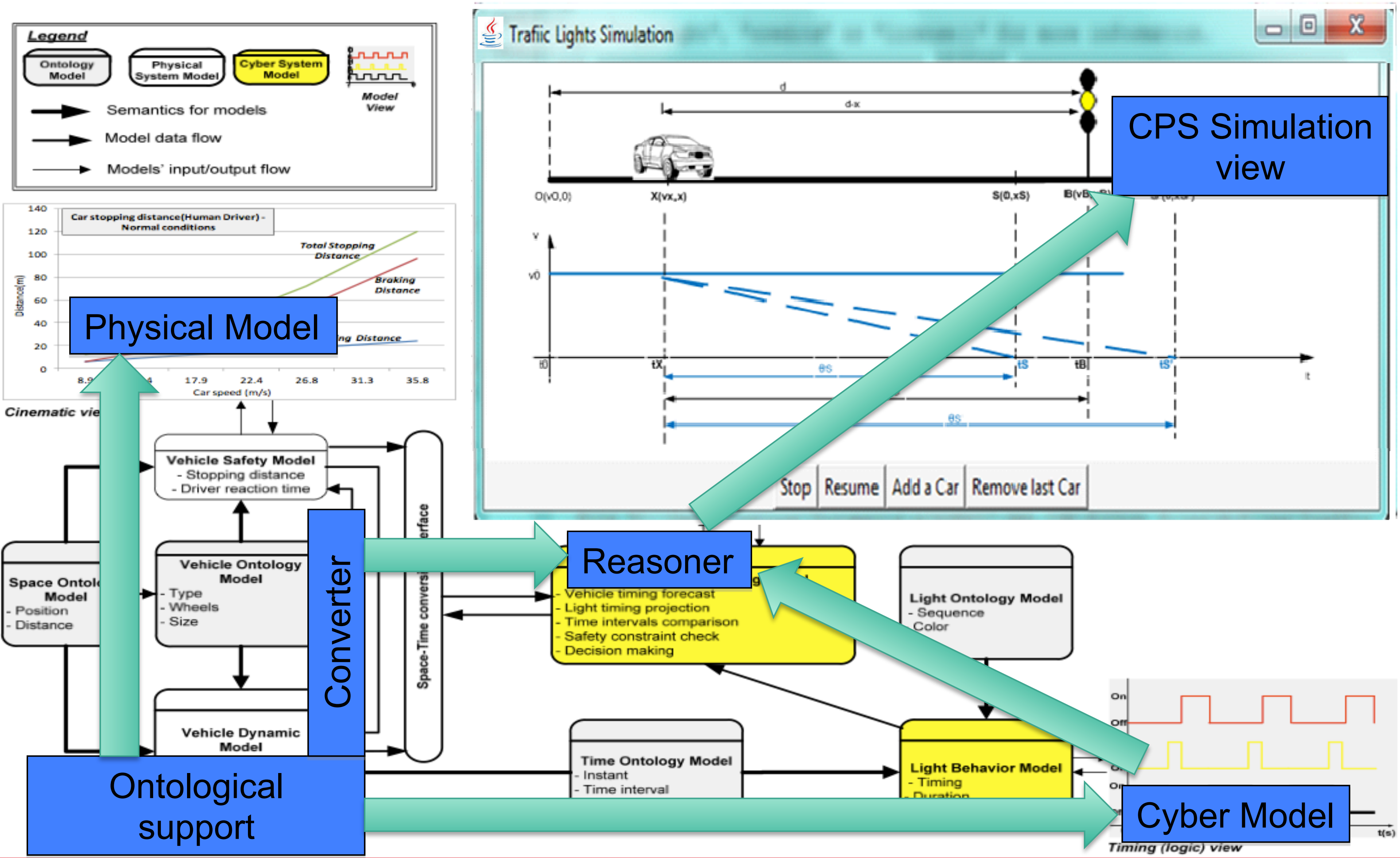


SYSTEM ARCHITECTURE – COMPONENTS AND INTEGRATION

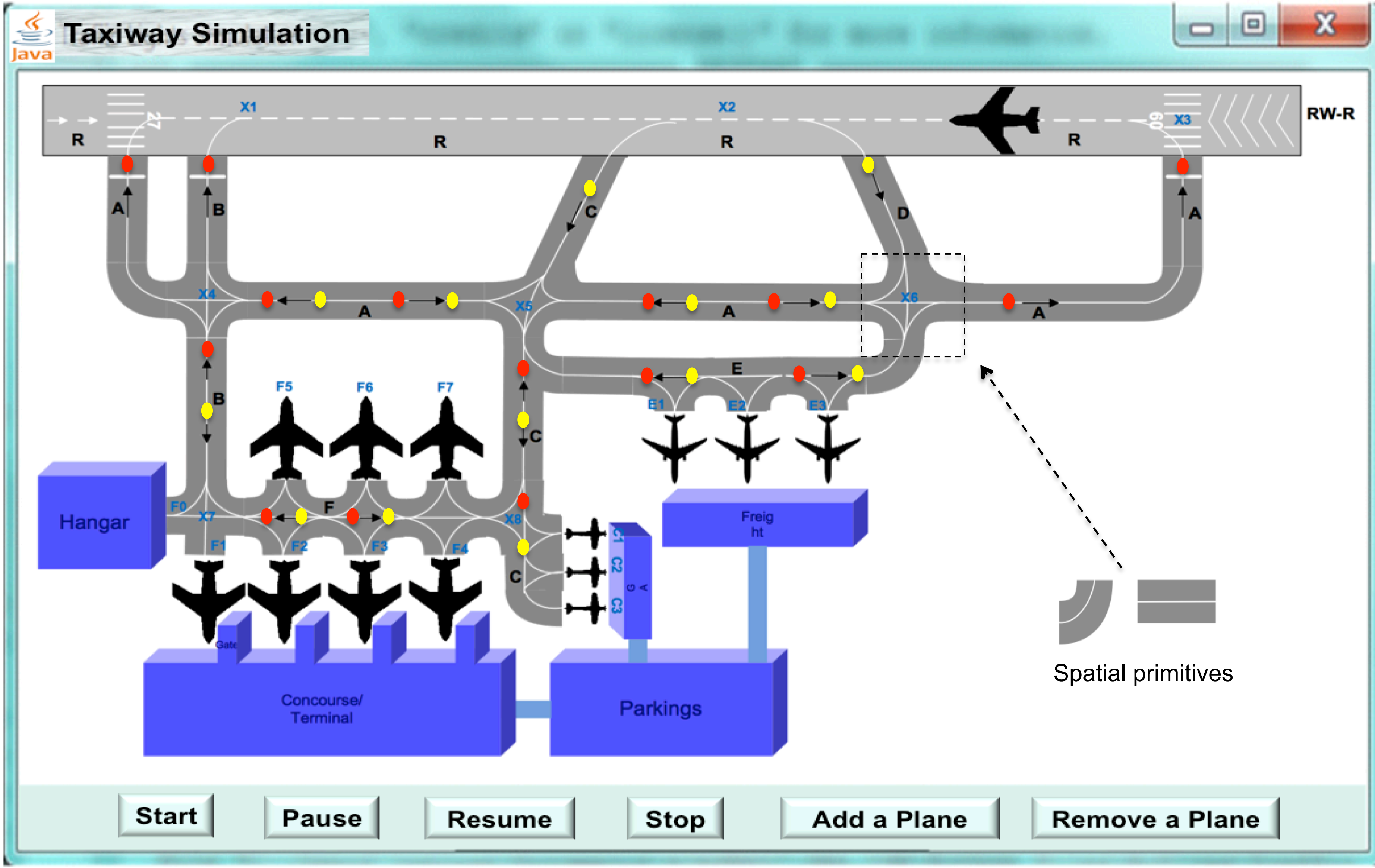


Applications

APPLICATION 1 : DILEMMA ZONE PROBLEM AT TRAFFIC INTERSECTION



APPLICATION 2 : AUTOMATED TAXIWAY SYSTEM AT AIRPORT



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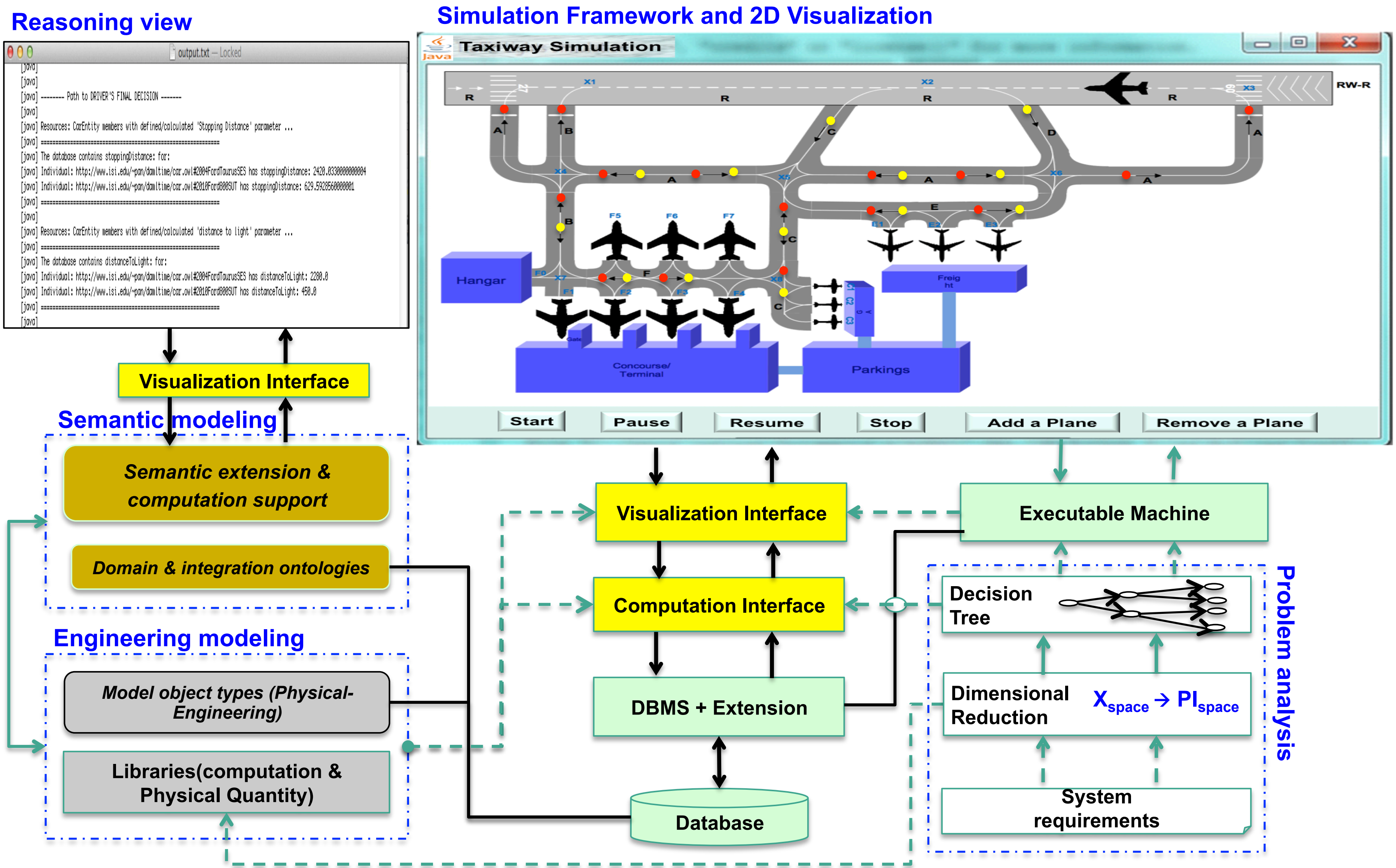
APPLICATION 2 : AUTOMATED TAXIWAY SYSTEM AT AIRPORT



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Thank You

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