Formal Methods and Tool-suites for CPS
Security, Safety and Verification

Lectures 1 and 2: MBSE for CPS

John S. Baras
Institute for Systems Research and Dept. of Electr. and Comp. Engin.
University of Maryland College Park, USA,
and ACCESS Centre Royal Inst. of Technology (KTH), Stockholm, Sweden,
and Inst. for Advanced Study Technical Univ. of Munich (TUM), Germany

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MARKTOBERDORF INTERNATIONAL SUMMER SCHOOL ON ENGINEERING SECURE AND DEPENDABLE SOFTWARE SYSTEMS
THE NEXT FRONTIER IN ENGINEERING RESEARCH AND EDUCATION

• First 50 years of the 21st century will be dominated by advances in methods and tools for the synthesis, implementation and operation of complex engineered systems to meet specifications in an adaptive, safe, (semi-) autonomous way

• Evident from the areas emphasized by governments, industry and funding agencies world-wide:
  
  – energy and smart grids
  – biotechnology
  – systems biology
  – nanotechnology
  – the new Internet and IoT
  – collaborative robotics
  – software critical systems
  – homeland security
  – custom materials design
  – systems healthcare
  – network science
  – smart enterprises
  
  – environment and sustainability
  – intelligent buildings and cars
  – precision health care
  – pharmaceutical manufacturing
  – broadband wireless networks – 5G
  – sensor networks
  – smart transportation systems
  – security-trust-privacy-authentication
  – cyber-physical systems
  – web-based social and economic networks
  – human - machine collaboration
  – neuromorphic AI
AKA

The Next Wonder – MBSE and MBE: from ideas to “making things and services”
Outline

- The Vision and its development
- What happened since then?
- Key challenges -- Model-based Systems Engineering
- Example applications: Microgrids, modern-aircraft, sensor networks, energy efficient buildings, robotics and micro-robotics, collaborative robotics, wireless security, social networks over the Web, Health Care (ICU), democratizing manufacturing, personalized medicine
- Reform Engineering Education
- Concluding remarks – future directions – open problems
The Two Faces of Information Technology in Engineering

(Baras -- 2003 White Symposium)

Ubiquitous presence of IT components as “building blocks”

Increasing use of “system level” design and manufacturing CAD tools
From IT abstractions to “hardware”  
*(Baras -- 2003 White Symposium)*

From DNA ‘programs’ to living organisms

From CAD schematics to chips
From IT abstractions to “hardware”  
(*Baras -- 2003 White Symposium*)
Why IT? Why the Two Faces?  
(Baras -- 2003 White Symposium)

- A means for interfacing heterogeneous components and controlling complexity
- Embedded software and systems
- Micro-sensors, micromotors, MEMS
- Manufacturing ‘ahead’ of design; design verification
- Development and use of formal models and methods
- Microarrays, metabolic pathways, systems biology
- Signaling and communication
- Languages for hardware, cells, ... (XML, UML, DCL, SBML)
- Learning from biology (integration)
Challenges: A Glimpse into the Future  *(Baras -- 2003 White Symposium)*

**RESEARCH**
- At the interface of bio - nano - info
- Self - assembled systems

**EDUCATION**
- Teach holistic engineering

**Computing over new physical domains**
- from abacus to qubits
- entanglement
- nuclear spin, electron spin
- photon polarization, ion trap

**Send a program over a network and at the other end receive hardware**

**Communicating minds**

**Swarm intelligence**
What has happened since then?

• Design and manufacturing from Boeing 777 aircraft to Boeing 787 aircraft ...

• Humans become integral part of systems -- *iPhone*, ...

• Cyber-Physical Systems (CPS) ...

• Social networks over the Web mushroomed ...

• Economic networks over the Web mushroomed ...

• Renewable energy, smart grid ...

• Individual human genome generation becomes fast, inexpensive ...
What has happened more recently?

• Multisensory environmental monitoring spreads...

• Autonomous and connected cars designed and tested ...

• Cloud Computing, “Big Data”, ...

• Health information technology spreads ...

• Internet of Things, Industrie 4.0, Industrial Internet

• First “printed” car ...

• “Crowd sourcing” and manufacturing ...

Boeing’s Seventh Wonder

(IEEE Spectrum, 1995 October)

The 777 incorporates the most advanced avionics of any commercial U.S. aircraft and is the first plane of any kind to be almost entirely computer-designed.

BOEING’S SEVENTH WONDER

Fresh start

The answers are in the new technology used in the 777 itself, and in the design-engineering revolution that stormed through Boeing, based in Everett, Wash., during the creation of its first all-new jetliner since the early 1980s. Advances in electronics and in computer-aided design, manufacture and simulation provided the foundation for the new technology. Using these tools and systems to an unprecedented extent, Boeing was able to start afresh with the 777, changing the way in which the company builds aircraft. The results have been so dramatic that practically every new Boeing flight product—from the new generation of the venerable 737 family and F-22 air superiority fighter to International Space Station and the proposed X-33 reusable launch vehicle—is adopting some part of the program pioneered by the 777.
**BOEING 787: CLEANER, QUIETER, MORE EFFICIENT**

The 787 Dreamliner delivers:

- 20%* reduction in fuel and CO₂
- 28% below 2008 industry limits for NOx
- 60%* smaller noise foot print

*Relative to the 767
MBSE for Fault Tolerant Vehicle Management Systems (Electrical, Hydraulic, etc.)

**Goal:** Synthesize logic to switch between generators and loads on-demand and to handle faults so as to stay within safe operating envelope.

Joint with UTRC

[Image: hamiltonsunstrand.com]
iPhone -- Smartphone

A remarkably innovative systems integration

Attention to the user
The device that can do “everything”

Mobile wallet gains currency

He not usually avoids carrying to fall by his wallet and reason adult a line, though a drumming also automatically adds faithfulness points to his Walgreens’ faithfulness card, also stored in his phone, and can assistance him redeem any banking he competence have downloaded from a Internet.

Soon, he will be means to do a same for his favorite sandwich during Subway. McCaughlin, arch rising payments officer during Mastercard, has been one of a initial to try out a Google Wallet mobile compensate complement introduced by a Internet hulk in May in partnership with Citigroup and Mastercard Worldwide.

Mobile wallet offered to UK shoppers

Google, Citi, MasterCard, First Data and Sprint team up to make your phone your wallet

Google Wallet will enable consumers to tap, pay and save with their phones

NEW YORK, May 26, 2011 (CNNW) – At an event today, Google, Citi, MasterCard, First Data and Sprint announced and demonstrated Google Wallet, an app that will make your phone your wallet so you can tap, pay and save money and time while you shop. For businesses, Google Wallet is an opportunity to strengthen customer relationships by offering a faster, easier shopping experience with relevant deals, promotions and loyalty rewards.

Mobile Wallets: Security and Privacy Questions Raised By New Google App

First Posted: 9/20/11 07:32 PM ET Updated: 9/20/11 07:32 PM ET

React

It is billed as the future of commerce: swiping a smartphone at the checkout counter instead of a credit card.

On Monday, Google made its move into the building market of mobile payment systems by launching Google Wallet, an app that stores users’ credit card information on their phones, allowing them to purchase goods by swiping their phones at stores.

http://wn.com/Google_Wallet
Future “Smart” Homes and Cities

• UI for “Everything”
  – Devices with Computing Capabilities & Interfaces

• Network Communication
  – Devices Connected to Home Network

• Media: Physical to Digital
  – MP3, Netflix, Kindle eBooks, Flickr Photos

• Smart Phones
  – Universal Controller in a Smart Home

• Smart Meters & Grids
  – Demand/Response System for “Power Grid”

• Wireless Medical Devices
  – Portable & Wireless for Real-Time Monitoring
Wireless and Networked Embedded Systems: Ubiquitous Presence
A Network Immersed World

A complex collection of sensors, controllers, compute nodes, and actuators that work together to improve our daily lives

- **From very small**: Ubiquitous, Pervasive, Disappearing, Perceptive, Ambient
- **To very large**: Always Connectable, Reliable, Scalable, Adaptive, Flexible

**Emerging Service Models**

- Building energy management
- Automotive safety and control
- Management of metropolitan traffic flows
- Distributed health monitoring
- Smart Grid
CYBER-PHYSICAL SYSTEMS
Our research identified the following fundamental challenges for the modeling, design, synthesis and manufacturing of CPS:

- Framework for developing cross-domain integrated modeling hubs for CPS;
- Framework for linking these integrated modeling hubs with tradeoff analysis methods and tools for design space exploration;
- Framework of linking these integrated synthesis environments with databases of modular component and process (manufacturing) models, backwards compatible with legacy systems;
- Framework for translating textual requirements to mathematical representations as constraints, rules, metrics involving both logical and numerical variables, allocation of specifications to components, to enable automatic traceability and verification.
Virtual Engineering Everywhere
Multi-Physics models

Helping over 30 different teams and skills in the company work together

Linking over 40 different EE design representations throughout the entire development process

Ensuring that the EE design flow is integrated at the same level of quality and performance as the 3D CAD system

Model based design and executable specification in the OEM/supplier chain

Albert Benveniste -- INRIA
Physical components are involved in multiple physical interactions (multi-physics)
Challenge: How to compose multi-models for heterogeneous physical components
Cyber-physical components are modeled using multiple abstraction layers
Challenge: How to compose abstraction layers in heterogeneous CPS components?

Dynamics: \( B(t) = \kappa_p(B_1(t), \ldots, B_j(t)) \)
- Properties: stability, safety, performance
- Abstractions: continuous time, functions, signals, flows,…

Software: \( B(i) = \kappa_c(B_1(i), \ldots, B_k(i)) \)
- Properties: deadlock, invariants, security,…
- Abstractions: logical-time, concurrency, atomicity, ideal communication,…

Systems: \( B(t_j) = \kappa_p(B_1(t_i), \ldots, B_k(t_i)) \)
- Properties: timing, power, security, fault tolerance
- Abstractions: discrete-time, delays, resources, scheduling,
MODEL BASED SYSTEMS ENGINEERING (MBSE)

Integrated System Synthesis Tools & Environments missing

Iterate to Find a Feasible Solution / Change as needed

Change structure/behavior model as needed

Assess Available Information

Define Requirements Effectiveness Measures

Create Behavior Model

Map behavior onto structure Allocate Requirements

Specifications Perform TradeOff Analysis

Create Sequential build & Test Plan

Generate derivative requirements metrics

Integrated Multiple Views is Hard!

Apply this to: Design, Manufacturing, Operations and Management TO THE WHOLE LIFE-CYCLE ⇒ MBE

Model - Based Information – Centric Abstractions

Model - based

UML - SysML - GME - eMFLON

Rapsody

UPPAAL

Artist Tools

MATLAB, MAPLE

Modelica / Dymola

DOORS, etc

CONSOL-OPTCAD

CPLEX, ILOG SOLVER,

SIEMENS, PLM, NX, TEAM CENTER
Layered MBSE -- Hierarchies

(Watson 2008, Lockheed Martin)
FOUR PILLARS OF SYSML

1. Structure

2. Behavior

3. Requirements

4. Parametrics
SysML Taxonomy
Using System Architecture Model as an Integration Framework

- Security and Trust Models and Analytics
- Human Behavior Models
- Verification Models
- Market Models and Analytics
- Analysis Models
- Cost Models Financial Analytics
- Hardware Models
- Software Models

System Architecture Model

Requirements Repository

Req’ts Allocation & Design Integration
System Modeling Transformations--Metamodelling (Models of Models)
The Challenge & Need:
Develop scalable holistic methods, models and tools for enterprise level system engineering

Multi-domain Model Integration via System Architecture Model (SysML)

BENEFITS
• Broader Exploration of the design space
• Modularity, re-use
• Increased flexibility, adaptability, agility
• Engineering tools allowing conceptual design, leading to full product models and easy modifications
• Automated validation/verification

APPLICATIONS
• Avionics
• Automotive
• Robotics
• Smart Buildings
• Power Grid
• Health care
• Telecomm and WSN
• Smart PDAs
• Smart Manufacturing

ADD & INTEGRATE

- Multiple domain modeling tools
  - Tradeoff Tools (MCO & CP)
  - Validation / Verification Tools
  - Databases and Libraries of annotated component models from all disciplines

“I Master System Model”

Update System Model

DB of system components and models

ILOG SOLVER, CPLEX, CONSOL-OPTCAD

Update System Model Tradeoff parameters

System Modeling Transformations
Requirements Engineering

• How to represent requirements?
  • Automata, Timed-Automata, Timed Petri-Nets
  • Dependence-Influence graphs for traceability
  • Set-valued systems, reachability, … for the continuous parts

• How to automatically allocate requirements to components?

• How to automatically check requirements?
  • **Approach**: Integrate contract-based design, model-checking, automatic theorem proving

• How to integrate automatic and experimental verification?

• How to do V&V at various granularities and progressively as the design proceeds – not at the end?

• **The front-end challenge**: Make it easy to the broad engineering user?
Smart Grids in a Network Immersed World

- **Generation**
  - Conventional: Coal, Nuclear, Oil / Gas, Hydro
  - Renewable: Solar, Wind

- **Transmission**
  - Smart Grid

- **Distribution**
  - Substation
  - Econometric models
  - Standards for process equipment energy
  - Integrated control & energy mgmt.

- **Utilization**
  - Residential/Commercial
  - Low-cost “embedded” energy sensors
  - Communications

ACEEE estimates +2x energy savings
Able to measure and manage carbon footprint per product line

Courtesy: Rockwell
Smart Grid – Microgrids Architecture

Grid 1.0
Legacy Grid

Grid 2.0
Smart Grid

Grid 3.0
Future Grid
Differences from Other Approaches

• Clear framework for integrating SysML with external tools

• Consol-Optcad can perform sophisticated trade-off studies based on FSQP algorithm

• Allows interaction with the user while the optimization is in process

• Consol-Optcad allows for design space exploration

• eMoflon Metamodeling tool-suite was used for the first time for such an integration
SysML and Consol-Optcad Integration

Overview

Meta-modeling Layer
(Enterprise Architect + eMoflon, Eclipse development environment)

Tool Adapter Layer
(Middleware)

Tool Layer
(Magic Draw, Consol Optcad)
Meta-modeling Layer - eMoflon

**Characteristics**

- Meta-models are following the Ecore format
- Story Diagrams are used to express the transformation rules
- Graph transformations is the underlying theory
- It generates Java code for the transformations

**Advantages**

- Graph transformation theory provides strong semantics and can lead to satisfaction of formal properties, i.e. correctness, completeness, etc.
- Graphical representation of meta-models and transformation rules
- Generated Java code could be easily integrated with modern tools
- Strong support/developing team
- Eclipse - open source environment
IMH and Consol-Optcad Integration

Consol-Optcad

- **Trade-off tool** that performs multi-criteria optimization for continuous variables (FSQP solver) – Extended to hybrid (continuous / integer)
- **Functional** as well as non-functional objectives/constraints can be specified
- Designer initially specifies good and bad values for each objective/constraint based on experience and/or other inputs
- Each objective/constraint value is scaled based on those good/bad values; fact that effectively treats all objectives/constraints fairly
- Designer has the flexibility to see results at every iteration (pcomb) and allows for run-time changing of good/bad values

![Performance Comb (Iter - 98) (Phase 2) (MAX_COST_SOFT - 0.997065)](image)

**Fig. 1:** Pcomb

**Fig. 2:** Example of a functional constraint
IMH and Consol-Optcad integration

Metamodeling Layer

- Both **metamodels** are defined in Ecore format
- **Transformation rules** are defined within EA and are based on graph transformations
- **Story Diagrams** (SDMs) are used to express the transformations
- **eMoflon** (TU Darmstadt) plug-in generates code for the transformations
- An Eclipse project hosts the implementation of the transformations in Java

![Fig. 4: Consol-Optcad metamodel](image1.png)

![Fig. 5: Story diagram](image2.png)
IMH and Consol-Optcad Integration

**Fig. 10:** Models in SysML

**Fig. 11:** Initiate transformation

**Fig. 12:** Consol-Optcad environment

**Fig. 13:** Perform trade-off analysis in Consol-Optcad
Microgrid Problem Formulation

Objectives

## Minimize Operational Cost:

\[ OM(\$) = \sum_{i=1}^{N} K_{OM_i} P_{i_{operation}} \]

## Minimize Fuel Cost:

\[ FC(\$) = \sum_{i=1}^{N} C_i \frac{P_{i_{operation}}}{n_i} \]

## Minimize Emissions:

\[ EC(\$) = \sum_{i=1}^{N} \sum_{i=1}^{M} a_k \left( EF_{ik} P_{i_{operation}} \right) / 1000 \]

- \( P_i \): power output of each generating unit
- \( t_i \): time of operation during the day for the unit \( i \)
- \( n_i \): efficiency of the generating unit \( i \)
- \( N \): number of generating units
- \( M \): number of elements considered in emissions objective
- \( K_{OM_i}, C_i, a_k, EF_{ik} \): constants defined from existing tables
Microgrid Problem Formulation

Constraints

• Meet electricity demand: \( P_i \geq Demand(kW) = 50 \cdot (0.6 \sin\left(\frac{\pi t}{12}\right) + 1.2) \)

  Functional constraint and shall be met for all values of the free parameter \( t \)

• Each power source should turn on and off only 2 times during the day

Constraints for correct operation of the generation unit

• Each generating unit should remain open for at least a period \( x_i \) defined by the specifications: \( t_{i\_off1} - t_{i\_on1} \geq x_i \) and \( t_{i\_off2} - t_{i\_on2} \geq x_i, \quad i = 1,2,...N \)

• Each generating unit should remain turned off for at least a period \( y_i \) defined by the specifications: \( t_{i\_on2} - t_{i\_off1} \geq y_i, \quad i = 1,2,...N \)

The problem has a total of 15 design variables, 10 constraints and 3 objective functions
Tradeoff Study in Consol-Optcad

**Iteration 1 (Initial Stage)**

- Hard constraint not satisfied
- Functional Constraint below the bad curve
- All other hard constraints and objectives meet their good values
- Usually the user does not interact with the optimization process until all hard constraints are satisfied
Microgrid: Trade-off Study

**Iteration 28 (User Interaction)**

- All hard constraints are satisfied
- Functional Constraint meets the specified demand. Goes below the good curve only for a small period of time but as a soft constraint is considered satisfied
- All objectives are within limits
- Because at this stage we generate a lot more power than needed we decide to make the constraints for fuel cost and emissions tighter
- At this stage all designs are feasible (FSQP solver)
Trade-off Study in Consol-Optcad

**Iteration 95 (Final Solution)**

- All hard constraints are satisfied
- All objectives are within the new tighter limits
- Functional Constraint meets the specified demand -- It never goes below the bad curve
New Integrated Modeling Hub

- Open source
- Open Modelica
- UML/SysML Papyrous
- SciLab
- Building results and models of the iTesla project (EU) [http://www.itesla-project.eu/](http://www.itesla-project.eu/)
- Libraries of components
- Examples from Norwegian Grid
- Validate components
- Hybrid systems models result
iTesla Models - Modelica

IEEE 14 bus system model
Model Validation -- Composability

- A model should never be accepted as a final true description
- of the actual power system
- Just a suitable “good enough” description of the system for
- Specific aspects
- Model validation: confidence, uncertainties, tolerances
- **Major challenge:** Composition and uncertainty quantification
Major challenge: Quantify accuracy and uncertainty as we move up and down the levels, for both logical and numerical variables
Port-Hamiltonian Models to the Rescue

Key ideas:

• Plant and controller – energy processing dynamical systems
• Exploit the interconnection – control as interconnection
• Shape energy
• Modify dissipation
• Work across multiple physics
• Work for many performance metrics not just stability
• Automatic composability -- scalable
• Underlying math models for Modelica!
Port-Hamiltonian Models: Power Grids

• Power grid structure components: generators, loads, buses, transmission lines, switch-gear, ...
• Handle transient stability problem naturally
• Power network as graph
  • Edges: generators, loads, transmission lines
  • Nodes: Buses
• Reduced graph – transmission lines
Edge Dynamics

Each edge element is represented as a port-Hamiltonian system

\[
\dot{x} = [J(x) - R(x)] \nabla H(x) + g(x)u, \\
y = g^T(x) \nabla H(x)
\]

where \( x \) is the state, \( J^t(x) = -J(x), R^t(x) = R(x) \geq 0 \), and \( H(x) \) are the interconnection, damping and energy functions, respectively.

The interconnection of all these port-Hamiltonian systems using Kirchhoff’s laws will result in a total port-Hamiltonian system.
Complete Model

In shorthand notation we have the port-Hamiltonian model

\[ \dot{x} = [\mathcal{J} - \mathcal{R}] \nabla H(x) + gu \]
\[ y = g^t \nabla H(x) \]

where

\[ \mathcal{J} = \begin{bmatrix}
0 & 0 & \mathbb{I} & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & M_1^t & M_2^t & 0 & 0 & 0 & 0 \\
-\mathbb{I} & -M_1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & -M_2 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & -\mathbb{I} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & \mathbb{I} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix} \]
Port-Hamiltonian Models

- Other port-Hamiltonian subsystems can be added like capacitor banks, transformers etc.
- Another model of the transmission line, e.g., partial differential equation models.
- Other load models.
- A different (simpler) port-Hamiltonian model of the generator.
- Techniques like Kron reduction can be used to simplify the graph.

- We have extended the concept to hybrid systems
- Port-Hamiltonian on hypergraphs
- Connections with Noether’s Theorem and Invariants – very useful in optimization
- Very useful in Uncertainty quantification
Adapt Grid Hierarchy for the Future: How?

Plug’n’play architecture
flat hierarchy, distributed, no time-scale separations, & model-free
**Latest Vision and Collaborations**

**UMD: Integrated Modeling Hub**

*Power grids, Smart grids*

- Multi-domain Model Integration
- System Modeling Transformations via System Architecture Model (SysML)

**ILOG SOLVER, CPLEX, CONSOL-OPTCAD**

**CMU: DyMonDS based Smart Grid in a Room Simulator**

*End-to-End Stable Optimal Dispatch Concepts*

**HU, UMD, NIST and Industry Testbeds**

**MBSE Challenge & Need:**

- Develop scalable holistic methods, models and tools for future grids
- Real-time distributed dispatch
- Distributed sensing and control
- Architecture design and evaluation

**Multi-metric tradeoffs**

- Design/Operation space Exploration
- System model updates
- Architecture exploration
- Real-time user interaction
Aircraft Vehicle Management System
VMS Problem Formulation

Objectives

Maximize serving of shedable loads: $\sum_{engine=1}^{M} (P_{engine} - \sum_{k=1}^{N_{eng}} (Load_{k_{non-shedable}} + Load_{k_{shedable}}))$

Minimize Fuel Cost: $\sum_{i=1}^{M} C_i \frac{P_i}{n_i}$

Minimize Procurement Cost: $\sum_{i=1}^{M} P_i \cdot n_i^2$

Constraints

Meet demand for “normal flight configuration”: $\forall engine \quad P_{engine} \geq \sum_{i=1}^{N} Load_{i_{non-shedable}}$

$P_i$ : power output of each engine (design variable)

$N$ : number of buses allocated to each engine

$M$ : number of engines in the current configuration

$n_i$ : efficiency of engine $i$

$Load_{i_{non-shedable}}$ : constant - non-shedable load of bus $i$

$Load_{i_{shedable}}$ : constant - shedable load of bus $i$

$C_i$ : constant - rate of consumption cost for each engine
VMS Tradeoff Study

Iteration 1 (Initial Stage)

- Hard constraints are satisfied
- One out of three objectives within limits

Iteration 16 (User Interaction)

- Objectives still not satisfied
- Very small improvement on the worst objective function value from 1st iteration
- We decide to make the utility objective (maximize serving of shedable loads) less tight
Trade-off Study in Consol-Optcad

Iteration 29 (Final Solution)

- Hard constraints are satisfied
- All objectives within specified limits

Results

- Values of the design variables
- Percentage of change from the initial value
To enable rich design space exploration across various physical domains and scales, as well as cyber domains and scales.
IBM Decision Optimization Center

Overview of ILOG Optimization

Decision Optimization Center

Application Development Tools
- Data Modeling
- Graphics (JViews)
- WAS

Model Development Tools
- CPLEX Studio (IDE)
- OPL Modeling Language

ILOG Concert Technology (C++, .NET, Java)

Optimization Engines
- Math Programming
  - CPLEX Optimizers
  (Simplex, Barrier, Mixed Integer)
- Constraint Programming
  - CPLEX CP Optimizer

Custom GUI/Batch App

Studio

Service APIs (Java)

Optimization Server

Data Server

Scenario Database

CPLEX Enterprise Server

CPLEX Optimization Studio
MBSE APPROACH TO ENERGY EFFICIENT BUILDINGS

Buildings Design
Energy and Economic Analysis

Windows and Lighting

HVAC

Domestic/International Policies, Regulation, Standards, Markets

Demonstrations, Benchmarking, Operations and Maintenance

Natural Ventilation, Indoor Environment

Networks, Communications, Performance Database

Sensors, Controls, Performance Metrics

Power Delivery and Demand Response

Building Materials, Misc. Equipment
Buildings as Cyber-Physical Systems

- **Research focus:** Platform-Based Design for Building-Integrated Energy Systems.
NET-zero Energy Building

NIST Net Zero Energy Residential Test Facility

Courtesy J. Kneifel (2012)
NET-zero Energy

Path to NZE

![Graph showing total annual costs vs. energy savings](image)

- **Cash Flow**
- **Mortgage**
- **Utility Bills**

Courtesy BEopt
CURRENT CAPABILITIES AND SOFTWARE

EnergyPlus

- Developed in 2001 by DOE and LBNL, currently v8.1
- Whole Building Energy Simulator – Weather, HVAC, Electrical, Thermal, Shading, Renewables, Water, Green Roof
- Steady state simulation down to 1 minute time intervals
- Reporting on built-in, component or system level properties.
  - Reports can vary in frequency: Annual, Monthly, Daily, Timestep
- Includes EML for HVAC controls (see MLE+)

EnergyPlus - Pros

- Highly detailed models for realistic as-builts
- Captures many of the complex physical interactions that outside and within a building
- Active and wide community and support

EnergyPlus – Cons

- Models can have long development time and steep learning curve

BEopt – Building Energy Optimization

- Developed by NREL
- Software that couples with EnergyPlus (and DOE2) that acts as an optimized simulation controller and provides easy analytic capabilities
- Extends functionality of EnergyPlus

BEopt – Pros

- Decreases time per simulation by simplifying scope of energy model
- Uses sequential search algorithm to reduce number of necessary simulations
- Lists discrete options for parameters
- Includes model dependencies between parameters
- Finds optimal designs for Bi-Objective Optimization of Life Cycle Cost vs Energy Savings
CURRENT CAPABILITIES AND SOFTWARE

**jEPlus**

- Developed by Yi Zhang and Ivan Korolija at De Montfort University, UK
- Java wrapper for EnergyPlus that simplifies parametric analysis
- Extends functionality of EnergyPlus

**jEPlus— Pros**

- Greatly enhances parametric analysis across all platforms
- Parametric tagging system makes it much easier to code for large state spaces

Courtesy Y. Zhang
## Problem Formulation

<table>
<thead>
<tr>
<th>Design Parameters</th>
<th>Description</th>
<th>Constraint</th>
<th>Initial</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_1$</td>
<td>Exterior Wall Insulation (R-Value)</td>
<td>$19 \leq x_1 \leq 44$</td>
<td>$x_1 = 19$</td>
<td>$\frac{\text{ft}^2\cdot\text{°F} \cdot \text{hr}}{\text{Btu}}$</td>
</tr>
<tr>
<td>$x_2$</td>
<td>Roof Insulation (R-Value)</td>
<td>$50 \leq x_2 \leq 75$</td>
<td>$x_2 = 50$</td>
<td>$\frac{\text{ft}^2\cdot\text{°F} \cdot \text{hr}}{\text{Btu}}$</td>
</tr>
<tr>
<td>$x_3$</td>
<td>Window (U-Value)</td>
<td>$0.2 \leq x_3 \leq 0.35$</td>
<td>$x_3 = 0.35$</td>
<td>$\frac{\text{Btu}}{\text{ft}^2\cdot\text{°F} \cdot \text{hr}}$</td>
</tr>
<tr>
<td>$x_4$</td>
<td>Window (SHGC)</td>
<td>$0.25 \leq x_4 \leq 0.35$</td>
<td>$x_4 = 0.35$</td>
<td>Unit-less</td>
</tr>
<tr>
<td>$x_5$</td>
<td>Infiltration (ACH)</td>
<td>$0.6 \leq x_5 \leq 3$</td>
<td>$x_5 = 3$</td>
<td>ACH</td>
</tr>
<tr>
<td>$x_6$</td>
<td>HRV/Ventilation (% Energy Recovered)</td>
<td>$0% \leq x_6 \leq 85%$</td>
<td>$x_6 = 0%$</td>
<td>%</td>
</tr>
<tr>
<td>$x_7$</td>
<td>Lighting (% Efficient Lighting)</td>
<td>$75% \leq x_7 \leq 100%$</td>
<td>$x_7 = 75%$</td>
<td>%</td>
</tr>
<tr>
<td>$x_8$</td>
<td>PV (Capacity)</td>
<td>$0 \leq x_8 \leq 10240$</td>
<td>$x_8 = 0$</td>
<td>W</td>
</tr>
</tbody>
</table>
MULTI-OBJECTIVE OPTIMIZATION

Initial Cost Objective Function

Minimize

\[ IC = \sum (IC_{Wall} + IC_{Roof} + IC_{Win} + IC_{Inf} + IC_{Vent} + IC_{Light} + IC_{PV}) \]

where

\[ IC_{Wall} = A_{Wall} \left( 0.0666 \, (x_1 - 19) + 0.7 \right) \]
\[ IC_{Roof} = A_{Roof} \left( 0.1 \, (x_2 - 49) + 2.5 \right) \]
\[ IC_{Win} = A_{Win} \left( 456.2 - 2633 \, x_3 - 216.6 \, x_4 + 3863 \, x_3^2 + 942 \, x_3 \, x_4 \right) \]
\[ IC_{Inf} = \frac{V_{room}}{8} \left( 0.52 \, x_5^{0.7462} \right) \]
\[ IC_{Vent} = 42(8.571 \, x_6^2 + 0.8571 \, x_6) + 1300 \]
\[ IC_{Light} = 0.2237 \left( 1281 - (-2676 \, x_7 + 3288) \right) \]
\[ IC_{PV} = 2.6 \, x_8; \]
Energy Use Objective Function

Minimize

\[
EU = \sum_{t=0}^{24} \frac{(P_{PV}(t) + P_{Lighting}(t) + \beta_t P_{HVAC}^{op})}{60000}
\]

\(\beta_t\) is the On/Off factor for the HVAC unit at timestep \(t\)

\(P_{HVAC}^{op} = 1000\)
Energy Use Objective Function

\[ P_{PV}(t) = \frac{-x^8}{10240} \left( 6970e^{-\left( \frac{t-14.66}{3.014} \right)^2} + 6870e^{-\left( \frac{t-10.55}{2.954} \right)^2} \right) \]
Energy Use Objective Function

\[ P_{\text{Lighting}}(t) = \begin{cases} 
0 & \text{for } 0 \leq t < 6 \text{ } \& \text{ } 8 \leq t < 18 \\
(0.25)(-2676 \, x_7 + 3288), & \text{for } 6 \leq t < 7 \text{ } \& \text{ } 22 \leq t < 24 \\
(0.5)(-2676 \, x_7 + 3288), & \text{for } 18 \leq t < 19 \\
(0.75)(-2676 \, x_7 + 3288), & \text{for } 7 \leq t < 8 \text{ } \& \text{ } 21 \leq t < 22 \\
(-2676 \, x_7 + 3288), & \text{for } 19 \leq t < 21 
\end{cases} \]
MULTI-OBJECTIVE OPTIMIZATION

Operational Cost Objective Function

Minimize

\[
OC = \sum_{t=0}^{24} \frac{C_{\text{tariff}}(t)[P_{\text{PV}}(t) + P_{\text{Lighting}}(t) + \beta_t P_{\text{HVAC}}^{\text{op}}]}{60000}
\]
Operational Cost Objective Function

\[ C_{\text{tariff}}(t) = \begin{cases} 
0.0978, & \text{for } 0 \leq t < 8 \\
0.1124, & \text{for } 8 \leq t < 12 \text{ & } 20 \leq t \leq 24 \\
0.1341, & \text{for } 12 \leq t < 20 
\end{cases} \]
MULTI-OBJECTIVE OPTIMIZATION

User Comfort Objective Function

Maximize

\[ UC = \sum_{t=0}^{24} \gamma_t \]

where

\[ \gamma = \begin{cases} 
1, & \text{for } T_{room,t} < T_{thresh} \\
0, & \text{for } T_{room,t} \geq T_{thresh} 
\end{cases} \]

Home Performance Objective Function

Minimize

\[ HP = \sum_{t=0}^{24} \beta_t \]
Heat Transfer Equations

\[ T_{room}[t] = \frac{Q_{net,t-1}}{C_p \cdot \rho \cdot V_{room}} + T_{room}[t - 1] \]

\[ C_p = 0.24 \ \frac{\text{Btu}}{\text{°F} \cdot \text{lb}_m} \]

\[ \rho = 0.075 \ \frac{\text{lb}_m}{\text{ft}^2} \]

\[ V_{room} = 12800 \ \text{ft}^3 \]
Heat Transfer Equations

\[ T_{\text{ext}}(t) = 81.96 - 6.614 \cos(0.2594t) - 7.6 \sin(0.2594t) \]
\[ + 1.347 \cos(0.5188t) + 1.306 \sin(0.5188t) \]
\[ - 0.1291 \cos(0.7702t) + 0.3703 \sin(0.7702t) \]
Heat Transfer Equations

\[ Q_{net} = Q_{wall} + Q_{roof} + Q_{win} + Q_{winrad} + Q_{infil} + Q_{vent} + Q_{int} + Q_{HVAC} \]

\[ Q_{wall} = \frac{A_{wall}}{x_1} (T_{ext}(t) - T_{room}[t]) \]

where \( A_{wall} = 1280 \text{ft}^2 \)

\[ Q_{roof} = \frac{A_{roof}}{x_2} (T_{ext}(t) - T_{room}[t]) \]

where \( A_{roof} = 2240 \text{ft}^2 \)

\[ Q_{win} = A_{win} x_3 (T_{ext}(t) - T_{room}[t]) \]

where \( A_{win} = 137.5 \text{ft}^2 \)
MULTI-OBJECTIVE OPTIMIZATION

Heat Transfer Equations

\[ Q_{\text{winrad}} = \frac{A_{\text{win}} E_{DN}(t) x_4 \cos \theta}{3.15} \]

\[ E_{DN}(t) = \begin{cases} 
-0.1729t^4 + 8.591t^3 - 166.7t^2 + 1497t - 4346, & \text{for } 5.17 < t < 19.93 \\
0, & \text{otherwise}
\end{cases} \]
Heat Transfer Equations

\[ Q_{inf} = \rho C_p x_5 \left( T_{ext}(t) - T_{room}[t] \right) \]
\[ Q_{vent} = 60 \dot{V}_{vent} \rho C_p \left( 1 - x_6 \right) \left( T_{ext}(t) - T_{room}[t] \right) \]
\[ Q_{int} = \frac{(P_{People} + P_{Lighting})}{3.412} \]
\[ Q_{HVAC} = \frac{3500 \, \beta_t}{3.412} \]

where \( \dot{V}_{vent} = 42.32 \, \text{CFM} \)
Heat Transfer Equations

\[ P_{People}(t) = \begin{cases} 
400, & \text{for } 0 \leq t < 8 \text{ & } 18 \leq t \leq 24 \\
0, & \text{for } 8 \leq t < 18 
\end{cases} \]
Simulation

Initial Values

Design Parameters:
\[
\begin{align*}
x_1 & \text{ - Exterior Wall Insulation [R] } = 19.00 \\
x_2 & \text{ - Roof Insulation [R] } = 50.00 \\
x_3 & \text{ - Window U-Value [U] } = 0.35 \\
x_4 & \text{ - Window SHGC [SHGC] } = 0.35 \\
x_5 & \text{ - Infiltration [ACH] } = 3.00 \\
x_6 & \text{ - HRV/Ventilation [% Energy Recovered] } = 0.00 \\
x_7 & \text{ - Lighting [% Efficient Lighting] } = 0.75 \\
x_8 & \text{ - PV [Watt] } = 0
\end{align*}
\]
MULTI-OBJECTIVE OPTIMIZATION

Simulation

Objective Function Results

- Energy Use (Minimize)
  - Minimum: 0
  - Maximum: 20

- Operational Cost (Minimize)
  - Minimum: 0.5
  - Maximum: 2.5

- User Comfort (Maximize)
  - Minimum: 0
  - Maximum: 1500

- HVAC Performance (Minimize)
  - Minimum: 0
  - Maximum: 800

- Initial Cost (Minimize)
  - Minimum: 0
  - Maximum: $2 \times 10^4$
Simulation

Next Iteration

Design Parameters:
x1 - Exterior Wall Insulation [R] = 30.00
x2 - Roof Insulation [R] = 50.00
x3 - Window U-Value [U] = 0.35
x4 - Window SHGC [SHGC] = 0.35
x5 - Infiltration [ACH] = 3.00
x6 - HRV/Ventilation [% Energy Recovered] = 0.00
x7 - Lighting [% Efficient Lighting] = 0.75
x8 - PV [Watt] = 0
MULTI-OBJECTIVE OPTIMIZATION

Simulation

Objective Function Results

- Energy Use (Minimize)
  - Minutes/day
  - Range: 0 to 20

- Operational Cost (Minimize)
  - $/day
  - Range: 0 to 2.5

- User Comfort (Maximize)
  - Minutes/day
  - Range: 0 to 1500

- HVAC Performance (Minimize)
  - Minutes/day
  - Range: 0 to 600

- Initial Cost (Minimize)
  - Range: 0 to 2 x 10^4
MULTI-OBJECTIVE OPTIMIZATION

Simulation

Next Iteration

Design Parameters:
\[ x_1 - \text{Exterior Wall Insulation [R]} = 30.00 \]
\[ x_2 - \text{Roof Insulation [R]} = 50.00 \]
\[ x_3 - \text{Window U-Value [U]} = 0.25 \]
\[ x_4 - \text{Window SHGC [SHGC]} = 0.25 \]
\[ x_5 - \text{Infiltration [ACH]} = 3.00 \]
\[ x_6 - \text{HRV/Ventilation [% Energy Recovered]} = 0.00 \]
\[ x_7 - \text{Lighting [% Efficient Lighting]} = 0.75 \]
\[ x_8 - \text{PV [Watt]} = 0 \]
MULTI-OBJECTIVE OPTIMIZATION

Simulation

Energy Use (Minimize)

Objective Function Results

Operational Cost (Minimize)

User Comfort (Maximize)

HVAC Performance (Minimize)

Initial Cost (Minimize)
JEPLUS+EA OPTIMIZATION
JEPLUS+EA OPTIMIZATION
JEPLUS+EA OPTIMIZATION
Integrating Siemens PLM Tools for MBSE in Energy Efficiency

- Teamcenter, 4GD, NX CAD, PLM elements like Cost
  - **Smart-grids** at various scales from a few houses to neighborhoods to regions
  - **Retrofit design** of existing houses for improved energy efficiency
  - **Zero or positive energy houses** by design
  - Partitions and design elements (4GD)
  - Manufacturing (read Construction) process management
  - Collaborative design and requirements management (Teamcenter)
  - **Linking Teamcenter, NX CAD, 4GD**, with our MBSE framework suite; especially with our advanced tradeoff and design space exploration tools
Smart Manufacturing refers to manufacturing production systems at the equipment, factory, and enterprise levels that integrate cyber and physical systems by combining:

- **smart operating systems** to monitor, control, and optimize performance
- **systems engineering-based** architectures and standards, and
- **embedded and/or distributed** sensing, computing, communications, actuation, and control technologies

...to enable **innovative production, products, and/or systems of products** that enhance **economic and sustainability performance**
Virtual Engineering Everywhere

(Automotive manufacturing, AUTOSAR,...)

Helping over 30 different teams and skills in the company work together

Linking over 40 different EE design representations throughout the entire development process

Ensuring that the EE design flow is integrated at the same level of quality and performance as the 3D CAD system

Model based design and executable specification in the OEM/supplier chain
Smart Manufacturing

OPTIMIZED: Rapid Customized Value Creation
- Higher value products
- Improved quality
- Improved throughput
- Increased equipment life / utilization

SUSTAINABLE: Leading Regulatory Compliance
- Improved safety
- Reduced energy and emissions
- Highly sustainable

DEMAND-DRIVEN: Accelerated Collaboration
- Higher product availability
- Reduced inventory
- Product lifecycle management

Agile, demand-driven

Smart Factory

Enterprise Business System ERP

Optimization

Production

Supply Chains

Sustainable

Plantwide

Suppliers

OEM Machine Builders

Distribution Center

Customer

Smart Grid
Microwave Transmit/Receive Modules

- 1-20 GHz frequency range (radars, satellite communications, etc.)
- Difficult and expensive to design and manufacture
**PROBLEM**

Integrate Electronic and Mechanical Design information interchange among tools used by designers

Identify alternative components
integration with part catalogs, corporate databases

Help generate and evaluate alternative designs
estimate cost, manufacturing time, reliability, etc.

evaluate tradeoffs

Help generate process plans
process parameters, time estimates, etc.

**SOLUTION**

Object-Relational Databases and Middleware to integrate heterogeneous distributed data sources:

- multi-vendor DB, text, data, CAD drawings, flat, relational, object DBs

Entity-Relation Diagrams to provide multiple expert views of the data and integrate product and process design phases into a single system environment

Hierarchical Task Network planning to explore alternate options at each level of the product:

- parts and material, processes, functions assemblies

Multicriteria Optimization for trade-offs: cost, quality, manufacturability, ...
IPPD System Architecture

- Electronic CAD (EEsof)
- Component-selection tradeoffs (CPLEX and HTN Planner)
- Mechanical CAD (Microstation)
- Cost Advantage
- HTN Planner
- Data Integration
- Northrop Grumman Enterprise Databases

Data Exchange Files
Tradeoff Analysis via Multicriteria Optimization
Tradeoff Analysis via Multicriteria Optimization (cont.)

Click on the solution number to select that solution.

The file containing the description of this problem cannot be found. Ensure there is a file called P1A.TXT in the same directory as the LP and NF files.
META – iFAB – AVM: Component Models

As of today:
- 131 component classes
- 469 component instances
- 43 parametric components
- 112 ITAR protected models
- 357 non-ITAR protected models
META – iFAB – AVM: Manufacturing Process Models Semantics Across Domains

As of today:

- 7 material shaping processes
- 19 general processes
- 231 machine instantiations
- 64 manual labor units
- 3,212 tools

Sources: Penn State ARL; GM Research
META – iFAB – AVM: Design Decomposition
Need to Improve Systems Engineering Methods and Tools Dramatically

Source: Paul Eremenko, DARPA/TTO
Integrating in Hubs

Siemens PLM Tools: Automotive
Wireless Sensor Networks Everywhere

Wireless Sensor Networks (WSN) for infrastructure monitoring

- Environmental systems
- Structural health
- Construction projects
- Energy usage
Supervisory Control & Data Acquisition (SCADA)

- Robust estimation
  - Noisy measurements
  - Lossy communication
- Real-time control
  - Safety
  - Performance

COTS IT for SCADA

- Cost ↓, Reliability ↑
- Digital and IP based: New vulnerabilities!
- Reliability ⇝ Security

Wired networks are costly to maintain
Typical industrial infrastructure ~ $10B

Wireless HART (Self Organizing Networks)

- Measurement 100%
- Communication 99.99%
- Data Management 100%

Total S Reduction = 99.99%

Courtesy: Emerson
MBSE for Wireless Sensor Networks: Contributions

• Developed a model-based system design framework for WSNs
  – Integrate both event-triggered and continuous-time dynamics
  – Provide a hierarchy of system model libraries

• Developed a system design flow within our model-based framework
  – Based on an industry standard tool
  – Simulation codes (Simulink and C++) are generated automatically
  – Support trade-off analysis and optimization
MBSE for Wireless Sensor Networks

• **Model libraries**
  – Application Model Library
  – Service Model Library
  – Network Model Library
  – Physical System Model Library
  – Environment Model Library

• **Development Principles**
  – Event-triggered: Statecharts in SysML
  – Continuous-time: Simulink or Modelica
System Framework

Wireless Sensor Networks
- Applications (Requirements)
- System Services (Information-oriented)
- Computation/Algorithms, Data Presentation, Communication Protocols
- Physical Systems (Functions and Resource)
- Environment

System Models
- Application Models (Functionality and Performance Reqs.)
  - Tracking
  - Detection
  - Monitoring
- Service Models (Distributed Data Store and Retrieval)
  - Query
  - Naming
  - Location
  - Syn
- Network Models (Communication and Management)
  - MAC
  - Routing
  - Mobility
  - Data
  - Topology Control
  - Power Control
- Physical Models (Functions and Performance)
  - Sensor
  - Actuator
  - Router
  - Base Station
  - Wireless Channel
- Environment Models
  - Phenomena
  - Geometry

Distributed Computing
Communication and Sensor Database
Physical World
MBSE for Sensor Networks
Component Based Networking: Network MBSE for MANET

The Challenge & Need:
Design DoD and Commercial MANET Adaptive to Dynamic Mission Requirements

Dynamic Interconnection and Interoperability
- Broadband wireless nets capable for multiple dynamic interface points
- Any node can serve as interface/gateway

Fig. 1: Intelligent Wireless Multi-Nets

Fig. 2: Component Based Networking
Component-Based Network Synthesis

- Reduced MANET cost and fielding time
- Modularity and re-use
- Increased agility in designing, modifying and fielding new MANET
- Broad design space exploration

Fig. 3: Network MBSE Toolset: integrating SysML Architecture Model with DB of network models, emulation-simulation models, tradeoff tools
• Internet explosion over all types of networks
• Satellites viable Internet “nodes”

1994 -- Initial Internet over satellite protocol, involved: splitting the connection, address spoofing, selective acknowledgment.

• They informed TCP that delay in ACKs was due to physical path delay and not to congestion (as TCP is designed to assume).
Collaboration with HNS

**1995** DirecPC

**1999** DirecDuo

**DW4020**
- Satellite IP router
- DHCP
- NAT
- Self-hosted
- Enterprise focus

**DW4000**
- PC-hosted, consumer terminal

**DW6000**
- Single module unit
- Integrated dial backup

**DW7000**
- 3x throughput increase
- High-speed inroutes to 1.6 Mbps
- Dual LAN subnets
- Integrated serial-to-IP conversion
- Multiband Support
- RIPv2

**HN7000S**
- DVB-S2 with ACM
- AIS Adaptive Inroute
- Closed-loop timing
- VRRP / PBR
- Integrated VoIP (HN7740S)

**INTRODUCED**
- Multimedia Appliance
- Voice Appliance

**TIA, ETSI, ITU Open Standard Platform**

2001 2002 2003 2004 2005 2006 2007

Continuous cost/performance improvement
Since 2011 satellite-based broadband Internet to planes has received much attention from airlines and the FCC, with deployment of in-flight satellite-based Internet service.
FAA NextGen

Next Generation Air Transportation System (NextGen)

- Aircraft Trajectory Based Operations
- Performance-Based Services
- Weather Assimilated into Decision-Making
- Position, Navigation, and Timing
- Equivalent Visual Operations
- Policy & Regulations
- Local/State Community
- Global Harmonization
- Net Centric Infrastructure Services
- Network-Enabled Information Access
Components for Routing Protocols

- Neighborhood Discovery Component (NDC)
  - Status of nodes that are close to me (2-hop neighborhood)

- Selector of Topology Information to Disseminate Component (STIDC)
  - What information should be broadcasted in the network

- Topology Information Dissemination Component (TDC)
  - How the information is shared

- Route Selection Component
  - Path selection Criteria
3 Platoon Mobility Scenario

Long connection from 20 to 0 (platoon heads)

<table>
<thead>
<tr>
<th>Type</th>
<th>Connection</th>
<th>Offered-load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intra-platoon</td>
<td>(1, 3), (2, 9), (4, 6), (7, 5), (20, 29),</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(14, 17), (16, 11), (17, 18), (19, 12),</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(21, 22), (23, 27), (23, 28)</td>
<td>12 kbps</td>
</tr>
<tr>
<td>Inter-platoon</td>
<td>(1, 18), (20, 11), (20, 0)</td>
<td>2.4 kbps</td>
</tr>
<tr>
<td></td>
<td>(10, 1), (21, 10)</td>
<td>6 kbps</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>OLSR-ETX</th>
<th>SPTC-ETX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saturation CL</td>
<td>~ 2 Mbps</td>
<td>~ 2 Mbps</td>
</tr>
<tr>
<td>TC message rate</td>
<td>923 kbps</td>
<td>890 kbps</td>
</tr>
</tbody>
</table>
Satellite Constellations

- More than 50% of the world’s population without Internet access; 3.7B people off line; Half of earth’s population occupies less than 1% of the land
- Mobile wireless is the largest technology platform in history
- Can bring broadband Internet to more people and more places
- More devices and things are getting connected: cars, meters, sensors, health care...
- Need connectivity fabric for everything and everyone
- OneWeb (Qualcomm, Virgin Galactic (Branson), Airbus, Arianespace): one constellation (700 satellites at 1,200km), great coverage, Internet access to underserved areas
- Integrates with terrestrial networks to extend 3G, 4G LTE and Wi-Fi services
- Creates huge opportunities for economic growth world-wide
**5G Vision**

*End-to-end ecosystem* to enable a fully mobile and connected society

*Value creation* towards customers and partners, with existing and emerging *use cases*

Delivered with consistent experience

*Enabled by sustainable* business models

---

**Network of networks,** i.e., a heterogeneous system comprising a variety of air interfaces, protocols, frequency bands, access node classes, and network types

---

**5G Use Cases**

**5G Value Creation**

**5G Business Models**

---

Virtualizing the Network – Network as a Service (NaaS)?
Network Slicing

5G network slices implemented on the same infrastructure

SRC: NGMN
MBSE for Robotic Arms and Grippers

- Transcend areas of application: from space to micro robotics
- Include material selection in design
- Include energy sources, resilience, reliability, cost
- Include validation-verification and testing
- Use integrated SysML and Modelica environment
- Link it to tradeoff tools CPLEX and ILOG Solver
- Demonstrate reuse, traceability, change impact and management
Application to Microrobotics

- Micro-robots design and manufacturing require control algorithm and physical layer (material and geometry) co-design.
- This insect-like robot is modeled in Modelica language using Differential Algebraic Equation.
- We are working on a Model-Based Systems Engineering approach to perform analysis, modeling and tradeoff for robotics and its material and control parameters.

Siemens Tools Utilization

- Design and analysis CAD model at the design phase
- Guide requirement to implementation from CAD design to physical simulation
Microrobot
Kinematics

- Coordinate transformations
  \[
  \left( \dot{V}_{3/0} \right)_{R_3} = \left( \dot{V}_{3/2} \right)_{R_3} + \left( \dot{V}_{2/1} \right)_{R_3} + \left( \dot{V}_{1/0} \right)_{R_3}
  \]

- Direct Kinematics
  \[
  \left( \dot{V}_{3/2} \right)_{R_3} = \begin{pmatrix}
    \dot{\theta}_3 e_z^3 \\
    l e_x^3 \times \dot{\theta}_3 e_z^3
  \end{pmatrix}
  \]
  \[
  \left( \dot{V}_{2/1} \right)_{R_3} = \begin{pmatrix}
    \dot{\theta}_2 e_z^2 \\
    (l_2 e_x^2 + l e_x^3) \times \dot{\theta}_2 e_z^2
  \end{pmatrix}
  \]
  \[
  \left( \dot{V}_{1/0} \right)_{R_3} = \begin{pmatrix}
    \dot{\theta}_1 e_z^1 \\
    (l_1 e_x^1 + l_2 e_x^2 + l e_x^3) \times \dot{\theta}_1 e_z^1
  \end{pmatrix}
  \]

Mechanical model of one single leg. One can express the motion of point P in terms of generalized coordinates and its derivatives using a coordinates transformation.
Structure of the leg model in Modelica block diagram. The joints rev, rev1, rev2 and rev3 are the joints with flexible material.

Simplified structure of the robot using the leg submodel. Highlighted submodel is an electrical motor model, includes a Pulse Width Modulation controller, which is the Cyber part of the robot.
New geometry alters the problem dramatically.

- Although the new joint dimension should improve stability, it is hard to verify.
- However, if old parameter is used, the robot will not be able to move at all due to high tension between its joints, unless motor output is increased dramatically. So no comparison is given here.
- By checking the limit cycle, we find that the PWM might still be helpful to regulate the jumping behavior.
Animation of First Model
Second Model
CPS Architectures

- **Architecture**: description of structure and behavior components of a system together with their configuration and interfaces and interconnections.

- **Architecture for CPS** is challenging: account for both the physical and cyber constraints – e.g., physical and material laws as well as geometric laws will guide the physical part.

- Various concepts of time and their constraints. Extensions of current distributed architectures for computers at all scales, including both digital and analog components need to be considered.

- Interplay between the principles and rules of architectures from the physical and cyber sides need to be considered and brought to harmony.
Materials-Geometry-Controls

Composite wing – new control algorithms
All-electric platform – new aircraft VMS

Smart suit – improve physical endurance & energy harvesting

Robotic lizards – new motion-material-geometry

Fast micro-robots – new joint design of geometry-material-controls – More stable and faster running
Social and Cognitive Robotics: Collaborative Autonomy
AUTONOMOUS SWARMS – NETWORKED CONTROL

- Component-based Architectures
- Communication vs Performance Tradeoffs
- Distributed asynchronous
- Fundamental limits
Social Networks over the Web

• We are much more “social” than ever before
  – Online social networks (SNS) permeate our lives
  – Such new lifestyle gives birth to new markets

• Monetize the value of social network
  – Advertising - major source of income for SNS
  – Joining fee, donation etc.
  – ...

• Need to know the common features of social networks
Social Networks -- Challenges

- We are much more “social” than ever before
  - Online social networks (SNS) permeate our lives
  - Such new lifestyle gives birth to new markets
- Monetize the value of social network
- Major characteristics of social networks
  - The small-world effect (6 degree of separation)
  - Scale-free degree distribution (power-law)
  - Community structure (clustering)
- Statistical models
  - Random Graph (Poisson, exponential)
  - Small-World
  - Preferential Attachment
- SNS applications (e.g. advertising) should consider these properties
Multiple Coevolving Multigraphs

- Multiple Interacting Graphs
  - **Nodes**: agents, individuals, groups, organizations
  - Directed graphs
  - **Links**: ties, relationships
  - Weights on links: value (strength, significance) of tie
  - Weights on nodes: importance of node (agent)
- **Value directed graphs with weighted nodes**
- **Real-life problems**: Dynamic, time varying graphs, relations, weights, policies
Simple Lattice $C(n,k)$

Small world: Slight variation adding $nk\Phi$

Adding a small portion of well-chosen links → significant increase in convergence rate
Expander Graphs

• First defined by Bassalygo and Pinsker -- 1973
• Fast synchronization of a network of oscillators
• Network where any node is “nearby” any other
• Fast ‘diffusion’ of information in a network
• Fast convergence of consensus
• Decide connectivity with smallest memory
• Random walks converge rapidly
• Easy to construct, even in a distributed way (ZigZag graph product)

• Graph $G$, **Cheeger constant $h(G)$**
  
  - All partitions of $G$ to $S$ and $S^c$,
    
    $$ h(G) = \min \frac{\text{#edges connecting } S \text{ and } S^c}{\text{#nodes in smallest of } S \text{ and } S^c} $$

• $(k, N, \varepsilon)$ **expander**: $h(G) > \varepsilon$; sparse but locally well connected ($1-SLEM(G)$ increases as $h(G)^2$)
Expander Graphs – Ramanujan Graphs
Examples of resulting topologies
Distributed self-organization

Goal: design a scheme that gives each node a vector of compact global information
Vehicle Platooning Problem

Controller $i$ applies linear feedback law based on information available to it:

$$u_i = \frac{1}{\deg(i)} \sum_{j \in N(i)} \left[ -k(x_i - x_j - \Delta_{i,j}) - b(\dot{x}_i - \dot{x}_j) \right] + \delta(1, i) \left[ -k(x_1 - x_{1,d}) - b(\dot{x}_1 - \dot{x}_{1,d}) \right].$$

Control objective: maintain reference inter-vehicle spacing under the constraint that individual control depends only on information available to that individual. The lead vehicle alone is provided the desired trajectory information $x_d(t)$

‘Local’ information patterns i.e. based only on sensed information from predecessor and follower
This problem has been studied extensively with this information pattern and the following limitations are known to occur for any ‘local’ information pattern.

• The least damped eigenvalue of the closed loop matrix scales as $O(1/N^2)$.

• String instability is inevitable- disturbances acting on an individual grow without bounds in the size of the platoon.

• It is not possible to achieve coherence or resemblance to a rigid lattice as the formation moves.

With technological advances, inter-vehicle communications are possible: More general information patterns feasible.

Bottom line:
Nearest neighbor type information patterns lead to inadequate control performance.
Choosing the Right Information Pattern

| Information pattern     | Communication load \(\sim |\text{Edges}|\) | Stability margin   |
|------------------------|---------------------------------------------|-------------------|
| Nearest neighbor type  | \(O(N)\)                                    | \(O(1/N^2)\)      |
| Complete graph         | \(O(N^2)\)                                   | At most \(O(1/N)\) |

- Is there something in between? Does there exist a “family” of graphs such that one can get improved control performance while limiting the communication load?

- Our result (Menon-Baras 2012):

| Expander families | \(O(N)\) | At most \(O(1/N)\) |
• No good models for aerodynamic interaction between different turbines.

• Need on-line decentralized optimization algorithms to maximize total power production.

Assign individual utility

\[ u_i(t) = \text{power produced by turbine } i \text{ at time } t \]

such that maximizing \[ \sum_i u_i(t) \] leads to desirable behavior.

Formation Control of Robotic Swarms

- Deploy a robotic swarm in unknown environment: obstacles, targets etc. have to be discovered.[3]

- The swarm must form a prescribed geometric formation.

- Robots have limited sensing and communication capabilities.

For rendezvous, design individual utility

$$u_i(s_i) = \frac{1}{|\{s_j \in S : |s_i - s_j| < r\}|} - \alpha \text{dist}_r(s_i, \text{obstacle}),$$

such that minimizing $\sum_i u_i(t)$ leads to desirable behavior.

Mobile Visual Sensor Network Deployment

• We wish to monitor events in different sites of varying interest levels.
• All robots monitoring a small set of high interest sites is undesirable w.r.t. coverage.
• Cost associated with information processing.
• How to deploy so “effective coverage” is ensured at “reasonable cost”.

Design individual utility

\[ u_i(s, c) = \sum_{s' \in NB(s,c)} \frac{q(s')}{n(s')} - f_i(c), \]

such that maximizing \( \sum_i u_i(t) \) leads to desirable behavior.

(here \( q(s) \) = interest in observing \( s \), \( n(s) = \) number of agents observing \( s \), \( NB(s,c) = \) subset of \( S \) observable from \( s \) when camera viewing angle= \( c \), and \( f_i(c) = \) processing cost when the camera viewing angle is \( c \).)

Like agents, system designer does not know exact functional form of the payoffs. The system designer may have “coarse information" about which agents' action can affect which others.

**Interaction graph** models such coarse information: It’s a directed graph where a link from i to j implies actions of agent i affect the payoff of agent j.

**Communication graph** models explicit inter agent communications: It’s a directed graph where a link from i to j implies agent i can send information to agent j.

The wind farm example is considered in the figure:
- blue lines are edges in the interaction graph and,
- the red lines in the communication graph.
Based on Marden et al\textsuperscript{[5]}, endow each agent with a state $x_i = (a_i, m_i); m_i \in \{0,1\}$ is the mood of agent $i$, with 1 corresponding to a “content” agent and 0 to a “discontent” one.

**Distributed Simple Algorithm**

Differences from the algorithm in \textsuperscript{[5]}:

- No explicit inter-agent communication is used in \textsuperscript{[5]}.
- Some assumptions on utilities are made in \textsuperscript{[5]} to prove feasibility.
- $\epsilon_t$ is held constant for some $t$ in \textsuperscript{[5]}.

**Exploration vs. exploitation?**

\textsuperscript{[5]} Marden, Young and Pao, “Achieving Pareto optimality through distributed learning”, 2011, Under review.
Component-based Networks and Composable Security

Universally Composable Security of Network Protocols:

- Network with many agents running autonomously.
- Agents execute in mostly asynchronous manner, concurrently several protocols many times. Protocols may or may have not been jointly designed, may or not be all secure or secure to same degree.

Key question addressed:

- Under what conditions can the composition of these protocols be provably secure?
- Investigate time and resource requirements for achieving this

Studying compositionality is necessary!
Universally Composable Security (UCS)

Results to date (Canetti, Lindell, ...) :

• When there is a clear majority of well behaving nodes (i.e. 2/3) **almost any functionality is secure under UCS**
• When there is no clear majority then UCS is **impossible** to achieve unless there are pre-conditions – typically some short of trust mechanism
• Introducing **special structure in the network** (e.g. overlay structure, small subset of absolutely trusted nodes) helps substantially in establishing UCS, even without preconditions
• **Many applications**: military networks, health care networks, sensor networks, SCADA and energy cyber networks
• **The challenge and the hope**: Use “tamper proof hardware” (physical layer schemes, TPM etc.) even on a small subset of nodes to provably (validation) establish UCS – role of fingerprints and physical layer techniques.
• **Establish it and demonstrate it?**
Cars are Heavily Computerized: Electronics in Cars and Vulnerabilities

UW/UCSD Work:

Kosher et al., IEEE Symposium on Security and Privacy, '10
- Reach CAN bus through diagnostic port

Checkoway et. al., USENIX Security, '11
- Remote attacks
- Insert virus into computer system in mechanic shop
- Bluetooth
- Telematics unit
- CD player
Hardware-Software integrated Security: Key Ideas and Challenges

- **Exploit characteristics (a.k.a. FINGERPRINTS) of physical layer**
  - Waveform, RF and hardware peculiarities
  - Embed artificial and stealthy ‘fingerprints’
- **Distribute assurance/trust function across software and hardware (increases difficulty to attacker significantly)**
- **Physically Unclonable Functions (PUFS)**
- **Trusted Platform Modules (TPM) and derivative technologies**
- **Secure Biometrics and Sensor Fingerprints**
- **Key Idea: Security Integration on the Portable Device**
- **Challenges:**
  (a) How to use informative time varying pieces of the biometric?
  (b) Develop anti-spoofing techniques using the sensor signature?
  (c) System integration and validation of the various fingerprints and physical layer techniques
  (d) Proof methods that security is improved – Information theoretic methods
- **Transformational concept:** Authenticate the device to the network and then the user to the device ⇒ reduces attack risk (fewer times via the net)
- **“Push” security defense to the boundary**
New Ideas: Hardware-Based Security

Using an external TPM?

→ Initial idea: Use an existing component-of-the-shelf like a TPM or SmartCard as root-of-trust
  - But...

→ Cost, PCB area,
→ Quality requirements, availability of suitable components (e.g. temperature range) and

→ Sensitivity to valid attacks
  - Reset attack (TPM is reset, manipulated µC continues operation)
  - Data exchange between µC and TPM not protected

Microcontroller

TPM/SmartCard

Solution

Microcontroller with integrated HSM!
Latest: Adaptive Component-Based MANET Security

- **Components of MANET Routing Protocols**
- **Neighborhood Discovery Component (NDC)**
  - Status of nodes that are close to me (2-hop neighborhood)
- **Selector of Topology Information to Disseminate Component (STIDC)**
  - What information should be broadcasted in the network
- **Topology Information Dissemination Component (TDC)**
  - How the information is shared
- **Route Selection Component**
  - Path selection Criteria

- **Cross-layer – MAC and Routing**
- **Detect attacks – mitigation strategies – adaptively change protocol component parameters and structure**
- **Distributed trust an integral part**
- **Treat it as a Feedback Control System!**
- **Part of the DARPA WND program**
Perception-Cognition and Co-Robots

The pressure of P on C
The return of analog computation?
Non-von Neumann Architectures?
Physics of computation?
Beyond Turing?

Cognition and knowledge generation from sensory perception – communicating with humans – collaboration
Not just obeying commands – the inverse problem
Learning Tasks, Changing Environments

- Teach through demonstrations
  - Easy training, hard to generalize to new constraints

- Program planning techniques
  - Generalize to constraints, manually design objectives
Temporal Logic, Robots, Human-Robot Teams

- Finite time logical constraints arise due to:
  - Task description
  - Decision making process
  - Inherent inter-system interactions
  - Other (a)causal dependencies

Constraints:
- Safety
- Human involvement
- Physical limitation
Path Planning with Temporal Specifications

- Q: How to generate trajectory/path based on temporal specifications such as ordering between actions, repetition of tasks, safety of the motions?
- State of the art: motion planning with temporal constraints without duration, such as Linear Temporal Logic (LTL).
- We have proposed a method for **timed temporal logics**, such as Metric Temporal Logic (MTL) for motion planning problem based on optimization\(^1\).
- A timed-automata based method is proposed here.

Robotic Motion Planning Problem

Given:
- A dynamic workspace (environment),
- A time constrained task ($\varphi$),
- A cost function.

Objective:
- Find the suitable control input such that the robot completes the given task and minimizes the cost function.

Constraints:
- Avoiding collisions with all static and moving obstacles in the workspace.
A Robotic Motion Planning Example

• Manipulation task planning\(^2\)
  – First, take food to customers and bring the empty plates back to the preparation area. Next, show the tip jar to the ones whom have already finished eating.

• The question is how fast to take the food to the customers, or what is a good time to ask for the tips from the customers. So timing aspects are important.

• Many robotic tasks require finite time constraints.

• LTL is unable to address finite time constraints and hence we need MITL.

Collaborative Planning and Re-planning with Finite-Time Task Constraints

Multiple fires, diverse conditions
Need to assess and plan/allocate

Starting from I, visit R3 within the time Interval I1, visit R4 within time interval I2; before visiting R3 or R4, robot must Visit R2. Eventually visit R1 and R5, and Complete the whole task in least time.

Resulting Continuous path In 3D space and time
Definition: The syntax of MITL\(^3\) formulas are defined according to the following grammar rules:

\[
\phi ::= T \mid \pi \mid \neg \phi \mid \phi \lor \phi \mid \phi U_I \phi
\]

where \(I \subseteq [0, \infty]\) is an interval with end points in \(\mathbb{N} \cup \{\infty\}\) and the end points have to be distinct. \(\pi \in \Pi\) is the atomic proposition.

More sophisticated MITL operators can be derived using the grammar defined above; such as: always in \(I_1 \equiv \perp U_{I_1}\), eventually always \(\Diamond_{I_1} \Box_{I_2}\) etc.

---

Timed Automata

- Clocks can be **reset** when taking an edge
- Assumption: all clocks are **zero** when entering the initial location initially
- A location invariant specifies the **amount of time that may be spent in a location**

Remark: An MITL formula can equivalently represented by a Timed Automaton
Timed Automata and Robotic Action

Robotic motion including manipulation task can be captured in timed automata
Timed Automata Based Planning Example

- Convert temporal logic formula to a timed automaton
  - Represent temporal logics as a tree structure
  - Every operator in the tree can be represented as a timed automaton with input and output
  - The product of them results into a timed automaton again

- Specs:
  - Visit A before B and visit B within [l,r]
- MTL:
  \[ \phi = (\neg B \mathbf{U} A) \land (\Diamond [l,r] B) \]
- Tree:
Generated timed automata and the fastest path using UPPAAL⁴

Safety Guarantees via Reachability Analysis

\[ \dot{\xi} = v \]
\[ \dot{v} = -ge_3 + \frac{F}{m} Re_3 \]
\[ \dot{R} = R\hat{\Omega} \]
\[ \hat{\Omega} = J^{-1}(-\Omega \times J\Omega + M) \]
Connected Cars: Internal

71 Sensors and 98 Switches

Engine

Color Key:
- Low Speed Sensor
- High Speed Sensor
- Safety Sensor
Connected Cars: External
Connected Cars: Cognitive and Collaborative

Current

Future
Key Challenge: Humans
We are developing novel frameworks to include humans in this collaborative networked CPS environment
Systems Biology

Goal of systems biology:
To integrate information on:
• Genes
• Proteins
• Molecular interactions
• Metabolism
• Other biological systems/networks

... in order to improve our understanding of the physiology of cells and organisms.

Systems Biology — The Ultimate Systems Challenge

Systems Biology
Integrative approach in which scientists study pathways and networks will touch all areas of biology, including drug discovery

Requires
• Quantitative models of properties of components and their interactions
• Computational methods to manage complexity
A Systems Biology Model for Alzheimer’s Disease

- Study the roles of cholesterol, LRP, ApoE and inflammation in disease pathogenesis
- Studied effect of simvastatin treatment on LRP and ApoE levels, in addition to changes in Aβ
- Developed a mathematical model that integrates energy & lipid metabolism, the inflammatory response & expression of key proteins
- Model results were verified using results from experiments
- No previously developed model has used systems biology nor multi-level networks to study AD
Forefront of AD research:
Interplay between lipid metabolism & inflammation

apoE:
- Coordinates re-distribution of cholesterol during growth, repair &

IL-1:
- Pro-inflammatory cytokine
- Expressed by microglia in response to:
  - Stress
  - ↑ Aβ
  - ↑ Glutamate
- Functions:
  - ↑ neurotransmitter turnover rate
  - ↓ activation threshold for HPA axis
  - Causes hypoglycemia
  - ↑ Acetylcholinesterase activity ⇒ ↓ ACh
- Synapase formation
  - Co-localizes w/ Aβ plaques

LRP-1:
- Transport of Aβ to blood
- Transfer of cholesterol to neurons & other CNS cells via apoE carrier binding

Brain
Neuron
apoE+Aβ
LRP-1
ApoE
Aβ
Cholesterol
Microglia
Astrocyte

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Model-Based Systems Engineering for ITU Management

Healthcare operations

Monitor performance, generate ideas, implement changes

Build models, analyze operations, predict changes
Using System Architecture Model as a MODEL Integration Framework

MATLAB, Scheduler, COQ, Planning, Fault Analysis, Cost Estimation

Geometry/Layout AUTOCAD, Architecture,

Patient, Equipment, Personnel (Nurses-Doctors)

System Architecture Model

Analysis Models

Requirements Repository

Req’ts Allocation & Design Integration

Patient and Resource Models

Software Models

Verification Models

VMS, UPPALL, IF, BIP, COQ

UML, UPPALL ARTIST, MAPLE, Policies-Rules
Implementation

Dynamic ICU Model

Multidimensional Markov Chain (MMC)

described using

UML Profile

UML Activity Diagram

Domain Specific Language (DSL)

Analysis Engine

Logical Inference Engine (Java)

(Multiple | Binary) Decision Diagram

ROMDD / MTBDD

Resolution Methods

Numerical Analysis (Matlab)

DOM parsed

XML Metadata Interchange (XMI)

XSLT (Xalan)

DTD Specified XML
State Reduction Achieved

Number of states as a function of number of steps in inference

Sawtooth pattern is the result of the project-compose pattern
MBSE based HCMS for Diabetes II and its functional connectivity
Reasoning Engine through MBSE Framework

**Health Quality Metric** combines patient health risk behavior and patient time history counting

\[ J_{hc}(i, m_i) = V_1^i \cdot O_1^i(m_i) + V_2^i \cdot O_2^i(m_i) + V_3^i \cdot O_3^i(m_i) \]

Set of triples of arrays: \((s, \mu, u)\)
Cardinality: \(N_p \times N_s \times n_\Delta^{(N_{\tau,\Delta}+1)} \times (n_\mu \times n_u)^{N_{\tau,\Delta}}\)
Each triple size: \(3 \times N_{\tau,\Delta} + 1\)

Set of triples \(O\)
Cardinality: \(N_p \times N_s \times n_\Delta^{(N_{\tau,\Delta}+1)} \times (n_\mu \times n_u)^{N_{\tau,\Delta}}\)
Developed Reasoning Engine of the HCMS, based on these disease models and metrics of health state time history: focus in these evaluations are systematic Tradeoffs (Pareto points)

Three computational methods developed and used

First method, **Evaluation by Monte Carlo Simulation (EMCS)**, uses the model in an exhaustive generation of all possible sample paths (time histories) for any number of patients

The second method **Fully Observable Multi-Criteria Optimization (FOMCO)** and the third **Partially Observable Multi-Criteria Optimization (POMCO)**, employ multi-criteria optimization to directly compute the Pareto points and associated selection of tests and interventions

Both use Dynamic Programming for computations
Reasoning Engine: Decision Making & Analytics Capabilities

Can provide answers to many practical questions, queries, problems, from health care management perspective

- Evaluate patient risk behavior impact on health care quality
- Evaluate “best” health care achievable
- Can learn from new data, treatment results, improve models
- Evaluate “value” of new proposed tests and interventions
- Provide aggregate statistics for insurance policies calibration
- Find best tests and interventions for patient type, disease state
- Evaluate effects of incentives and rewards for health “maintenance”
- Evaluate sequences of tests and treatments for reversing disease
Revolutionizing Drug Manufacturing: Organ-on-a Chip -- Biochips

Wyss-Lung on a chip -- 2010

Wyss-Gut on a chip -- 2012
REVOLUTIONIZING DRUG TESTING

• Rapidly approaching untenable situation in human health -- Blockbuster drugs, which cure major diseases afflicting huge populations, are being pulled from the shelves (e.g., Vioxx) for unforeseen side-effects.
• They are being replaced by drugs that have smaller market potential and more localized impact (subpopulations, e.g., FluMist).
• Current cost of developing a drug and getting it to market exceeds $1B and process takes over ten years
• These competing forces cannot be resolved without truly transformational changes in the way drugs are discovered, developed, and approved.
• This need is exacerbated by the emergence of personalized medicine – a natural outcome of high throughput sequencing technologies.
Personalized Medicine

*Use of genetic and non-genetic molecular information to individualize prevention, diagnosis, treatment and prognosis for each person with greater precision.*

The paradigm of personalized medicine, PMC
personalizedmedicinecoalition.org
Design Space Exploration: Queries and Complexity

- Large, complex systems have many tunable parameters
- To perform tradeoff analysis at system level, a simplified view of the underlying components must be available
- **Challenge**: create an abstract, tractable representation of underlying components.
- **Hypothesis**: Although components are not perfectly decoupled, structure provides useful information for parametric decomposition
- The query itself influences the shape of the resulting graph
- A query that is not local can create links between non-local variables
- The resulting graph and analysis complexity is dependent on the query
Query Induced Hierarchies

Diagram showing different query induced hierarchies with nodes labeled $x_1$, $x_2$, $x_3$, $x_4$, and $x_5$.

- $x_1$ as head
- $x_2$ as head
- $x_3$ as head
- $x_4$ as head
- $x_5$ as head
Abstraction as Summation/Aggregation

Abstraction by applying \( \sum_{x_4} \sum_{x_5} f(X) \)

\[
= \sum_{x_4} \sum_{x_5} f_A(x_1)f_B(x_2)f_C(x_1,x_2,x_3) \cdot f_D(x_3,x_4)f_E(x_3,x_5)
\]

\[
= f_A(x_1)f_B(x_2)f_C(x_1,x_2,x_3) \cdot \sum_{x_4} \sum_{x_5} f_D(x_3,x_4)f_E(x_3,x_5)
\]

Summation remains local!

• Summing out variables creates abstract, higher level views of the data.
Factor Join Trees in Systems Design Space Exploration and Decomposition

• **Results/Contributions:**
  • Starting from an undirected graph representation of the system developed a “divide and conquer” methodology and tool to choose subsets of nodes that completely separate the graph.
  • Separation produces interfaces -- leads to system decomposition in trees; “width” of a decomposition the size of the largest system component while “treewidth” is the minimum possible width over all tree decompositions.
  • Decomposition complexity is exponential in treewidth and linear in problem size.
  • By using novel organization of tradeoff queries for design space exploration, the method leads to chordal systems – decomposition performed in linear time.
Tradeoff Queries

• The query itself influences the shape of the resulting graph

• A query that is not local can create links between non-local variables

• The resulting graph and analysis complexity is dependent on the query
Example: Quadrotor

SysML Parametric Diagram ➔ Functional Dependence Graph

$f_1(x_1)$

$f_2(x_2)$

$f_3(x_3)$

$f_4(x_4)$

$f_5(x_5)$

$f_6(x_6)$

Define $f_k(x_k)$

$f_k(x_k) = \text{Current constraint}$

$x_6 = \{\text{Weight, FlightCurrent}\}$

Figure: SysML Parametric Diagram (Factor Graph)
Example: Quadrotor

SysML Parametric Diagram ➔ Functional Dependence Graph ➔ Join Tree

**Figure:** Functional Dependence Graph (step 1)
Example: Quadrotor

SysML Parametric Diagram ➔ Functional Dependence Graph ➔ **Join Tree** ➔ Factor Join Tree

*Figure: Join Tree (step 2)*
Example: Quadrotor

SysML Parametric Diagram ➔ Functional Dependence Graph ➔ Join Tree ➔ Factor Join Tree ➔ **Summary Propagation**

![Diagram](image)

**Figure:** Summary Propagation (step 4): \( \oplus = \text{Projection}, \otimes = \text{Intersection} \)

Complexity of system analysis: reduced from \( D^7 \) to \( 3D^4 + D^2 \)
Define $f_k(x_k)$

Visualization

Design options

Feedback
How to Use It?

• Input constraints of SysML Parametric Diagrams
• Interact with our tool to generate a factor join tree
• Roll back if necessary
• Create SysML Block Diagrams
• Revise the original SysML Parametric Diagrams
• Analyze the system using summary propagation
Digital Manufacturing Design Innovation Institute (DMDII)

- Announced February 25, 2014, 2014 by President Obama

- Headquartered in Chicago, Illinois

- Academic-Industry-Government “Mega Project” $320M co-funding, 5 years

- **Goal**: Revitalize manufacturing along the lines described in this lecture

- “Infinite number of virtual factories and an open-source manufacturing platform”
“Democratizing” Manufacturing

• **Goal**: Transforming more ordinary people to “makers” of products and services

• Helping small and medium size companies to manufacture products and services – **bridge the “gap”** from innovation, prototyping, to manufacturing

• General Electric (GE) opens manufacturing fab lab to spark ideas and participation in manufacturing through making

• Several companies have also opened up similar “open” labs: Ford etc.

• Several regional manufacturing centers (industry-university-government) are being established in various regions of USA

• “Industrial Internet” (USA) and “Industrie 4.0” (GE-EU) arrive
Crowdsourcing Manufacturing

• **Google’s Project ARA**: Smartphones are composed of modules (of the owner’s choice) assembled into metal frames.

• **Ubundu Edge Project**: crowdsourcing the most radical smartphone yet “Why not look for the best upcoming tech and throw it together to stay ahead of the competition?”

• **Crowdsourcing** the development and manufacturing of *small unmanned aerial vehicles*
Need to Transform Engineering Education

- Move from a *reductionist* scientific approach to an *integrative* scientific approach

- The challenge is to synthesize engineering systems so as to be able to generate predictable system behavior and performance by integrating behaviors and performance of system components

- *Compositional synthesis, manufacturing and life-cycle management* of complex engineered systems

- This compositional synthesis advances engineering to the next frontier, way beyond ‘plug and play synthesis’
Both Supplemented by Technical Electives
form many Technical Areas

THE ISR SE PROGRAMS IN BRIEF

MSSE

ENPM-SE

DEGREE REQUIREMENTS
The following courses are required:

Systems Engineering Core
ENSE 621 Systems Engineering Principles
ENSE 622 System Modeling and Analysis
ENSE 623 Systems Engineering Design Project
ENSE 624 Human Factors in Systems Engineering

Management Core
ENSE 626 Systems Life Cycle Cost Estimation
ENSE 627 Quality Management in Systems

Those choosing the thesis option also take ENSE 799 Master’s Thesis (for six credits) as well as an additional four electives. Those choosing the non-thesis option take an additional six electives.

DEGREE REQUIREMENTS
The ENPM Systems Option requires four courses from the systems engineering core, three courses from the management core, and four electives. The courses are identical to the MSSE curriculum.

Systems Engineering Core
ENPM 641 Systems Engineering Principles
ENPM 642 System Modeling and Analysis
ENPM 643 Systems Engineering Design Project
ENPM 644 Human Factors in Systems Engineering

Management Core
ENPM 646 Systems Life Cycle Cost Estimation
ENPM 647 Quality Management in Systems

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A Bold Experiment

Starting early in the education chain

Undergraduates working with industry and government mentors on SE projects
Comparative Impact on Transforming Life-Work-Society

- Typography
- Microelectronic chips
- The PC
- The Internet
- MBSE
Concluding Remarks -- Challenges

- Further work on meta-models needed
- Create libraries with patterns of component models annotated by properties and metrics
- Develop a lot more uncertainty models and their composability; deterministic and stochastic
- Integrate multi-criteria optimization, constraint based reasoning, and logic
- Link the above to the integrated modeling hubs that allows return “values”
- Link to query management for design space exploration allowing many views
- Develop requirement representations for automatic verification: constraints, metrics, rules, semirings, soft semirings, automata, timed automata, Petri nets, process models, contracts, model-checking, automatic theorem proving, include uncertainties
- Develop automatic suggestions for feasibility or improvements
- Integrate all the above, especially composability and compositionality
- Provide users with ability to select “slices of tools” and integrate them
- Address the “front end” to make it affordable and easy to use
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References


References


Thank you!

baras@isr.umd.edu
301-405-6606
http://dev-baras.pantheonsite.io/

Questions?