# Systems Engineering Education at the University of Maryland: Undergraduate and Graduate Programs Experiences


**John S. Baras**

**Institute for Systems Research and**
**Depts. of ECE, CS, ME, AE, Bioeng., DOIT, AMSSC,**
**University of Maryland College Park, USA**
**School of EECS, Royal Institute of Technology (KTH), Sweden**
**Institute for Advanced Study, Technical Univ. of Munich (TUM), Germany**



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# 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**

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***AKA***

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

**Now we need to integrate with**
**Data-based methods (ML, AI)**

# The Challenge and the Need

- Complexity of systems is increasing rapidly: heterogeneous physics, cyber components, humans
- Need methodology and tool suite to model systems, perform tradeoffs for design space exploration
- Answer “what if?” “what is the impact if?”
- Address whole systems engineering life cycle: design, manufacturing/implementation, operations, policies
- Must allow easy integration with domain specific tools
- Must be easy to learn and use
- Must allow analysis and answers at various levels (from high level management to low level engineering)

# UMD -- MBSE Key Steps

**We developed and teaching the following key steps for the modeling, design, synthesis, manufacturing, operation, of complex systems:**

- 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**.

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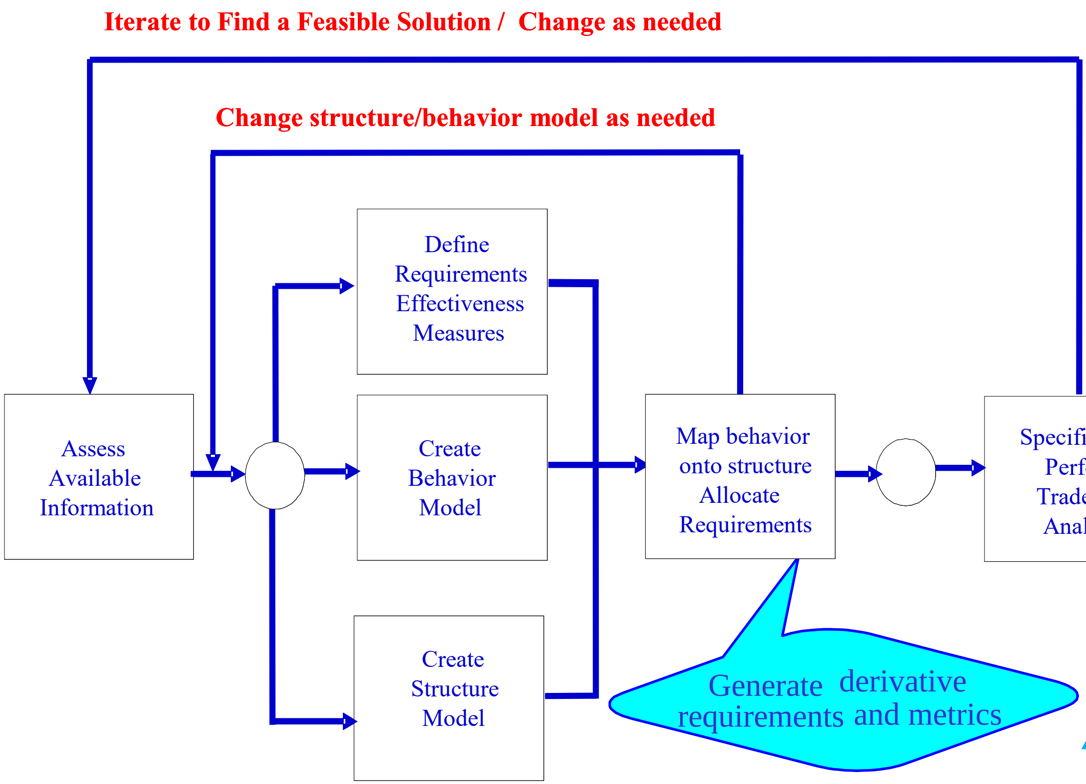
# Specific Examples

- VLSI design and manufacturing
- Electromechanical systems design and manufacturing
- Virtual manufacturing/virtual companies
- Telecommunication networks design
- Telecommunication and information networks management
- Appliance design and manufacturing; PCs, DSPs, boards, micromechanical systems
- System on a chip
- Modular aircraft: Joint Advanced Striker
- Lean aircraft and aerospace design and manufacturing
- “Boeing’s seventh wonder” IEEE Spectrum, 1995
- Air Traffic Control
- Network security
- System of systems
- Systems Biology, Systems Medicine

# UMD MODEL-BASED SYSTEMS ENGINEERING PROCESS

## PRODUCT: Integrated System Synthesis Methods & Software Tool Suites

UML - SysML - GME - eMFLON
ANSYS Model Center
Rapsody
UPPAAL
MATLAB, MAPLE
Dassault Systemes Dymola, CATIA, PLM
CONSOL-OPTCAD
IBM CPLEX ILOG Optimization Studio
GUROBI
SIEMENS PLM, NX, TEAM CENTER




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

# UMD Rigorous Framework for Model-Based Systems Engineering

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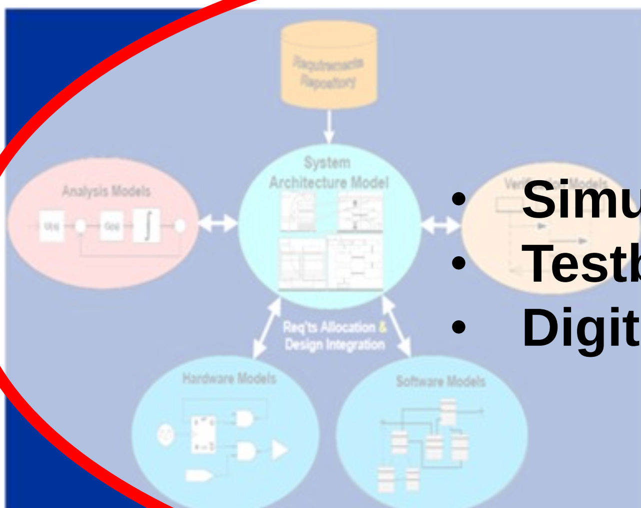
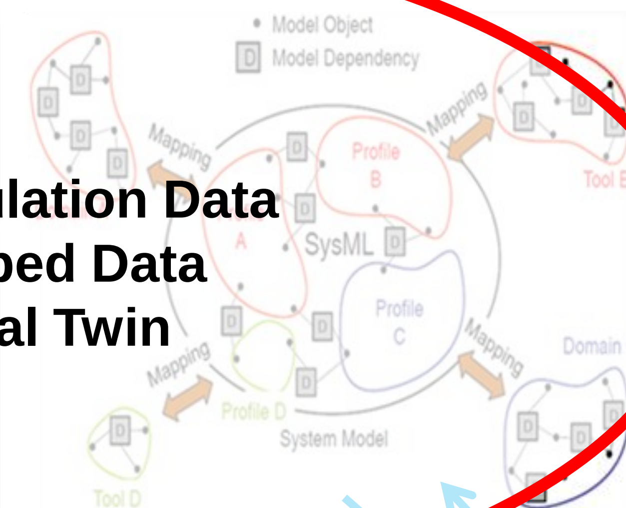
## PRODUCT – Proposed DATA DRIVEN ENHANCEMENTS

**Scalable holistic methods, models, tools for enterprise level SE**

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

System Modeling Transformations




- **Simulation Data**
- **Testbed Data**
- **Digital Twin**

Design space exploration

“ Master System Model”

Tradeoffs

IBM Optimization Studio, CPLEX, CONSOL-OPTCAD

**Machine Learning & Artificial Intelligence**

### ADD & INTEGRATE

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

Libraries of components and models

**Machine Learning & Artificial Intelligence**

### 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

# Transforming Engineering Education – Incorporate Systems 'Thinking'

- Develop systematic ways to engineer component-based architectures for synthesis and manufacturing of complex systems from heterogeneous components and supply chains
- Address directly the need for the two fundamental shifts in engineering design
  - **moving forward from the 'design to manufacture and assemble' to 'integration and product-life cycle mangement' of heterogeneous components. Thus we do not need to insist anymore on 'orthogonality of concerns' for the components. They can overlap or be 'quasi-orthogonal'.**
  - **the ubiquitous embedded IT components allow better integration and most importantly via programmability allow for new functionalities to be created and for easier insertion of new technologies in a system during its life-cycle.**
- What is happening in aerospace and automotive industry is a good example.
- These trends are becoming pervasive in all engineered systems.

# Educational Needs / Background

- Need to "see the bigger picture" earlier

- Current undergraduates are different from past and heterogeneous
  - Heterogeneity will increase; especially among the very best; the candidate "creators" of future engineering breakthroughs

- Basic calculus, physics and chemistry already done at a very good level among the best high schools; AP courses; College bypass
- Computers as indispensable communication-modeling-experimentation tools
- Programming replaces calculus; a "representation" symbology
- The Internet; access to knowledge that is easily searchable; multimedia depositories of experiments
- Virtual 3-D Labs
- Easier to collaborate

# MS in Systems Engineering

## TWO DEGREE OPTIONS

### MASTER OF SCIENCE SYSTEMS ENGINEERING (MSSE)

The broadly-based, cross-disciplinary MSSE program is offered by the Institute for Systems Research. Students benefit both academically and professionally by:

- Being exposed to a wide range of systems engineering principles, including software tools for modeling and optimization, decision and risk analysis, stochastic analysis, and human factors engineering;
- Becoming familiar with the financial and management issues associated with complex engineering systems; and
- Acquiring a deep understanding of one particular application area.

Designed with substantial industry input, the MSSE program covers a range of topics, from systems definition, requirements, and specifications, to systems design, implementation, and operation, in addition to the technical management of systems projects. Students specialize in computer and software, information, control, manufacturing or process systems; communications and networking; signal processing; or operations research. Drawing on the engineering, computer science, and management experience of University of Maryland faculty, the program makes optimum use of the university's advanced facilities, including symbolic capabilities, engineering workstations, and computer communication networks.

### MASTER OF ENGINEERING SYSTEMS ENGINEERING (ENPM)

The Professional Master of Engineering Program (ENPM), Systems Engineering, is offered through the A. James Clark School of Engineering's Office of Advanced Engineering Education. The ENPM is a practice oriented, part-time graduate program designed to assist engineers in the development of their professional careers and to provide the technical expertise needed in the business, government, and industrial environments. Late afternoon and evening classes are taught by the College Park faculty and experienced adjunct faculty at the College Park campus, designated learning centers in Maryland, and online.

# The Programs in Brief

## MSSE

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.

**Both Supplemented by Technical Electives form many Technical Areas**

## ENPM-SE

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

# Selected Topics from Project Management Component

## Project Management

ENCE 620 Risk Analysis in Engineering

ENCE 423 Project Planning, Scheduling and Control

ENCE 662 Introduction to Project Management

ENCE 665 Management of Project Teams

ENCE 667 Project Performance Measurement

ENCE 624 Managing Projects in a Dynamic Environment

ENCE 627 Decision and Risk Analysis for Project Management

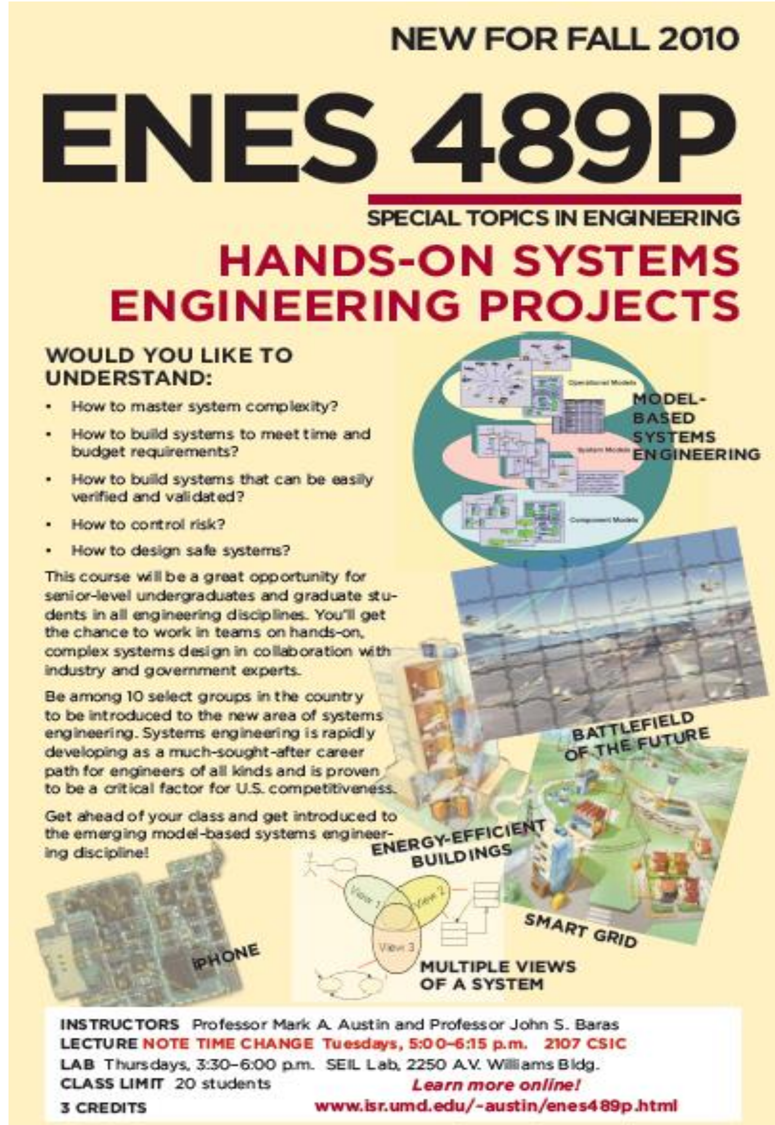
# Three Core Courses in the ISR MSSE Program

- **ENSE 621 Systems Concepts, Issues and Processes** (3)
  This course (along with ENSE 622/ENPM 642) is an introduction to the professional and academic aspects of systems engineering. Topics include models of system lifecycle development, synthesis and design of engineering systems, abstract system representations, visual modeling and unified modeling language (UML), introduction to requirements engineering, systems performance assessment, issues in synthesis and design, design for system lifecycle, approaches to system redesign in response to changes in requirements, reliability, trade-off analysis, and optimization-based design.
- **ENSE 622 Systems Requirements, Design and Trade-Off Analysis** (3)
  This course builds on material covered in ENSE 621/ENPM 641, emphasizing the topics of requirements engineering and design and trade-off analysis. The pair of courses serves as an introduction to the professional and academic aspects of systems engineering. Liberal use will be made of concepts from the first course, ENSE 621/ENPM641, including models of system lifecycle development, synthesis and design of engineering systems, visual modeling and unified modeling language (UML), requirements engineering, systems performance assessment, issues in synthesis and design, design for system lifecycle, approaches to system redesign in response to changes in requirements, reliability, trade-off analysis, and optimization-based design.
- **ENSE 623 Systems Projects, Validation and Verification** (3)
  This course builds on material covered in ENSE 621/ENPM 641 and ENSE 622/ENPM 642. Students will work in teams on semester-long projects in systems engineering design, using the modeling framework developed in the preceding two courses in the sequence to explore system designs that are subjected to various forms of testing. Students will be using all of the concepts from prior courses, as well as topics introduced in this class including validation and verification, model checking, testing, and integration.

# A Bold Experiment

***Starting early in the education chain***

Undergraduates working with industry and government mentors on SE projects



# ENES 489P: Hands-On Systems Engineering Projects

**Course Contents.** The course consists of lectures and hands-on project development in the laboratory. The lecture topics covered include:

1. Systems Engineering in Mainstream US Industry
2. Models of Systems Engineering Development
3. Economics of System Development
4. Strategies of Systems Engineering Development
5. Foundations of Model-Based Systems Engineering
6. Modeling abstractions for System Behavior and System Structure
7. Introduction to Languages for Visual Modeling of Systems (UML, SysML).
8. Requirements Gathering and Organization
9. Requirements Allocation and Flow-down
10. Requirements Traceability
11. Functional Allocation to Create the System-Level Design
12. Simplified Approaches to Tradeoff Analysis
13. System Implementation, Testing, Validation and Verification

# Capstone Course

- Systems Thinking up front
- Groups of 3-5 students on projects – hands-on
- Industry as customers, co-workers, judges
- Learn the concepts and methods and tools on the job
- 7/24 open lab to work on projects

# ENES 489P Spring 23 Projects List

- Space Frame Build Automation System (SFBAS)
- Autonomous Search, Track, and Rescue Operations (ASTRO) drone
- Orbital Detection Intelligence Network (ODIN)
- Remote Patient Monitoring (RPM)
- MedStation
- Drone to Drone Intercepting System (D2DIS)
- Automated Greenhouse System
- EVRide Electric Scooters
- Infrared Missile
- Surveillance Drone Wildlife Monitoring
- Aerial Disaster Management System (ADMS)
- Automated Greenhouse

# 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'**

# Key Questions for Undergraduate Engineering Education

***How to implement the best changes to prepare students for system level design and compositional synthesis?***

***A change of culture is required!***

- **What are the common elements?**
- **How to best prepare Engineering students?**
- **How early to introduce what?**

# Undergraduate Engineering Education

- Educational Challenge: undergraduate courses with system level thinking
- My three favorite topics:
  - System Models for Synthesis (calculus, logic, physics)
  - Signals and Measurements Representation and Processing
  - Optimization, Trade-off analysis, Feedback
- To be taught in all Engineering Departments, supported by appropriate hands-on applications (a la Medical School)
- Will help create communication between disciplines via the appropriate IT abstractions

# *Thank you!*

baras@umd.edu

301-405-6606

https://johnbaras.com/

# *Questions?*