NAVAL POSTGRADUATE SCHOOL

Education in Complex Systems for Systems Engineers

NDIA 15th Annual Systems Engineering Conference

Paper 14597

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SYSTEMS ENGINEERING
ESTABLISHED 2002

Introduction & Background

Read my paper!

As engineers, we communicate via information-dense media. The poor communication style of endless bullet-list Neanderthal grunts leads to a poor cognitive style counter to critical thinking and engineering reasoning.

Education in Complex Systems for Systems Engineers

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Abstract
This paper explores the potential benefits and disadvantages associated with providing a course (or part of a course) in complex systems as part of a systems engineering graduate degree program. An overview of systems engineering education programs and a history of SE curricular design provides context for this exploration. Curriculums other than systems engineering that include courses in complexity, nonlinear dynamics, emergence, chaos, decentralized synchronization through stigmergy, scale-free networks and related topics are also examined. The application of these concepts to design problems is assessed, particularly for engineers in the defense domain. Complex systems learning objectives tailored for systems engineers are proposed. Finally, a framework on which to base a trade-off analysis to determine if such topics should be included in an existing or developing graduate degree program is recommended.

Complexity

Order
Mechanical systems
Newtonian laws
Bell curves
Plans
Predictability
Control
High overhead
Little communication

Complexity
Biological systems
Capability
Power Laws
Priorities
Adaptation
Leverage
Agility
Critical Point

Chaos
Many domains
Laws of chaos
Strange Attractors
Reactions
Flexibility
Variety
Low overhead
Instability

Sarah Sheard

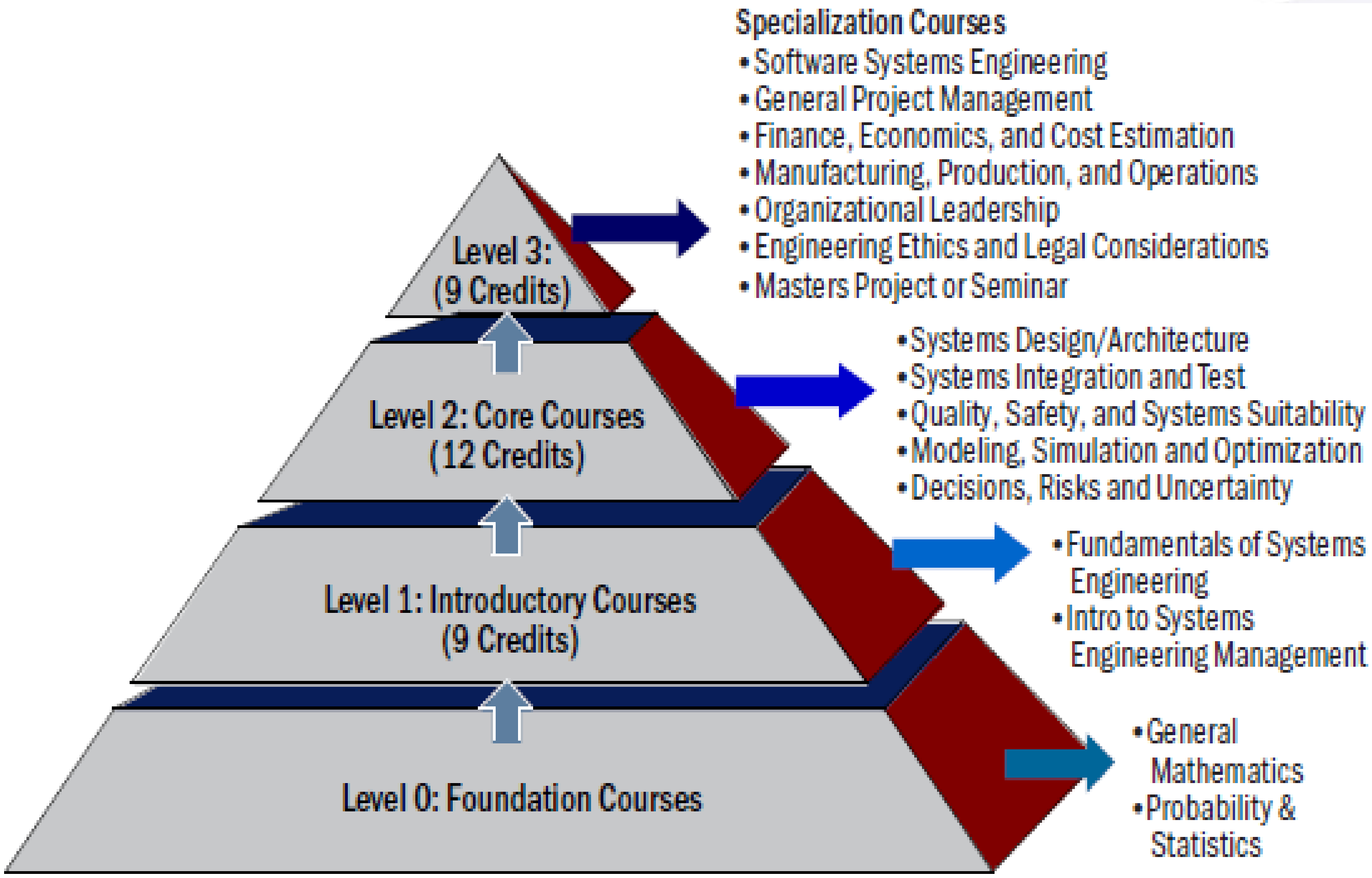
Linda Beckerman

Yaneer Bar-Yam

These systems . . . have come to be called *complex systems*, not to be confused with merely very *complicated* systems like microprocessors and aircraft carriers.

Generic SE Curriculum

Proposed Reference Framework



[Jain, et al, 2007]

SE Curriculum Framework Course Categories

Level	Category	Course Type
0	Pre-requisite Courses	Probability & Statistics
0		Linear, Matrix, Differential Equations
1	Fundamentals: Generic or Domain Specific	Fundamentals of Systems Engineering
1		Fundamentals of Software Systems Engineering
1		Introduction to Systems Engineering Management
1		Introduction to Domain Specific
2	System Life Cycle Technical Processes	Mission Needs, Systems Concept, System Requirements, Requirements Analysis
2		Systems Architecture, Systems Design and Development
2		Modeling, Simulation and Optimization
2		System Integration and Test, Field Testing
2		Manufacturing, Production, Operations, Retirement
2		Systems Suitability: Quality, Safety, Reliability, Supportability
3	System Life Cycle Project Processes	Decisions, Risks and Uncertainty
3		Configuration Management, Information Management
3		Project Management, Finance, Economics, Accounting
4	Other System Life Cycle Processes	Enterprise Systems
4		Acquisition and Supply
4	Other Broad Areas Applicable to Systems Engineering	Systems Thinking
4		Creativity and Problem Solving
4		Subject Matter Expert Domain Specific
5	Capstone	Masters Thesis, Project or Seminar

[Squires & Cloutier, 2010]

Guidance Informing SE Education

SPRDE-SE/PSE Systems Engineering Competency Model

Competency	Name	Element	Definition
1	Technical Basis for Cost	Element 1	Provide technical basis for comprehensive cost estimates and program budgets that reflect program phase requirements and best practices using knowledge of cost drivers, risk factors, and historical documentation (e.g. hardware, operational software, lab/support software).
2	Modeling and Simulation	Element 2	Develop, use, and/or interpret modeling or simulation in support of systems acquisition.
3	Safety Assurance	Element 3	Review Safety Assurance artifacts to determine if the necessary SE design goals and requirements were met for: Safe For Intended Use (SFIU), warfighter survivability, user safety, software safety, environmental safety, Programmatic Environmental, Safety and Health Evaluations (PESHE), and/or Critical Safety applications.
4	Stakeholder Requirements Definition	Element 4	Work with the user to establish and refine operational needs, attributes, performance parameters, and constraints that flow from the stakeholder described capabilities, and ensure all relevant requirements and design considerations are addressed.
5	Requirements Analysis	Element 5	Ensure the requirements derived from the stakeholder-designated capabilities are analyzed, decomposed, functionally detailed across the entire system, feasible and effective.
6	Architecture Design	Element 6	Translate requirements into alternative design solutions. The alternative design solutions include hardware, software, and human elements; their enabling processes; and related internal and external interfaces.
6	Architecture Design	Element 7	Track and manage design considerations (boundaries, interfaces, standards, available production process capabilities, performance and behavior characteristics) to ensure they are properly addressed in the technical baselines.
6	Architecture Design	Element 8	Generate a final physical architecture based on reviews of alternative designs.
6	Architecture Design	Element 9	Conduct walkthroughs with stakeholders to ensure that requirements will be met and will deliver planned systems outcomes under all combinations of design usage environments throughout the operational life of a system.
7	Implementation	Element 10	Manage the design requirements and plan for corrective action for any discovered hardware, software, and human deficiencies

Guidance Informing SE Education

ABET EC2010 Criterion 3

(a) an ability to apply knowledge of mathematics, science, and engineering
(b) an ability to design and conduct experiments, as well as to analyze and interpret data
(c) an ability to design a system, component, or process to meet desired needs within realistic constraints, such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability
(d) an ability to function on multidisciplinary teams
(e) an ability to identify, formulate, and solve engineering problems
(f) an understanding of professional and ethical responsibility
(g) an ability to communicate effectively
(h) the broad education necessary to understand the impact of engineering solutions in a global, economic, societal and environmental context
(i) a recognition of the need for, and an ability to engage in, life-long learning
(j) a knowledge of contemporary issues
(k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice

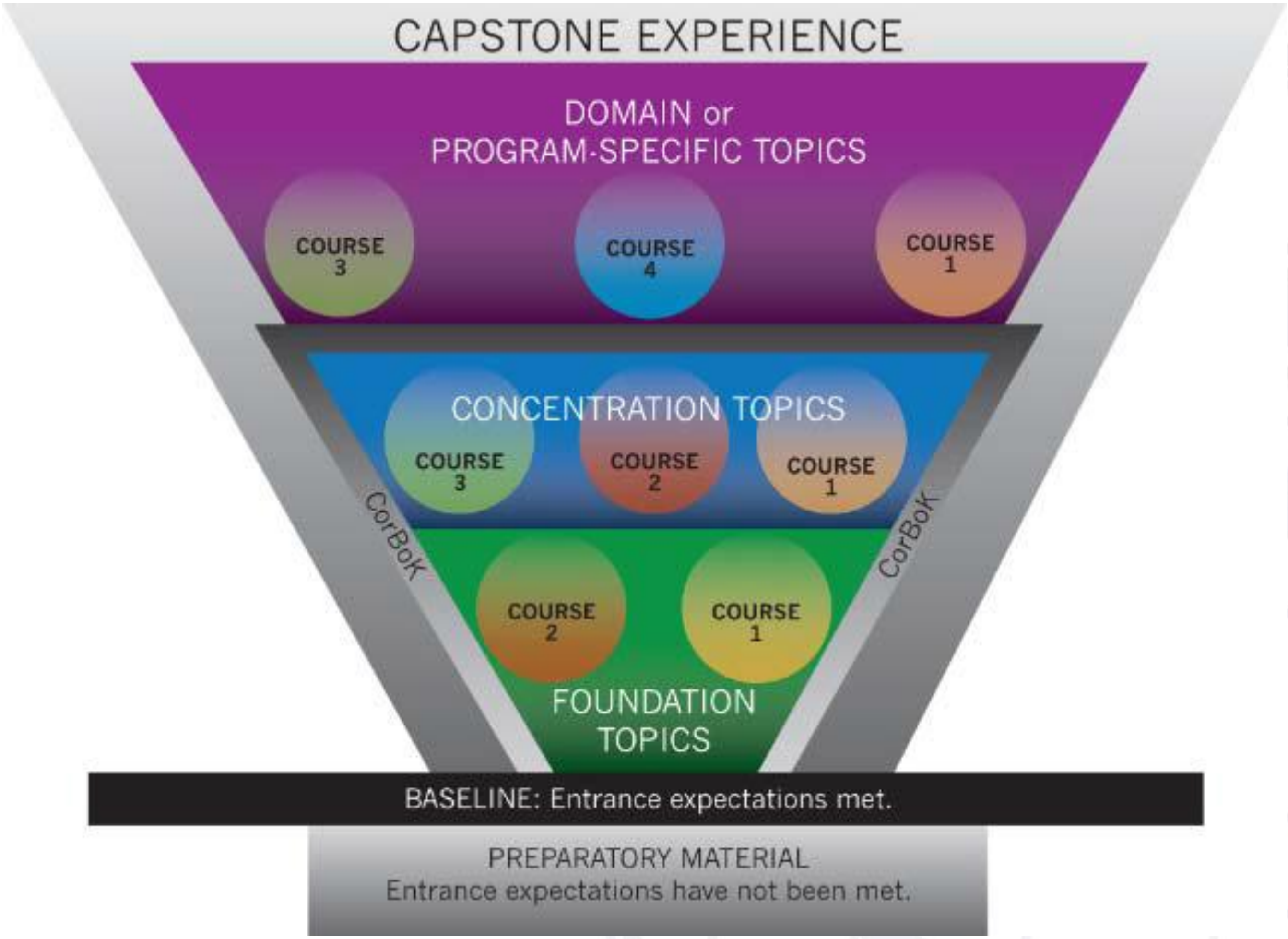
Guidance Informing SE Education

CDIO Syllabus v2.0 at Second Level of Detail

1 DISCIPLINARY KNOWLEDGE AND REASONING	**3 INTERPERSONAL SKILLS: TEAMWORK AND COMMUNICATION**
1.1 KNOWLEDGE OF UNDERLYING MATHEMATICS AND SCIENCE	3.1 TEAMWORK
1.2 CORE FUNDAMENTAL KNOWLEDGE OF ENGINEERING	3.2 COMMUNICATIONS
1.3 ADVANCED ENGINEERING FUNDAMENTAL KNOWLEDGE, METHODS AND TOOLS	3.3 COMMUNICATIONS IN FOREIGN LANGUAGES
2 PERSONAL AND PROFESSIONAL SKILLS AND ATTRIBUTES	**4 CONCEIVING, DESIGNING, IMPLEMENTING, AND OPERATING SYSTEMS IN THE ENTERPRISE, SOCIETAL AND ENVIRONMENTAL CONTEXT**
2.1 ANALYTICAL REASONING AND PROBLEM SOLVING	4.1 EXTERNAL, SOCIETAL AND ENVIRONMENTAL CONTEXT
2.2 EXPERIMENTATION, INVESTIGATION AND KNOWLEDGE DISCOVERY	4.2 ENTERPRISE AND BUSINESS CONTEXT
2.3 SYSTEM THINKING	4.3 CONCEIVING, SYSTEMS ENGINEERING AND MANAGEMENT
2.4 ATTITUDES, THOUGHT AND LEARNING	4.4 DESIGNING
2.5 ETHICS, EQUITY AND OTHER RESPONSIBILITIES	4.5 IMPLEMENTING
	4.6 OPERATING

Guidance Informing SE Education

Graduate Reference Curriculum for Systems Engineering (GRCSE)



Part of BKCASE - http://www.bkcase.org/fileadmin/bkcase/files/GRCSE_0.5/GRCSE_Version0_5_Final.pdf

Complexity in non-SE Programs

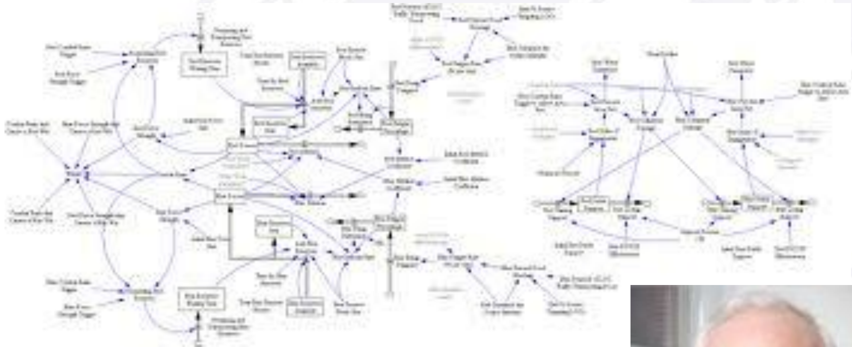
- INFO I690 Mathematical Methods for Complex Systems
- INFO I585 Biologically Inspired Computing

"… fractals, emergent behavior, chaos theory, cooperative phenomena, and complex networks"

- MAP 6211 Introduction to Dynamical Systems and Chaos

"… one-, two- and higher dimensional flows, oscillator theory, maps, attractors, bifurcations, chaos"

- Phys 580 Empirical Analysis of Nonlinear Systems
- Math 550: Introduction to Dynamical Systems

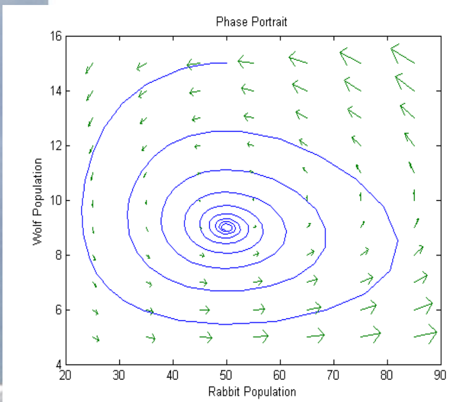


… educate "enterprise designers" who would use quantitative approaches to describe endogenous system feedback and computer modeling of nonlinear system dynamics

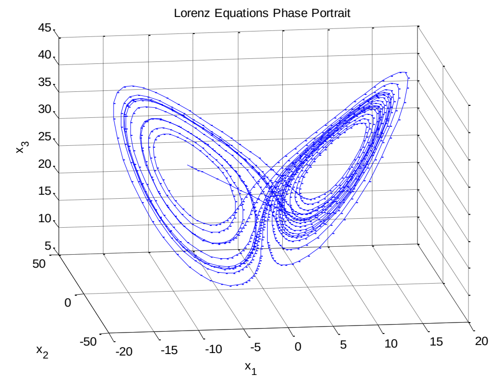
Jay Forrester

Applying Complexity in Design

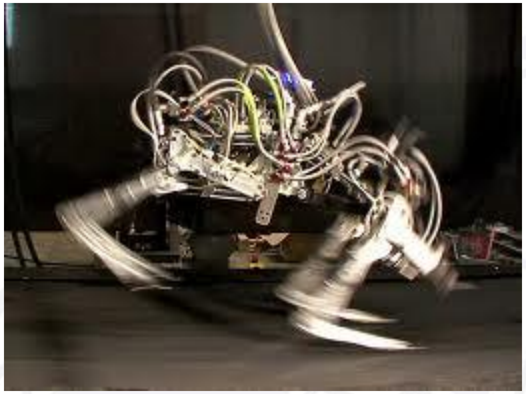
$$\dot{N}_1 = aN_1 - bN_1N_2 - eN_1^2$$
$$\dot{N}_2 = -cN_2 + dN_1N_2$$

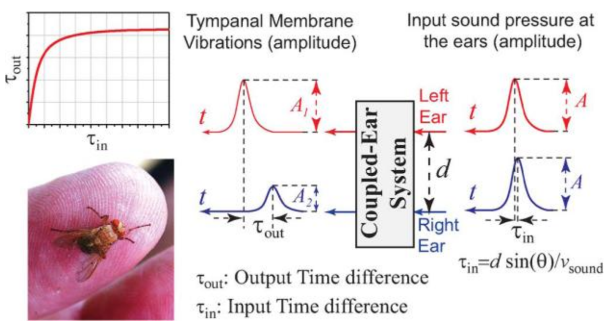


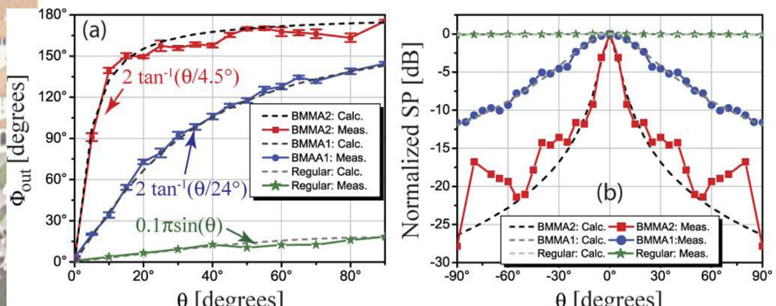
$$\dot{x} = \sigma(y - x)$$
$$\dot{y} = rx - y - xz$$
$$\dot{z} = xy - bz$$



Nonlinear dynamics







Boston Dynamics

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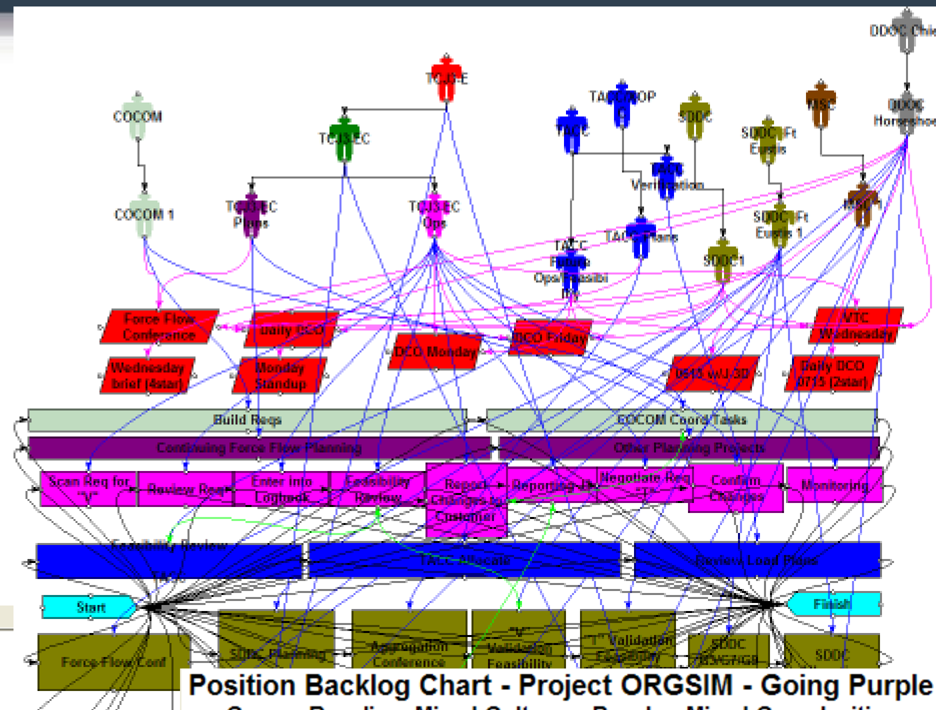
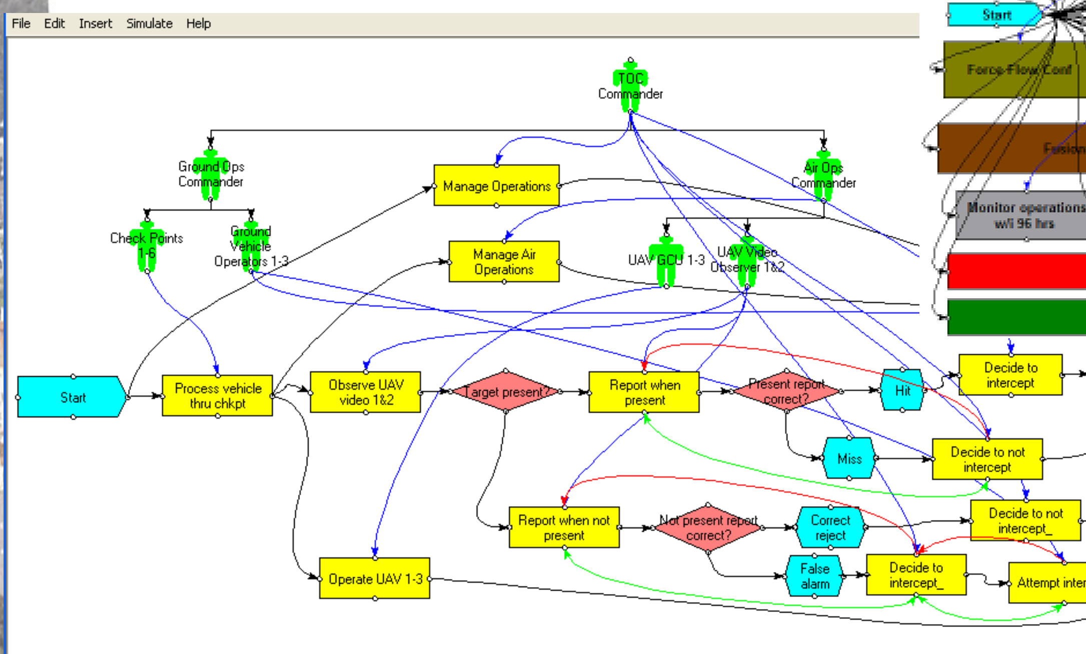
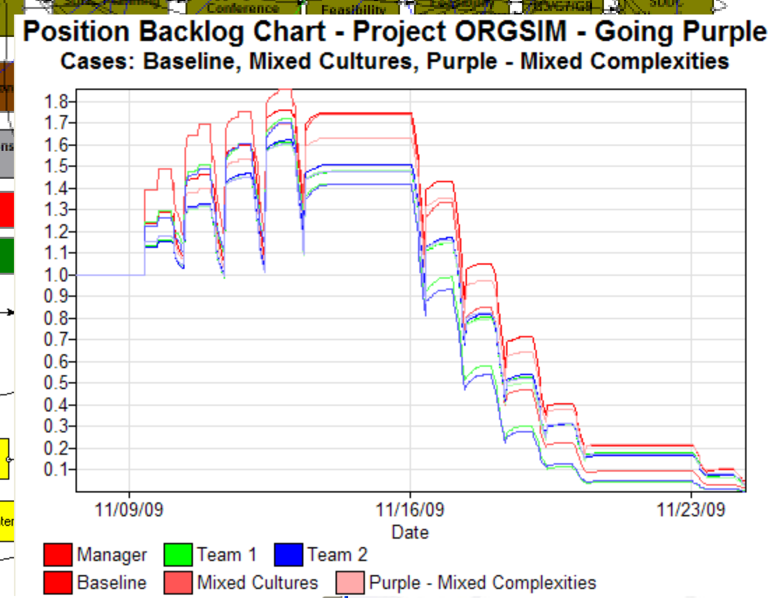
Applying Complexity in Design

Small-world Networks

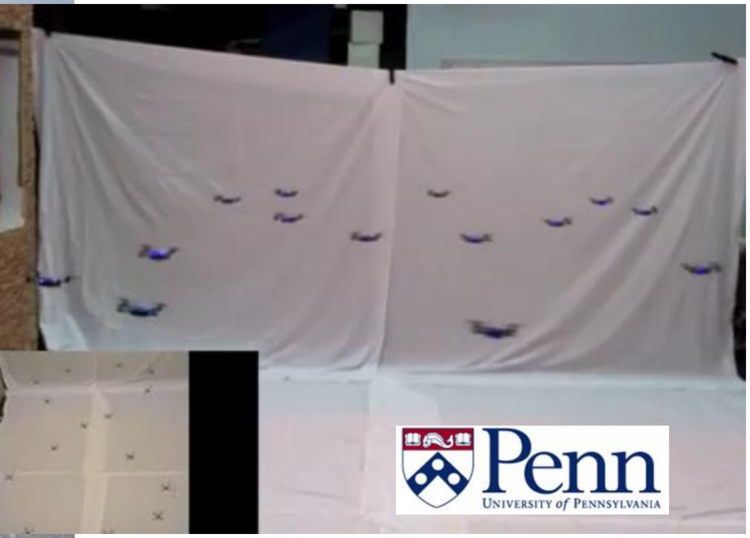




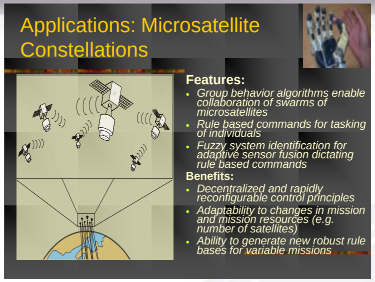


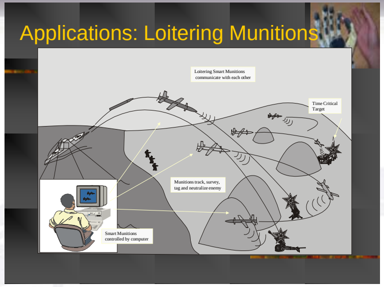
Applying Complexity in Design

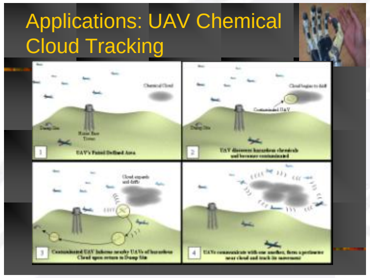
Swarming-Stigmergy-PFSA

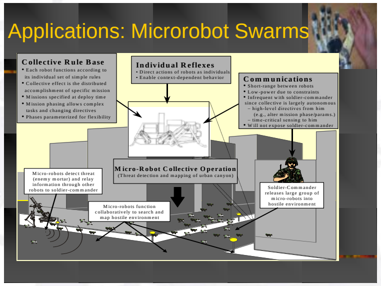


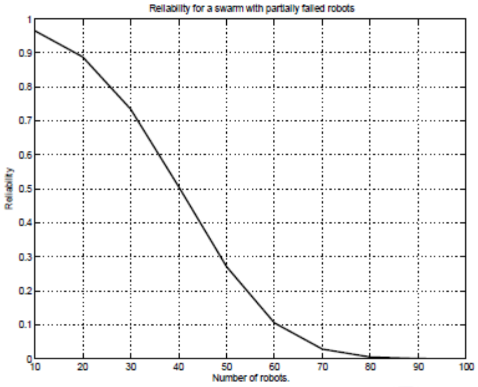
Ravi Vaidyanathan

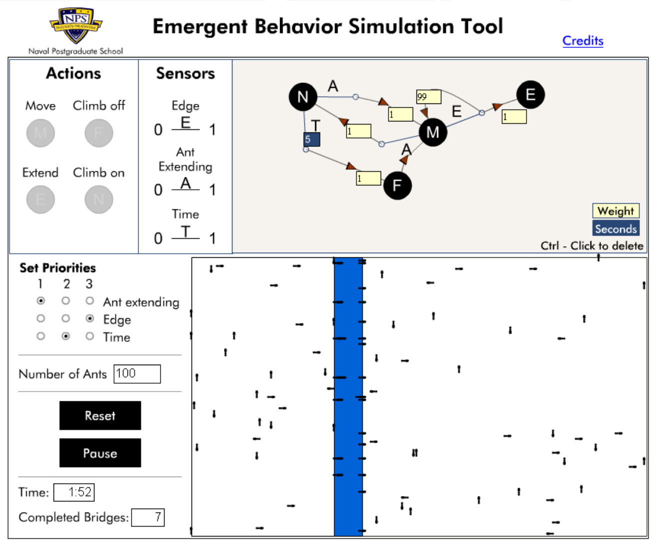












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Recommended Learning Objectives

Nonlinear Dynamics

- Define nonlinear systems and differentiate them from linear systems
- Create 1-, 2-, and 3-dimension phase portraits
- Determine fixed points of sets of nonlinear systems; characterize them in terms of their stability and apply Jacobian matrices to quantify their behavior; map basins of attraction and eigenvectors
- Use phase portraits to characterize limit cycles
- Create computer models of nonlinear systems based on sets of nonlinear equations
- Use computer models of nonlinear equations to explore the effects of changing system parameters and initial conditions

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Recommended Learning Objectives

Complex Adaptive Systems and Decentralized Systems

- Create models of probabilistic finite state automata
- Given a description of individual agent behavior, draw a state-transition diagram including states and triggers
- Describe how adaptive agents impact a system's macroscopic behavior
- Define the terms 'robustness' and 'stability' in the context of complex systems
- Characterize a system based on its diversity (across types and within types)
- Describe the strengths and weaknesses of decentralized systems compared to centralized control; determine in which situations one would be better than the other

Recommended Learning Objectives

Small World Networks

- Define the terms ‘node,’ ‘link,’ ‘hub’ (or ‘high-degree node’), ‘clustering,’ ‘small world network’ and ‘scale-free network’
- Determine average path length, clustering coefficient, and degree distribution of a given network
- Describe how network resilience is related to average path length and clustering
- Model the impact of node failure in different kinds of network configurations

Recommended Learning Objectives

Applied Complex Systems Design

- Apply complexity theory to ‘evolve’ rather than to ‘design’ a system; describe the impact of environmental forces and mutation
- Describe the impact of self-modifying components
- Leverage emergence by designing in parameters that lead to stable desired outcomes even in changing environments
- Apply diversity by employing different types of elements (homogeneity is efficient, but not robust); explore trade-offs in diversity within types and across types
- Identify elements that work on different time-scales in different layers
- Apply the concept of “satisficing” for second-priority components
- Consider network effects, especially human-centric networks; model changes and alternative designs to quantify robustness and identify vulnerable nodes
- Describe how design and development organizations are themselves complex systems

some adapted from Sheard [2009]

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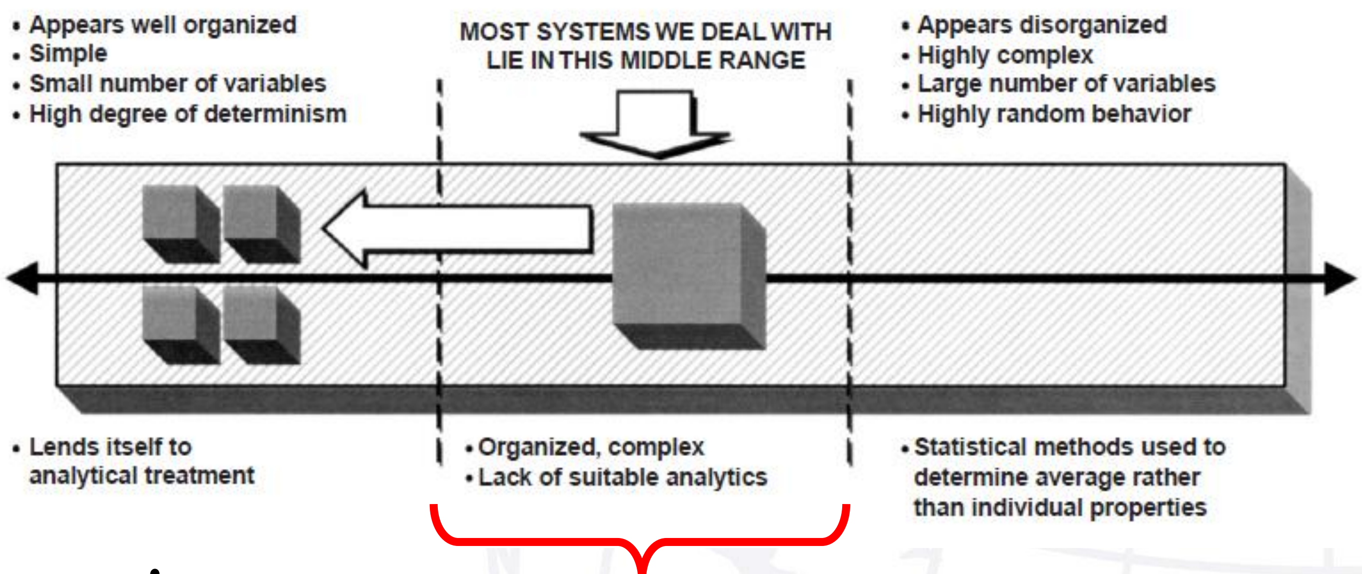
A Framework for Assessing Cost & Benefits



Read my paper!

Complex systems engineering should complement and not replace traditional approaches.

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