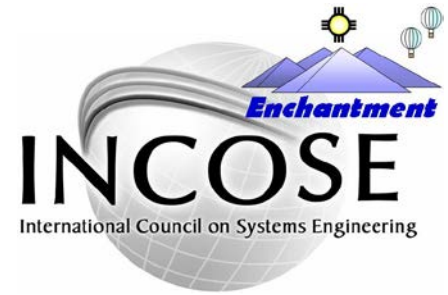# Enchantment Chapter Monthly Meeting

11 November 2015 – 4:45-6:00 pm:

A Complexity Primer for Systems Engineers

Dr. Jimmie McEver, Sr. Scientist, Johns Hopkins U. Applied Physics Laboratory
Jimmie.McEver@jhuapl.edu

Abstract: Complexity is increasingly being recognized as a fundamental challenge across the life cycle of engineered systems, arising in the environmental context for which systems are developed, the ecosystems in which they will be used, and the systems themselves. The INCOSE Complex Systems (CxS) Working Group recently developed a primer on complexity as a brief introduction to concepts and approaches for systems engineers and program/project managers who suspect they may encounter complexity-related challenges. The primer describes how complexity can be identified in an environment, a problem space, or a solution space, and discusses guiding principles and approaches for effective systems thinking and systems engineering in these contexts. In this talk, Dr. McEver, Chair of the Complex Systems Working Group and one of the primer co-authors, will present key concepts from the Primer, and discuss other activities of the working group.

Download slides today-only from GlobalMeetSeven file library or anytime from the Library at www.incose.org/enchantment

NOTE: This meeting will be recorded

A Few Words First

Courtesy – Please mute your phone (*6 toggle)
Enchantment Chapter Board of Director Elections happening now. Please vote.

You're invited!

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Enchantment Chapter

The *2015 INCOSE Holiday Social* will be held in the Porter Room at the Chama River Brewing Company (505.342.1800), 4939 Pan American Freeway, in Albuquerque from *5:00 - 7:30 PM* on *December 4, 2015*. Cocktails with appetizers at 5:00 PM, followed by a three-course dinner (menu on page 2) at 6:00 PM.

Paul Mann, Special Executive Services, Executive Director, *U.S. Army White Sands Missile Range (WSMR)*, will be our speaker. Mr. Mann is responsible for the development, approval, and implementation of all scientific and technical policies and procedures as well as resource management plans and programs for WSMR.

Cost: *$20/person* payable only by **cash or check** at the event. Attendees receive 1 ticket for a cocktail, a glass of wine, or a beer. *RSVP to Mary Compton, mlcompt@sandia.gov, 505.845.9268, by Monday, November 30, 2015.*

RSVP By November 30th!

And Now - Introductions

A Complexity Primer for Systems Engineers

Things to Think About

How is complexity affecting your work?

What did you hear that will influence your thinking?

What is your take away from this presentation?

Speaker Bio

Dr. Jimmie McEver is a Senior Scientist in the Asymmetric Operations Sector of the Johns Hopkins University Applied Physics Laboratory, and Chair of the INCOSE Complex Systems Working Group.

He is currently working with the U.S. Department of Defense to develop strategies and quantitative analytic methods for the acquisition and systems engineering of capabilities for cyberspace operations.

He has worked with the U.S. DoD Command and Control Research Program and selected NATO Study Panels on issues associated with network enabled command and control and C2 assessment, contributing to the development of the *NATO Network Enabled Capability C2 Maturity Model* and concepts of C2 agility.

He was a member of The Technical Cooperation Program's Action Group on Complex Adaptive Systems for Defense. He currently chairs the Complex Systems Working Group in INCOSE and the Technical Committee on Information and C2 Systems in the American Institute for Aeronautics and Astronautics.

He holds a Ph.D. in Physics from the Georgia Institute of Technology, and a Master of Public Policy from the John F. Kennedy School of Government at Harvard University.

A Complexity Primer for Systems Engineers

November 11, 2015

Dr. Jimmie McEver
Senior Systems Scientist, JHU Applied Physics Laboratory
Chair, INCOSE Complex Systems Working Group

jimmie.mcever@jhuapl.edu

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Agenda

- Brief overview of Complex Systems WG

- Complexity Primer for Systems Engineers

Complex Systems (CxS) WG Overview

- Organized in 2006 from Systems Science WG

- Co-chairs: Dr. Jimmie McEver, JHU/APL
                       Mr. Michael Watson, NASA/MSFC

- 46 INCOSE members participated in discussions at IW 2015

https://connect.incose.org/WorkingGroups/ComplexSystems/

Purpose and Objectives

- The purpose of the Complex Systems Working Group is to enhance the ability of the systems engineering community to deal with complexity.

- The CxS Working Group works at the intersection of complex systems sciences and SE, focusing on systems beyond those for which traditional systems engineering approaches and methods were developed.

- Complex Systems Working Group objectives
  - Communicate the complexity characteristics to systems engineering practitioners
  - Provide knowledge and expertise on complex systems in support of other INCOSE working groups working in their systems engineering areas
  - Facilitate the identification of tools and techniques to apply in the engineering of complex systems
  - Provide a map of the current, diverse literature on complex systems to those interested in gaining an understanding of complexity.

- Although analysis is important, the goal is to make a difference in synthesis (creation of new systems).

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Candidate Activities

- Expand on Mat French MBSE in Complexity Contexts work begun in 2014

- Expand on selected Primer topics; evolve into wiki to facilitate evolution and access; develop annotated complexity bibliography

- Work with US Government partners to identify WG initiatives to help address current systems challenges (digital engineering, engineering resilient systems, open architecture based approaches for engineering complex systems)

- Identify relationships and strengthen interactions with other INCOSE WGs (and with complexity groups in other organizations)

- Workshop or other joint meeting with AIAA Complex Aerospace Systems Exchange organizers

- Maturity Model for the Complex SE capability of an organization or endeavor

- Organize webinars to discuss WG initiatives and topics of interest

A Primer on Complexity for Systems Engineers

- The INCOSE Complex Systems Working Group has drafted a primer to introduce complexity concepts and approaches to practicing systems engineers

- Members of the primer development team

  - Sarah Sheard
  - Eric Honour
  - Jimmie McEver
  - Dorothy McKinney
  - Alex Ryan
  - Stephen Cook
  - Duane Hybertson

  - Joseph Krupa
  - Paul Ondrus
  - Robert Scheurer
  - Janet Singer
  - Joshua Sparber
  - Brian White

Motivation: The Implications of Complexity

- Systems engineering has evolved to improve our ability to deal with scale and interdependency though the life cycle of engineered systems

- Systems are becoming increasingly dynamic and interdependent, with growing emphasis on adaptiveness

Source: Sarah Sheard, *Complexity and Systems Engineering, 2011*
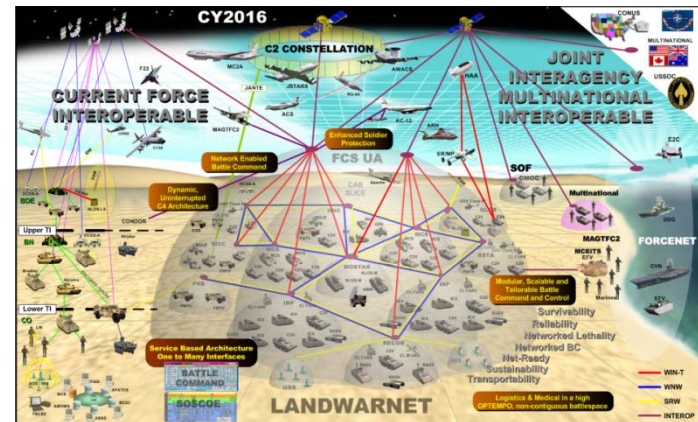
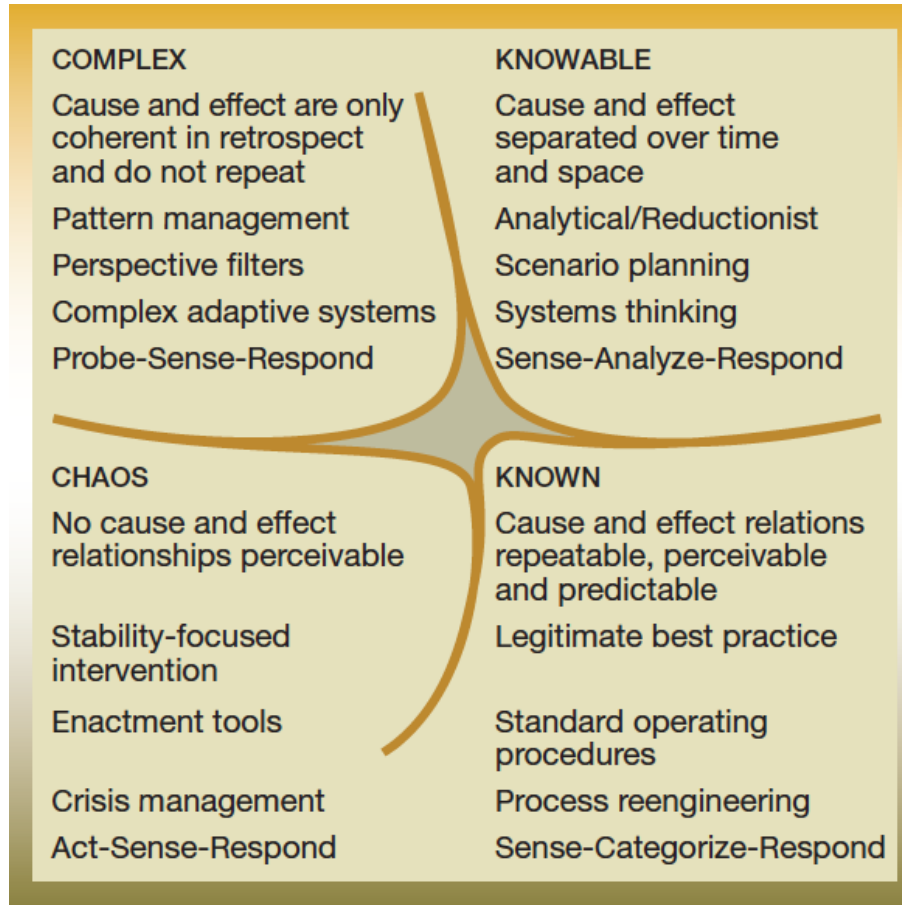Source: Monica Farah-Stapleton, IEEE SOS conference, 2006

- BUT, complexity places new demands on systems engineers that require more than extensions of "classical" SE practice

Classes of Systems Problems:
Kurtz and Snowden's Cynefin Framework

Cynefin domains

Complex systems, characterized by interdependence, self-organization, and emergence – new tools and approaches are needed

Massively-complicated systems present challenges of *scale* and *interface accounting* – extensions of traditional methods/tools can help

Chaotic systems can only be reacted to; can attempt to transform into another domain

Simple and complicated systems are straightforward to deal with using traditional systems engineering / mgmt approaches

COMPLEX
Cause and effect are only coherent in retrospect and do not repeat
Pattern management
Perspective filters
Complex adaptive systems
Probe-Sense-Respond

KNOWABLE
Cause and effect separated over time and space
Analytical/Reductionist
Scenario planning
Systems thinking
Sense-Analyze-Respond

CHAOS
No cause and effect relationships perceivable

Stability-focused intervention

Enactment tools

Crisis management
Act-Sense-Respond

KNOWN
Cause and effect relations repeatable, perceivable and predictable
Legitimate best practice

Standard operating procedures
Process reengineering
Sense-Categorize-Respond

Source: Kurtz and Snowden, "The new dynamics of strategy: Sensemaking in a complex and complicated world," *IBM Systems Journal*, **42** (3), 2003.

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What do we mean by complexity?

- No easy, agreed-upon definition
- We often call something complex when we cannot fully understand its structure or behavior: it is uncertain, unpredictable, complicated, or just plain difficult (see Sillitto (2009): Subjective Complexity)
- Concepts that seem essential
  - Emergence: Features/behavior associated with the holistic system that are more than aggregations of component properties
  - Multi-scale behavior: System not describable by a single rule, structure exists on many scales, characteristics are not reducible to only one level of description.
  - A system with self-organization, analogous to natural systems, that grows without explicit control, and is driven by multiple locally operating, socio-technical processes, usually involving adaptation

Complex vs Complicated

Complex system

Complicated system

Traffic jams exhibit:

- **Self-organization** and **Emergence** – local actors and decisions interact to create larger patterns
- **Memory** – even after an obstacle is removed the jam can persist for hours
- **Counter-intuitive outcomes** – e.g., Braess' Paradox – adding capacity to the network can degrade network performance

Modern transit vehicles exhibit:

- **Large numbers of interacting systems** – fuel, electrical, engine, transmission, safety, etc.
- **Aggregate** properties, but not emergence – e.g., range, top speed…
- Unexpected outcomes still possible, but origin is different
- Transit *systems* may be complex

The opposite of "complex" is "decomposable", not "simple"

Source: Alex Ryan

Hallmarks and Implications of Complexity

How complexity makes it different

Hallmarks of complexity	Impact on Decision Maker
Interdependence	Cannot treat by decomposition
Nonlinearities	Extrapolation of current conditions → error
Open boundaries	Cannot focus only on processes inside boundary
Multi-scalarity	Have to address all relevant scales
Causal & influence networks	Challenge: develop 'requisite' conceptual model within time and information resource constraints
Emergence	Unknown risks and unrecognised opportunities
Complex goals	Goals may change, be unrealistic, vague
Adaptation & innovation	'Rules' change, interventions stimulate adaptation
Opaqueness	Many possible hypotheses about causal paths, insufficient evidence to discriminate

Adapted from Grisogono, Anne-Marie and Vanja Radenovic, The Adaptive Stance –Steps towards Teaching more Effective Complex Decision-Making, International Conference on Complex Systems, June 2011.
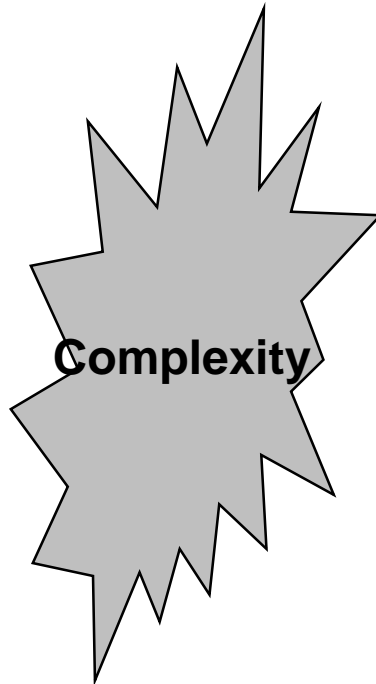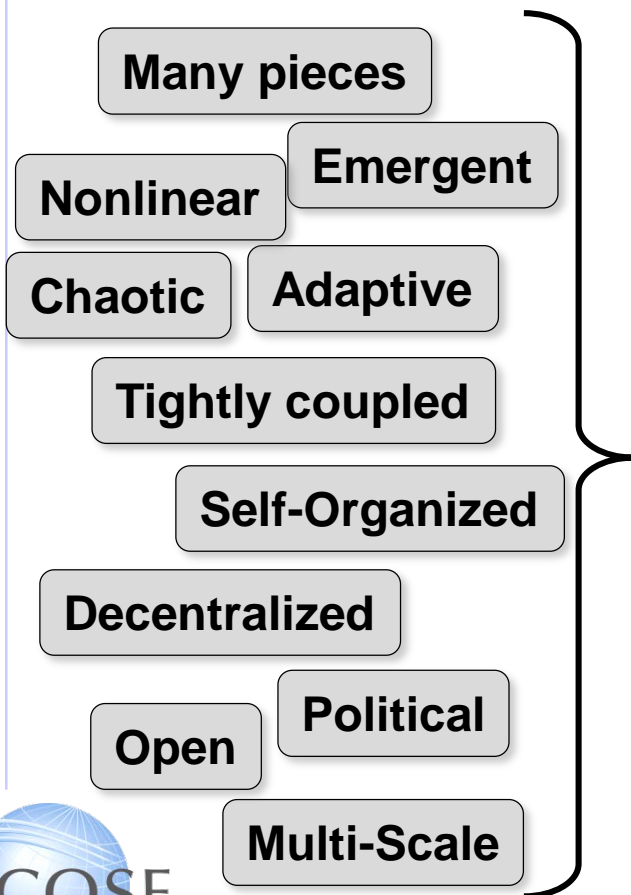
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Sources of Complexity

- **System**
  - Large number of components, many intricate interdependencies
  - Adaptive components, interactions
  - Interfaces with human users or other complex entities
  - Evolving technology

- **Environment**
  - Operational environment
    - Problem you're trying to solve changes
    - Conditions under which you're trying to solve a problem change
    - Way that you elect to solve the problem changes
  - System environment
    - Changes to elements of the larger SoS

- **Design/management**
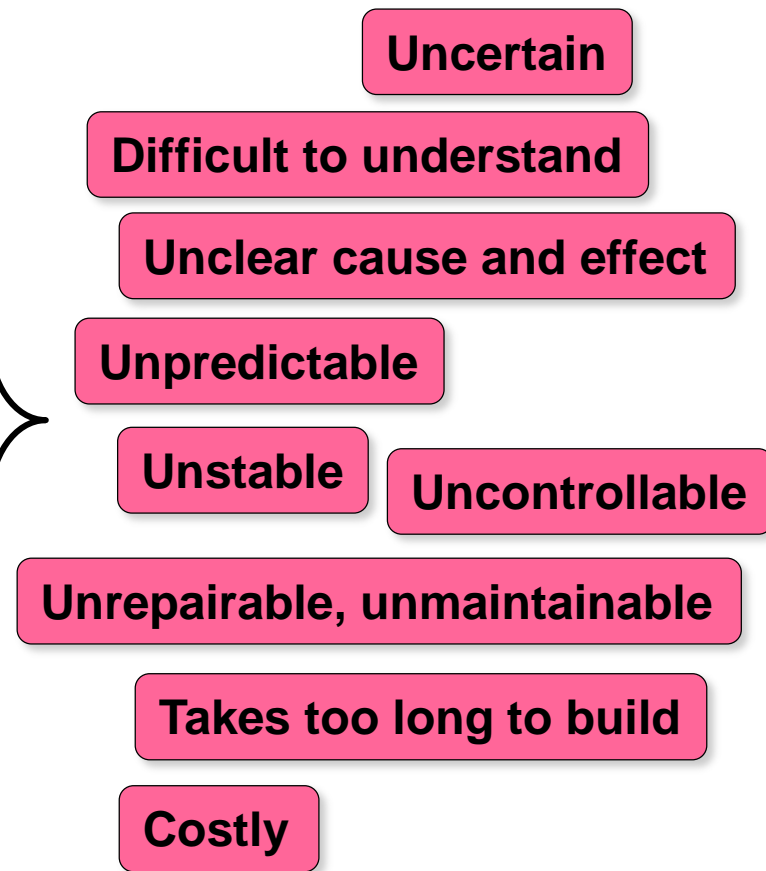 - Large number of people and organizations involved

System Complexity as SE Challenges

System Characteristics
(Objective Complexity)

Cognitive Characteristics
(Subjective Complexity)

Many pieces

Emergent

Nonlinear

Chaotic

Adaptive

Tightly coupled

Self-Organized

Decentralized

Political

Open

Multi-Scale

Complexity

Uncertain

Difficult to understand

Unclear cause and effect

Unpredictable

Unstable

Uncontrollable

Unrepairable, unmaintainable

Takes too long to build

Costly

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Complexity and Systems Development

- You need complexity to respond to complexity
  - Provides degrees of freedom to needed to deal with/work in complex, volatile and uncertain environments
- But developing and using complex systems have their own challenges
  - Less ability to plan and predict
  - Problems/systems not neatly decomposable – interdependencies between subsystems grow beyond ability to deal with them in traditional ways
  - Uncomfortable phenomena arise, such as normal accidents, black swans, catastrophic fragility

Ashby's Law of Requisite Variety

A model system or controller can only model or control something to the extent that it has sufficient internal variety to represent it.

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Candidate approaches:
Selected Guiding Principles

 V

Think like a gardener, not a watchmaker

- Grow, don't build
- Focus on the ecosystem
  - Extensible substrate
  - Rules and feedback for adaptation
- Influence and intervene vice design and control


Take an adaptive stance

- Enable and improve adaptation capabilities
  - Observe system behavior
  - ID and create variation
  - Selecting the best versions
  - Amplify the fit of the selected versions

Candidate approaches:
Selected Guiding Principles

Think at multiple levels and from multiple perspectives

- Systems may create different value at different levels and from different perspectives
- Need to look at systems and requirement from diverse perspectives
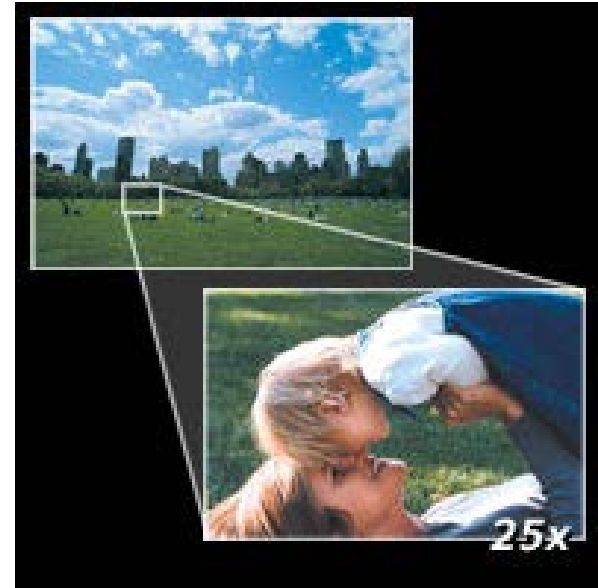
- System behavior may be fundamentally different at different levels
- The decomposed problem is a different problem

Candidate approaches: Selected Guiding Principles

- Combine courage with humility
- Use free order
- Identify and use patterns
- See through new eyes
- Collaborate
- Achieve balance
- Learn from problems
- Meta-cognition

- Focus on desired regions of the outcome space rather than specifying detailed outcomes
- Understand what motivates autonomous agents
- Maintain adaptive feedback loops
- Integrate problems

Candidate approaches: SE Methods
Environmental Complexity

	Requirements Elicitation and Derivation	Trade Studies	Solution Architecture and Design	Development Process
Environment susceptible to unpredictable but high-consequence events and/or recursive complexity	Use power laws to characterize relevant phenomena Focus elicitation on agility vice optimizing to particular assumptions	Make dimensions of agility key trade-space attributes Use trades to ID aspects of the problem space that will drive the system architecture	Design for resilience to "beyond-design-envelope" events to provide robustness and timely recovery to a minimally functional state.	Resilience analysis Enterprise development: study how enterprises or societies survive catastrophes.

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Candidate approaches: SE Methods
System/Solution Complexity

	Requirements Elicitation and Derivation	Trade Studies	Solution Architecture and Design	Development Process
Complexity in System Design & Development (General)	Use multi-scale modeling (linking macro- and micro-level models), including exploratory analysis and agent-based modeling, and experimentation: • To generate insight into the implications of derived requirements • As the basis for trade studies and to inform trade-off decisions		Emphasize selection of robust and adaptive elements and structures over optimizing to meet current requirements	Use Systems-of-Systems methodologies to synchronize constituent systems; incentivize collaboration. Ensure prototyping and experimentation are used.

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Applicability of Generalized Analytic Methods: The Cook Matrix

- Lists and briefly describes modeling and analysis methods from a wide range of disciplines
- Candidate approaches to consider in modeling complex systems problems

Analyze	Diagnose	Model	Synthesize
Data Mining	Algorithmic Complexity	Uncertainty Modeling	Design Structure Matrix
Splines	Monte Carlo Methods	Virtual Immersive Modeling	Architectural Frameworks
Fuzzy Logic	Thermodynamic Depth	Functional / Behavioral Models	Simulated Annealing
Neural Networks	Fractal Dimension	Feedback Control Models	Artificial Immune System
Classification & Regression Trees	Information Theory	Dissipative Systems	Particle Swarm Optimization
Kernel Machines	Statistical Complexity	Game Theory	Genetic Algorithms
Nonlinear Time Series Analysis	Graph Theory	Cellular Automata	Multi-Agent Systems
Markov Chains	Functional Information	System Dynamics	Adaptive Networks
Power Law Statistics	Multi-scale Complexity	Dynamical Systems	
Social Network Analysis		Network Models	
		Agent Based Models	
		Multi-Scale Models	

Candidate approaches:
Analytic tools for the Complex SE Toolkit?

- Some are emerging for "massively complicated" SE
  - MBSE tools and methods
  - Emerging thinking on T&E in large test spaces
- For complex SE, some exist – but are not designed for or aligned with SE community
- Complex SE (or CxSE) requires more than just tools
  - Not a "run the tool, get the answer" problem
  - Requires understanding of the nature of complexity and how to deal with volatility and deep uncertainty
    - Mindset, experience (and education)
  - Tools needed are those that will enable this understanding
- A key role of the systems engineer is to facilitate this understanding across his/her stakeholder communities

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Next Steps (for the Primer and the WG)

- Present Primer for INCOSE technical review

- Continue to socialize primer as a resource for INCOSE members

- Expand on selected Primer topics; evolve into wiki to facilitate evolution and access; develop annotated complexity bibliography
  - Construct Concept Map for complex systems knowledge

- Leverage primer (and other) approaches to address (or at least generate new insight into) community "hard problems"
  - Cybersecurity
  - Evolutionary Acquisition
  - Systems of systems

- Engage with other working groups to identify intersection topics we can work together

A Complexity Primer for Systems Engineers

Things to Think About

How is complexity affecting your work?

What did you hear that will influence your thinking?

What is your take away from this presentation?

Please

The link for the online survey for this meeting is

www.surveymonkey.com/r/enchant_11_11_15

www.surveymonkey.com/r/enchant_11_11_15

Look in GlobalMeet chat box for cut & paste link.

Slide presentation can be downloaded now/anytime from:

The library page at: www.incose.org/enchantment

Recording will be there library tomorrow.