A Complexity Primer for Systems Engineers

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Agenda

- Brief overview of Complex Systems WG
- Complexity Primer for Systems Engineers

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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/

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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

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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

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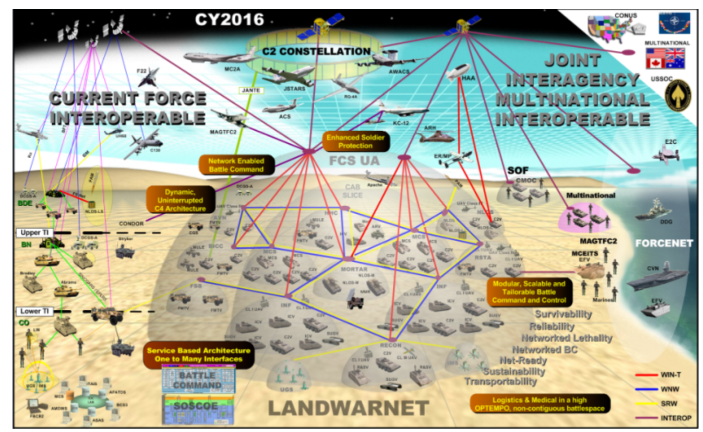
Motivation: The Implications of Complexity

- 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

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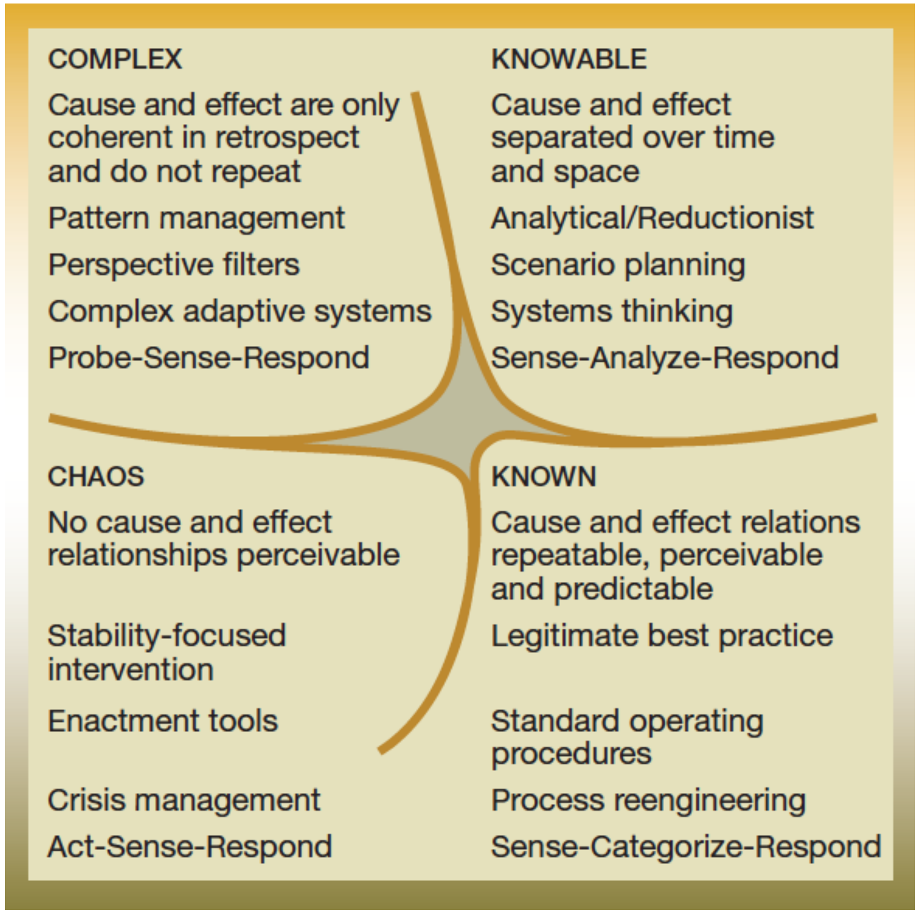
Classes of Systems Problems:
Kurtz and Snowden's Cynefin Framework

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

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

Cynefin domains



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

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

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

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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

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Complex vs Complicated

Complex 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

Complicated system

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"

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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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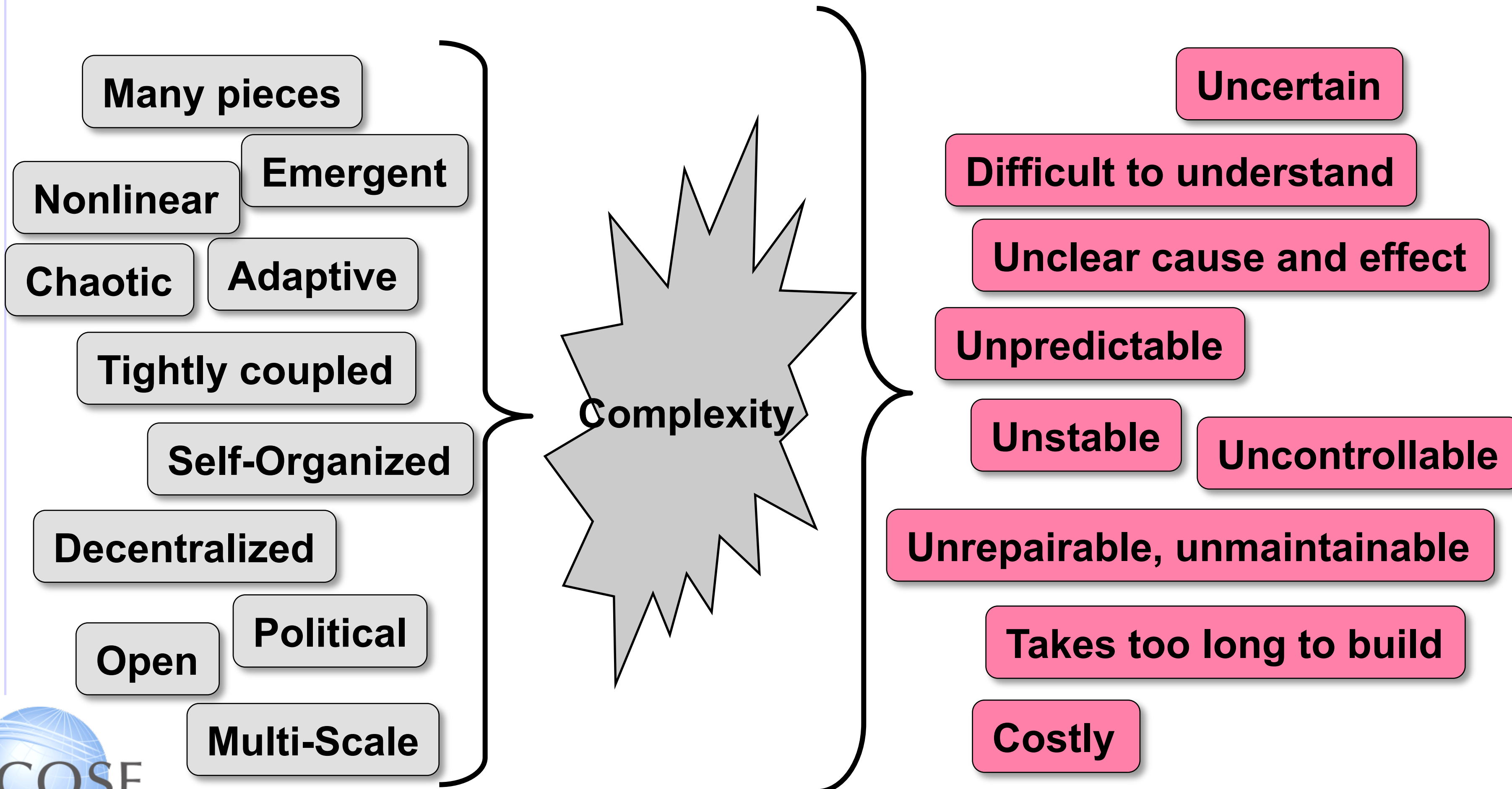
Sources of Complexity

- 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)



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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

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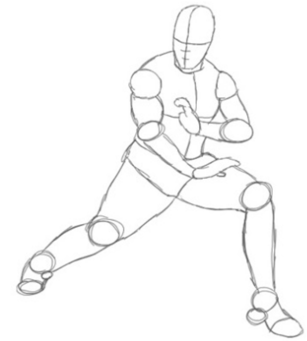

Think like a gardener, not a watchmaker

- 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

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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

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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	

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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

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