System Engineering in the 21st Century - Implications from Complexity Theory

Linda J. Vandergriff, D.Sc.

The Aerospace Corporation

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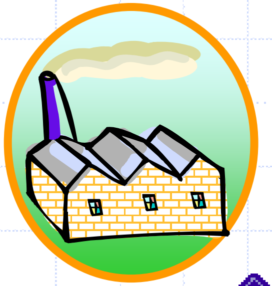
21st Century Environment

- Industrial Age
  - Woolen Mills & Factories
- Physical Capital
- Product Focused
- Characteristics
  - Control
  - Long Floats / Stability
  - Forecasting & Slow change
  - Mass Production
  - Complicated but Decomposable
  - Independent
- MOEs
  - Efficiency
  - Quality



- Intelligence Age
  - Customer Service & Products
- Intellectual Capital
- Customer Focused
- Characteristics
  - Empowerment
  - Short Floats / Edge of Chaos
  - Limited Predictability & Dynamic
  - Responsive Expertise / Adaptability
  - Complex with Emergent Behaviors
  - Interdependent
- MOEs
  - Effectiveness
  - Value

20th Century SE Paradigms cannot fully accommodate 21st Century Realities

Why Should Systems Engineers Study Complexity?

- Complexity science addresses many natural phenomena and modern systems
  - Examples range from ant-hills, ants themselves, to weather and climates, political and economy systems, to technical systems such as the Internet and computers
  - These systems have behavioral and structural features in common
- Provides insight to guide successful acquisitions
  - Traditionally decision problem space assumes a closed system* that is linear, decomposable, and predictable
  - Many new acquisitions are for complex systems are open systems** that violate all three assumptions
    - Nonlinear
    - Interdependent components and with environment
    - Limited forecast horizon

Acquisition of Complex Systems requires more than just good technical System Engineering

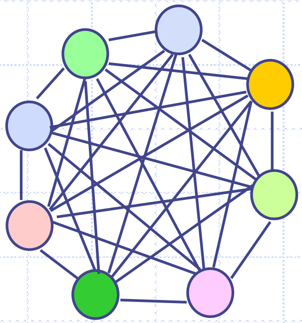
Complicated Versus Complex

- The root of complicated means "to fold"
  - Complicated systems can be decomposed and recombined without loss of function
  - Newtonian mechanics and basic SE are based on this concept that the universe, while complicated, can be decomposed and understood as merely the sum of the pieces
- The root of complex means "to weave"
  - A complex system is woven and if a thread is pulled it unravels
  - A complex system can be composed of simple and/or complicated rules and subsystems
  - A complex system has emergent behavior based upon the interaction and relationships of the parts
  - Rare that parts can be interchanged without changing the nature of the performance in at least a subtle manner

Complicated is the opposite of simple
Complex is the opposite of independent

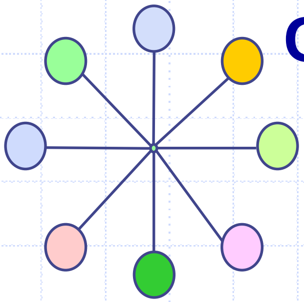
Achieving the Emergent Behavior of Interoperability

Interface Control Documents (ICDs) “Complicated”



- Each interface separately defined
- Evolutionary path prohibitive
  - Never gets cheaper
  - Each new system needs all I/Fs
- Minimal chance that additional system happens to be interoperable

Common interface standards “Simple”



- Standard interfaces
  - Defined once
  - Used by all
- Evolutionary path identified
  - Each system built to the same stds
  - Can evolve in sync if stds evolve
- Better chance that additional system will be interoperable

Both can be complex systems, one is complicated the other simple.

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How are Complexity and Chaos related?

Complex Adaptive System (CAS) research has shown system behavior falls into four distinct classes

Zones of Chaos or Complexity Behavior Classes

Class I – Steady State	SE Practices needed
Class II – Static Patterns	SE Practices needed
Class III – Wild Variations ("Chaos")	+ Robustness needed
Class IV* – Extended Transients	+ Agility needed

*Actually operates between Class II and Class III

Focus is on how to acquire systems in Class IV or "the edge of chaos"

Complex System Attributes

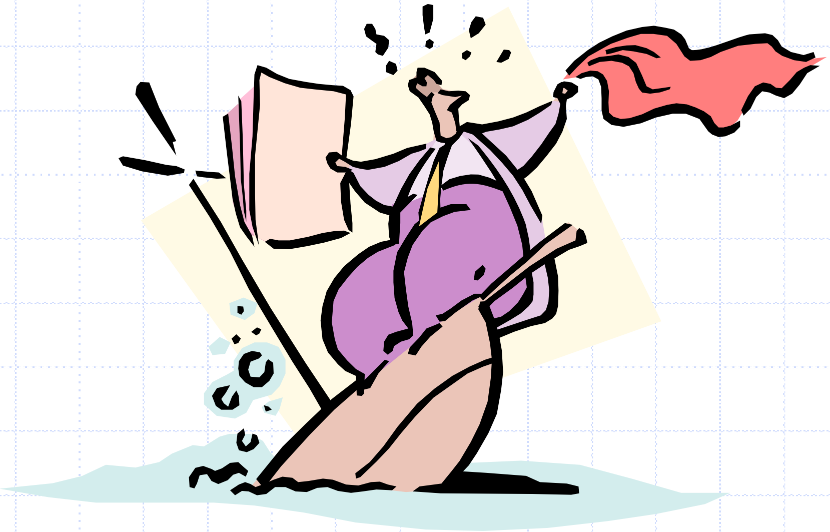
Complex System Definition: The term complex system formally refers to a system of many parts which are coupled in a nonlinear fashion. Natural complex systems are modeled using the mathematical techniques of dynamical systems, which include differential equations, difference equations and maps. Because they are nonlinear, complex systems are more than the sum of their parts because a linear system is subject to the principle of superposition, and hence is literally the sum of its parts, while a nonlinear system is not. (Wikipedia 2006)

- Interconnectedness with the environment and itself
- Non-linearity of coupling
- Emergence of system properties and behaviors
- Self-organization to adapt to “fit”ness landscape

Complex System Attributes - Interconnectedness

Interconnectedness with the environment and itself

- System and Environment co-evolve because it is an open system
- Short term trends, long term high uncertainty
- Boundaries are difficult to determine due to interaction across the boundaries
- History and prior states may have an influence on future states (hysteresis)
- Contains feedback loops (damping & amplifying feedback) potential for unexpected cascading catastrophic failures



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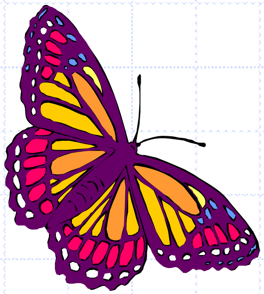
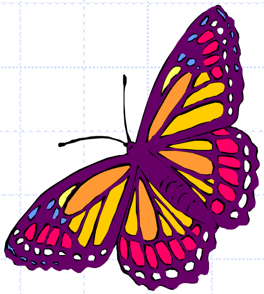
Complex System Attributes – Non-linearity



> ***"Will a Butterfly flapping its wings in Brazil, cause a Tornado in Texas?"***
> ***Lorenz***



Non-linearity

- Small perturbation may cause a large effect (butterfly effect) (Little money, large benefit)
- Large perturbation may cause little or no effect (Lots of money, no benefit)
- Modeling of a system is less reliable, never enough parameters
- Use cases provide insight but not predictability

Complex System Attributes - Emergence

Emergence

- Complex systems more than the sum of the individual parts
- Can be a dynamic process (occurring over time), such as the evolution over thousands of successive generations
- Can happen over disparate size scales, such as the neurons interactions in a human brain capable of thought (even though the constituent neurons are not individually capable of thought)
- Simple rules produce complex behaviors and vise versa
- Technology in combination provide benefit (e.g. lasers & fiber optics)

Emergence is the appearance of a property or behavior not previously observed as a functional characteristic of the system components

Complex System Attributes – Self-organization

Self-organization

- Leadership and vision enable adaptation to changing environment
- Diverse agents competing provide best fit solutions - need empowerment
- Diverse agents interacting can lead to innovation and better solutions

Need clear and consistent channels of communication such as effective architecture products, intelligence management tools, and Communities of Practice.

Complex System Tips for System Engineers

- Lead with clear and consistently communicated enterprise-wide vision
  - Require clear definition of roles, responsibilities, and authority
  - Use architecture products to inform stakeholders (agents) decision-making and trace decision implementation
  - Provide architecture vectors with appropriate metrics help guide lower decisions
- Address rapidly changing environments and the co-evolutionary systems
  - Focus on needed capabilities early and delay technology implementations
  - Set key acquisition goals as agility and effectiveness versus efficiency
  - Assume minimal predictability with many potential futures
  - Buy insurance with options when indicated and terminate options when no longer needed
- Institute tiered situationally aware decision-making in both time and place
  - Provide guidance and institute incremental changes
  - Integrate situational awareness and implementation monitoring
  - Ensure cross-disciplinary and virtual enterprise communications
- Address system factors contributing to success and failure
  - Examine Doctrine, Organization, Training, Materiel, Leadership & Education, Personnel, and Facilities (DOTMLPF) solutions
  - Identify potential use cases, scenarios, sources of cascading failures, and other similar systems