Role of Complexity in Resilience

Presented by Mr. Kenneth Cureton to the

INCOSE Resilient Systems Working Group (RSWG) Webinar

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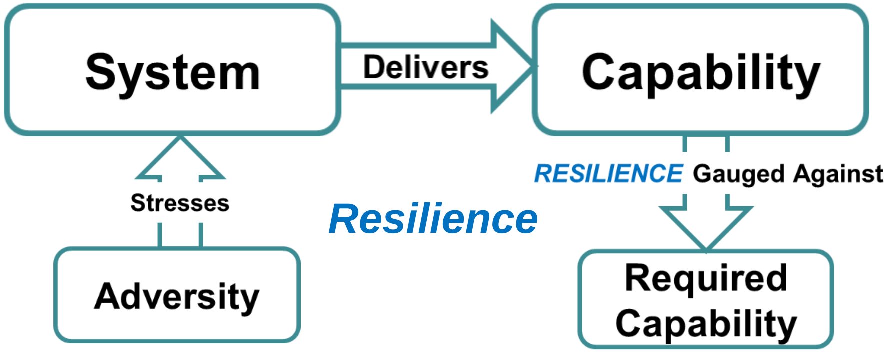
INCOSE Resilient Systems Working Group and other sources as marked at the bottom of slides

What is System Resilience?

System Resilience is the ability of an Engineered System to provide required capability when facing adversity



- **As defined by International Council on Systems Engineering (INCOSE) Resilient Systems Working Group (RSWG)**
- **Adversity is ANY condition that may potentially impact or degrade the desired capability of a system**

Source: INCOSE RSWG https://www.incose.org/communities/working-groups-initiatives/resilient-systems

Achieving System Resilience

- **The Three Objectives to obtain the Value of Resilience: (Taxonomy Layer 1)**
  - ***Avoid*** **adversity**
  - ***Withstand*** **adversity**
  - ***Recover*** **from adversity**
- **Means of achieving Objectives: (Taxonomy Layer 2)**

✔ • *Adaptive Response*	• *Integrity*	• *Tolerance*
✔ • *Agility*	✔ • *Manage Complexity* ⬅	• *Transform*
• *Anticipation*	• *Prepare For*	• *Understand*
• *Constrain*	• *Prevent*	
• *Continuity*	• *Re-architect*	
• *Disaggregation*	• *Redeploy*	
✔ • *Evolution*	• *Robustness*	
• *Graceful Degradation*	• *Situational Awareness*	

✔ Typically found in Complex Systems

Source: INCOSE Systems Engineering Body of Knowledge (SEBoK) https://sebokwiki.org/wiki/System_Resilience
(see SEBoK System Resilience section references for more details)

Means of Achieving Resilience Objectives (6 of 6)

Taxonomy Layer 3: *Architecture, Design, & Operational Techniques to Achieve Resilience Objectives*

- absorption
- buffering
- defense in depth
- diversification
- ✔ dynamic representation
- internode interaction & interfaces
- modularity
- physical & functional redundancy
- protection
- ✔ repairability (self-repairability)
- segmentation
- threat suppression
- analytic monitoring & modeling
- coordinated defense
- detection avoidance
- drift correction
- effect tolerance
- least privilege
- neutral state or safe state
- privilege restriction
- realignment
- replacement
- substantiated integrity
- unpredictability
- boundary enforcement
- deception
- distribution
- ✔ dynamic positioning
- ✔ human participation (in the loop)
- ✔ loose coupling
- non-persistence
- proliferation
- reconfiguring
- ✔ restructuring (self-restructuring)
- substitution
- virtualization

✔ Typically found in Complex Systems

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(see SEBoK System Resilience section references for more details)

What are Complex Systems?

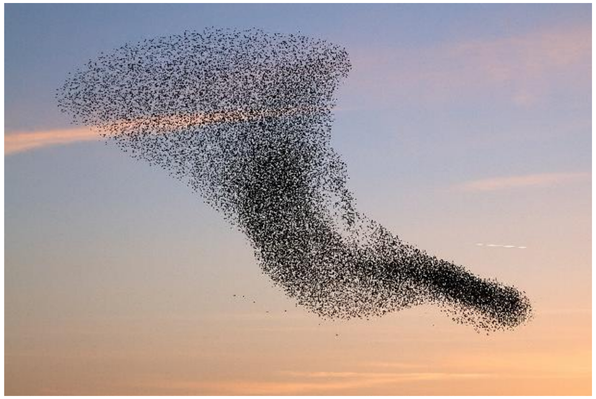
- A **Simple System** has elements, the relationship between the states of which, once observed, are readily comprehended
- A **Complicated System** has elements, the relationship between the states of which can be unfolded and comprehended, leading to sufficient certainty between cause and effect
- A **Complex System** has elements, the relationship between the states of which are weaved together so that they are not fully comprehended, leading to insufficient certainty between cause and effect
  - As seen by this definition, traditional systems engineering approaches, which assume some form of order and deterministic behavior so the relationship between cause and effect is understood, do not handle complex systems engineering well (Especially for Complex Adaptive Systems)
- Note that a System may have portions that are Simple, Complicated, and Complex– and those portions may change!

Note– these definitions are currently being refined by the INCOSE Complex Systems Working Group (CSWG)

Source: INCOSE Complex Systems Working Group-- A Complexity Primer for Systems Engineers Revision 1 2021
Available to INCOSE members at INCOSE Store: https://connect.incose.org/Pages/Product-Details.aspx?ProductCode=ComplexPrimer

What is Emergent Behavior in Complex Systems?

- ***Expected Emergence*** **(weak emergence) which is desired (or at least allowed for) in the system structure**
  - **Preferably Beneficial, Desirable, or Value-adding but may be Undesirable**
  - **Example: Murmuration of Birds**
    "Winging at speeds of up to 40 miles per hour, an entire flock of birds can make hairpin turns in an instant"
    - **Interaction between individual birds based on visual cues**
    - **Safety in numbers-- birds that stay together tend to survive together**



- ***Unexpected Emergence*** **(strong emergence) for emergence not observed until the system is simulated or tested or until the system encounters in operation a situation that was not anticipated during design and development**
  - **Often Undesirable but possibly may be Beneficial, Desirable, or Value-adding**

Note– these definitions are currently being refined by the INCOSE Complex Systems Working Group (CSWG)

Source: INCOSE Systems Engineering Body of Knowledge (SEBoK) https://sebokwiki.org/wiki/Emergence
(see SEBoK Emergence section references for more details)

How can Resilience Impact Complex Systems?

- **Many Means of achieving Resilience Objectives (Taxonomy Layer 2) may impact a Complex System in Positive or Negative ways**
  - **Especially "Manage Complexity"**
    - **Goal: System Complexity not "unnecessarily complex"– i.e., only that level of complexity required to achieve performance objective, resilience objectives, and encourage *beneficial* emergent behavior**
    - **Not necessarily "eliminate complexity"**
  - **Complex System characteristics (especially Emergent Behavior) may also impact System Resilience**
    - **Goal: Avoid "Brittle Modes" through comprehensive system-level modeling, simulation, and testing-- then iterate the system design or operational procedures until an affordably acceptable level of system resilience is achieved**
- **Many Architecture, Design, & Operational Techniques to Achieve Resilience Objectives (Taxonomy Layer 3) may also impact a Complex System in Positive or Negative ways**
  - **Similar goals as above**

Complex Networked System Architecture Characteristics

Now to focus on Resilience in Popular Complex Systems:

- Complex Networked Systems (e.g., The Internet)

- **Seven Critical Characteristics:**

  1) **Clustered Element (Node) Interaction**
     - Only a few nodes interact to achieve a particular capability, other clusters of nodes may be interacting at the same time for to achieve similar or different capabilities in parallel
       - Taxonomy Layer 3 "Loose Coupling" applied here
  2) **Nonlinear Interaction**
     - Local "Cause-and-Effect" are not Linearly Related
     - Interaction between nodes strongly affected by internal/external system interactions (feedback)
       - Taxonomy Layer 2 "Adaptive Response", "Agility" and "Evolution" applied here
       - Taxonomy Layer 3 "Restructuring" applied here

Derived from: James Moffat, "Complexity Theory and Network Centric Warfare," The DoD Command & Control Research Program (CCRP) publication (September 2003) ISBN 1-893723-11-9 http://dodccrp.org/files/Moffat_Complexity.pdf

Complex Networked System Architecture Characteristics

- **7 Critical Characteristics (continued):**
  3) **Decentralized Control**
     - **Most interactions between nodes is based on local coevolution (nodes evolving based on interaction with related nodes)**
     - **Guided by a central authority, but not rigidly controlled by that authority**
       – **Taxonomy Layer 2 “Adaptive Response”, “Agility” and “Evolution” applied here**
       – **Taxonomy Layer 3 “Loose Coupling” applied here**
  4) **Nonequilibrium Order**
     - **System is usually “off balance” in terms of space/time correlations of external interactions: System Dynamics oscillation, no overall long-term steady state**
     - **Typically reactive to stimuli (but according to action plans)**
       – **Taxonomy Layer 2 “Adaptive Response”, “Agility” and “Evolution” applied here**
       – **Taxonomy Layer 3 “Loose Coupling” applied here**

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Complex Networked System Architecture Characteristics

- **7 Critical Characteristics (continued):**
  5) Adaptation
     - System is constantly adapting to internal and external stimuli
     - Clusters or avalanches of local interaction constantly being created and dissolved across the System
     - Bottom-up correlation effects in space and time, usually not from top-down imposition of general policy/procedure
       - Taxonomy Layer 2 “Adaptive Response” and “Evolution” applied here
       - Taxonomy Layer 3 “Loose Coupling” applied here
  6) Collectivist Dynamics
     - Ability of nodes in the System to locally influence each other, and for those effects to “ripple” through the System and its environment-- exhibits Nonlinear, Emergent, Adaptive behavior
     - Allows continual feedback between evolving states of nodes in the System
       - Taxonomy Layer 2 “Adaptive Response” and “Evolution” applied here

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Complex Networked System Architecture Characteristics

- **7 Critical Characteristics (continued):**

  7) **Self-Organization & Clustering**

     - **Typically a large number of locally-interacting nodes, each evolving in response to the environment created by the rest of the System and according to the Ecosystem in which the System resides**
     - **Typical response is to evolve in mostly-parallel paths (coevolution)**
     - **Typically resulting in clustering of coevolving nodes**
     - **Enables Emergent Behavior**
       - **Taxonomy Layer 2 “Adaptive Response”, “Agility” and “Evolution” applied here**
       - **Taxonomy Layer 3 “Loose Coupling” and “Restructuring” applied here**

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Influencing Emergent Behavior in Complex Networked Systems

Four Principles of Emergence: (in Complex Networked Systems)

P1: Condition of Emergence

- **An avalanche condition, or a critical state, has to exist prior to the occurrence of emergence (typically related to the number of cooperating nodes)**
  - **Too few nodes: unlikely to support emergence**
  - **Too many nodes overall: propensity to split into a set of smaller cooperating nodes (analogy: Work environment with many potential members)**
  - **Too many cooperating nodes in a set: likely to stifle emergence (analogy: Work Teams with too many assigned members)**

P2: Emergent behavior is inversely proportional to the degree of bondage between systems

- **The more tightly the component nodes are coupled, the less likely that the global emergent behavior will prevail**
  - **Emergent behaviors (generally) do not arise in closed hierarchically structured systems (analogy: Military Teams in drill conditions)**

Source: http://www.incose.org/chicagoland/docs/LA/Emergent%20Behavior%20of%20SoS.pdf
"Emergent Behavior of Systems-of-Systems" by John C. Hsu & Marion Butterfield, February 7 2009, 2009 Mini-Conference of INCOSE LA Chapter

Four Principles of Emergence: (continued)

P3: Emergent behavior is non-linear

- Emergent behavior is more than the sum of added component systems
  - The output is not proportional to the inputs (analogy: Work Teams, Sport Teams – where adding one highly-effective person or removing one disruptive person often has a significant impact on the entire Team)

P4: Emergent behavior is self-organized

- Self-organization is a process in which the internal organization of a system increases in complexity without being dictated by an outside source
  - Outside source may be a central authority that provides general guidance but not rigidly-dictated rules (analogy: Work Teams, Sport Teams– often operating according to standard procedures or "play books" but not micro-managed)

Source: http://www.incose.org/chicagoland/docs/LA/Emergent%20Behavior%20of%20SoS.pdf
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Influencing Emergent Behavior in Complex Networked Systems

- **Anticipated Desirable/Undesirable Emergent Behavior (expected)**
  - **Typically a design or operational goal: encourage desirable emergent behavior; discourage undesirable emergent behavior**
  - **Note: usually cannot guarantee that desirable emergent behavior WILL occur– can only try to optimize P1, P2, P3, and P4 conditions**
    - **Resilient Systems Engineering should focus on those conditions**
  - **Note: usually cannot guarantee that undesirable emergent behavior will NOT occur– can only try to select stifling P1, P2, P3, and P4 conditions**
    - **Resilient Systems Engineering should focus on those conditions**

Derived From: Madni, Azad M., "Transdisciplinary Systems Engineering: Exploiting Convergence in a Hyper-Connected World", © Springer International Publishing AG 2018, ISBN 978-3-319-62183-8, Library of Congress Control Number: 2017947157

Influencing Emergent Behavior in Complex Networked Systems

- **Unanticipated Desirable/Undesirable Emergent Behavior (unexpected)**
  - **May arise from design conditions but often from system upgrades or modifications; changes in people and their processes**
    - **Resilient Systems Engineering should strive to detect such behavior through comprehensive system-level modeling, simulation, and testing-- then iterate the system design or operational procedures**

Derived From: Madni, Azad M., "Transdisciplinary Systems Engineering: Exploiting Convergence in a Hyper-Connected World",
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Summary

1. **Resilient Systems Engineering & Design can Positively Guide Complex Systems Engineering & Design**
   - **Follow Taxonomy Layer 2 and 3 guidance, especially "Complexity Management"**
   - **Focus on promoting and supporting expected, desirable emergent behavior**
   - **Take steps to effectively stifle unexpected, undesirable emergent behavior**
2. **Complex Systems Engineering & Design often Impacts Resilient Systems Engineering & Design**
   - **Consider critical characteristics of Complex Systems**
   - **Consider conditions of potential emergent behavior**

Questions?

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Backup Slides

Backup Slides follow

Candidate approaches to Emergent Properties or Behaviors in Solution System:

- **Maximize description of emergent properties in scenarios and mission definition**
- **Employ Real-World and Digital Twin experimentation to ensure relevant effects are explored at different levels of aggregation**
- **Acknowledge the limits to the value of decomposition-based methods; emergence is a collective phenomenon that requires aggregation – emergence will not be observed until the system is considered as a whole**
- **Conduct development activities always within context of the whole**
- **Employ collaborative development processes so that information about design decisions are visible throughout the project**
- **Prototyping and holistic testing are critical to explore and check for the manifestation of emergent behavior**

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Applicability to Resilience: Characteristics of Complexity

Characteristic	Definition
Diversity	The structural, behavior, and system state varieties that characterize a system and/or its environments.
Connectivity	The connection of the system between its functions and the environment. This connectivity is characterized by the number of nodes, diversity of node types, number of links, and diversity in link characteristics. Complex systems have multiple layers of connections within the system structure. Discontinuities (breaks in a pattern of connectivity at one or more layers) are often indications of complex system connectivity. Simple and some complicated systems may be characterized by simpler structures such as hierarchies.
Interactivity	The behavior stimulus and response between different parts of a system and the system with its environment. Complex systems have many diverse sources of stimulus and diverse types of responses. The correlation between stimulus and response can be both direct and indirect (perhaps separated by many layers of system connectivity). The types of stimuli and responses vary greatly. The levels of stimuli and responses can range from very subtle to very pronounced. The timeframe for system responses can vary hugely.
Adaptability	Complex systems proactively and/or reactively change function, relationships, and behavior to balance changes in environment and application to achieve system goals.
Multiscale	Behavior, Relationships, and Structure exist on many scales, are ambiguously coupled across multiple scales, and are not reducible to only one level.
Multi-perspective	Multiple perspectives, some of which are orthogonal, are required to comprehend the complex system.
Behavior	Complex system behavior cannot be described fully as a response system. Complex system behavior includes nonlinearities. Optimizing system behavior cannot often be done focusing on properties solely within the system.
Dynamics	Complex systems may have equilibrium states or may have no equilibrium state. Complex system dynamics have multiple scales or loops. Complex systems can stay within the dynamical system or generate new system states or state transitions due to internal system changes, external environment changes, or both. Correlation of changes in complex systems to events or conditions in the system dynamics may be ambiguous.

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Applicability to Resilience: Characteristics of Complexity

Characteristic	Definition
Evolution	Changes over time in complex system states and structures (physical and behavioral) can result from various causes. Complex system states and structures are likely to change as a result of interactions within the complex system, with the environment, or in application. A complex system can have disequilibrium (i.e., non-steady) states and continue to function. Complex system states and structures can change in an unplanned manner and can be difficult to discern as they occur. The changes in the states and structure of a complex system are a natural function of (is often present in) the complex system dynamics. Changes can occur without centralized control, due to localized responses to external and/or internal influences.
System Emergence (general)	Features/behavior associated with the holistic system that are more than aggregations of component properties.
Unexpected Emergence (Complex)	Emergent properties of the holistic system unexpected (whether predictable or unpredictable) in the system functionality/response. Unpredictable given finite resources. Behavior not describable as a response system. (Covered on next slide)
Disproportionate Effects	Details seen at the fine scales can influence largescale behavior. Small scale modifications can result in radical changes of behavior. Scale can be in terms of magnitude of effect or aggregate amount of change. Weak ties can have disproportionate effects.
Indeterminate boundaries	Complex system boundaries are intricately woven with their environment and other interacting systems. Their boundaries can be non-deterministic. The boundary cannot be distinguished based solely on processes inside the system.
Contextual Influences	All systems reside in natural and social environments and relate to these. In the relationship between the system and the natural and social environments there can be complexity. This complex interaction depends on the social application of the system. Social systems often strive to achieve multiple, sometimes incompatible, objectives with the application of the same system.

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