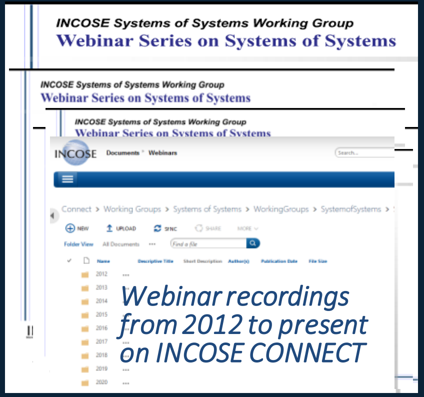
Systems of Systems & Complexity
INCOSE SoS Working Group Initiative

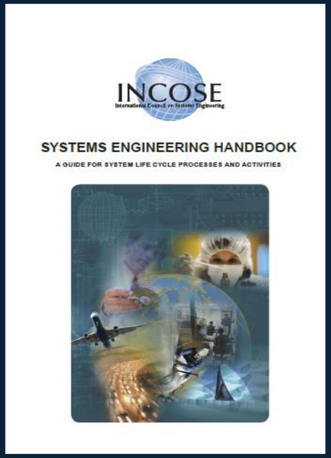
Dr. Judith Dahmann

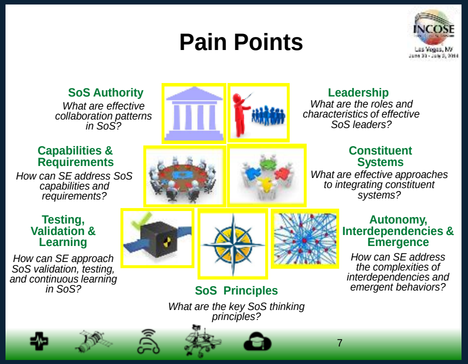
December 2021

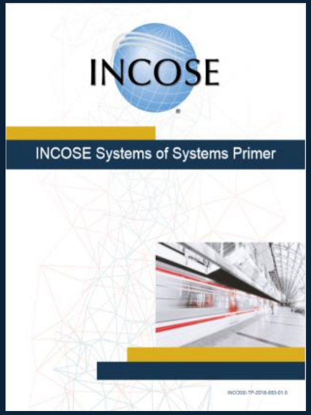
MITRE | SOLVING PROBLEMS FOR A SAFER WORLD

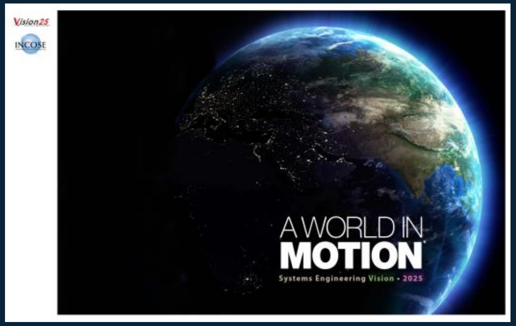
INCOSE Systems of Systems Working Group

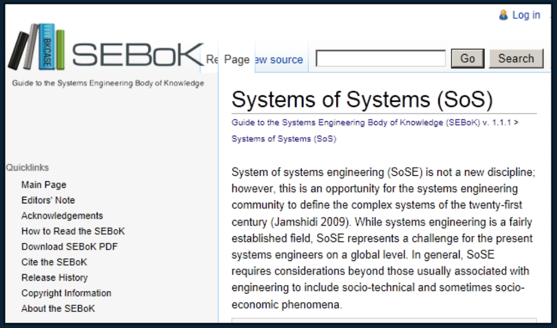




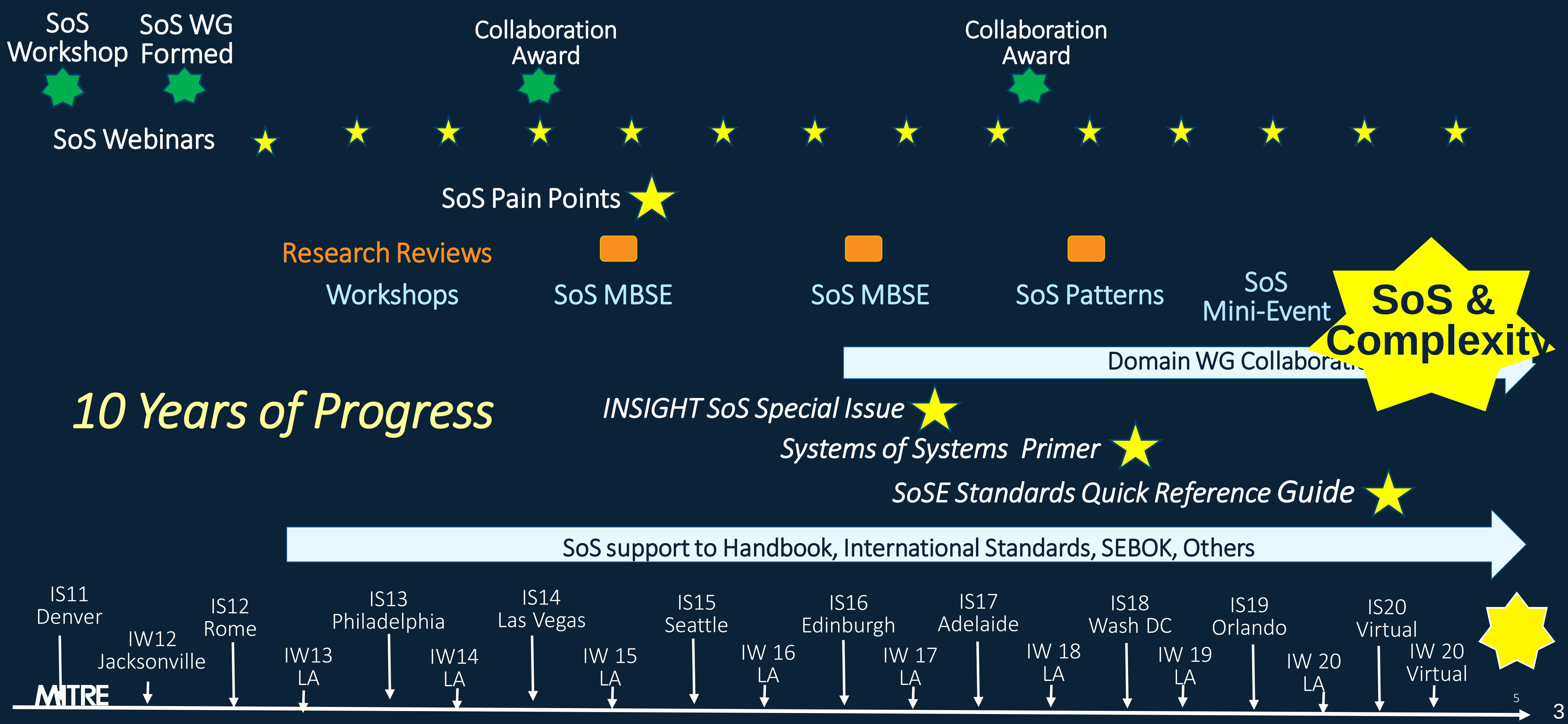








SoS Working Group Activities in Review



Systems of Systems & Complexity Project Core Team


Judith Dahmann


Eric Honour


Dan DeLaurentis


Ali Raz


Stephen Cook

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Systems of Systems and Complexity

“emergence is noted as a common characteristic of SoS particularly in SoS composed of multiple large existing systems, based on the challenge (in time and resources) of subjecting all possible logical threads across the myriad functions, capabilities, and data of the systems in an SoS.

.... there are risks associated with unexpected or unintended behavior resulting from combining systems that have individually complex behavior. These become serious in cases which safety, for example, is threatened through unintended interactions among the functions provided by multiple constituent systems in a SoS.”

https://www.sebokwiki.org/wiki/Systems_of_Systems_(SoS)

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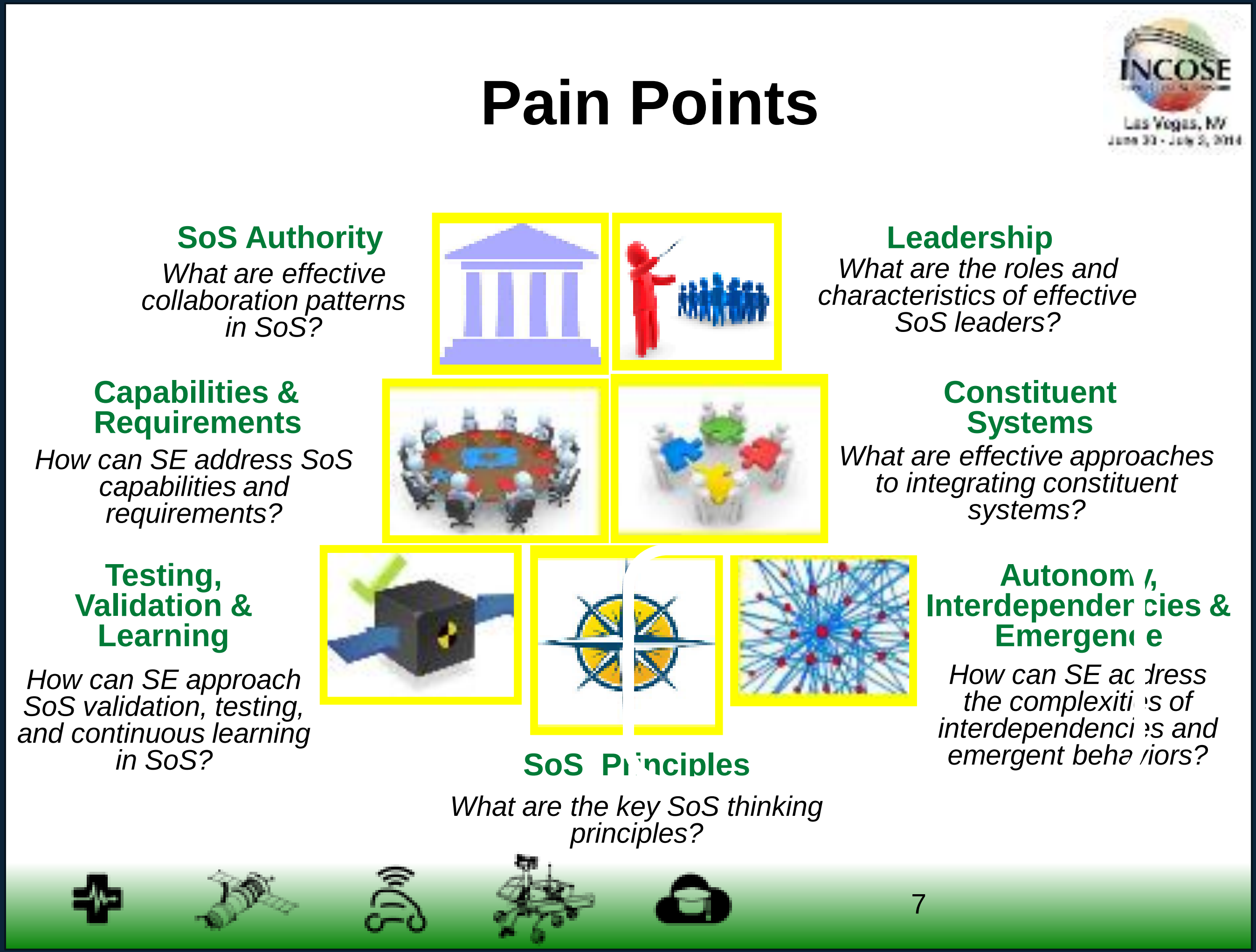
SoS Complexity



Taming Complexity:
A System of Systems Challenge

Complex Adaptive Systems Conference

Baltimore, MD
November 2011

Sources of SoS Complexity

- Systems
- Users/stakeholders
- Development
- Operations

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Technical Complexity Across Systems

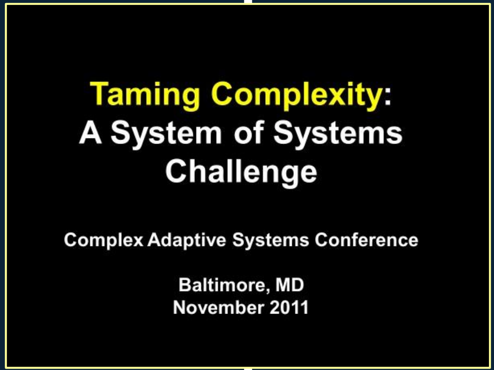
Diversity in system concept, design, control structures, data syntax, semantics…..

User/Stakeholder Complexity

Independent system owners and stakeholders with their own goals, objectives, motivations……

SoS Development Complexity

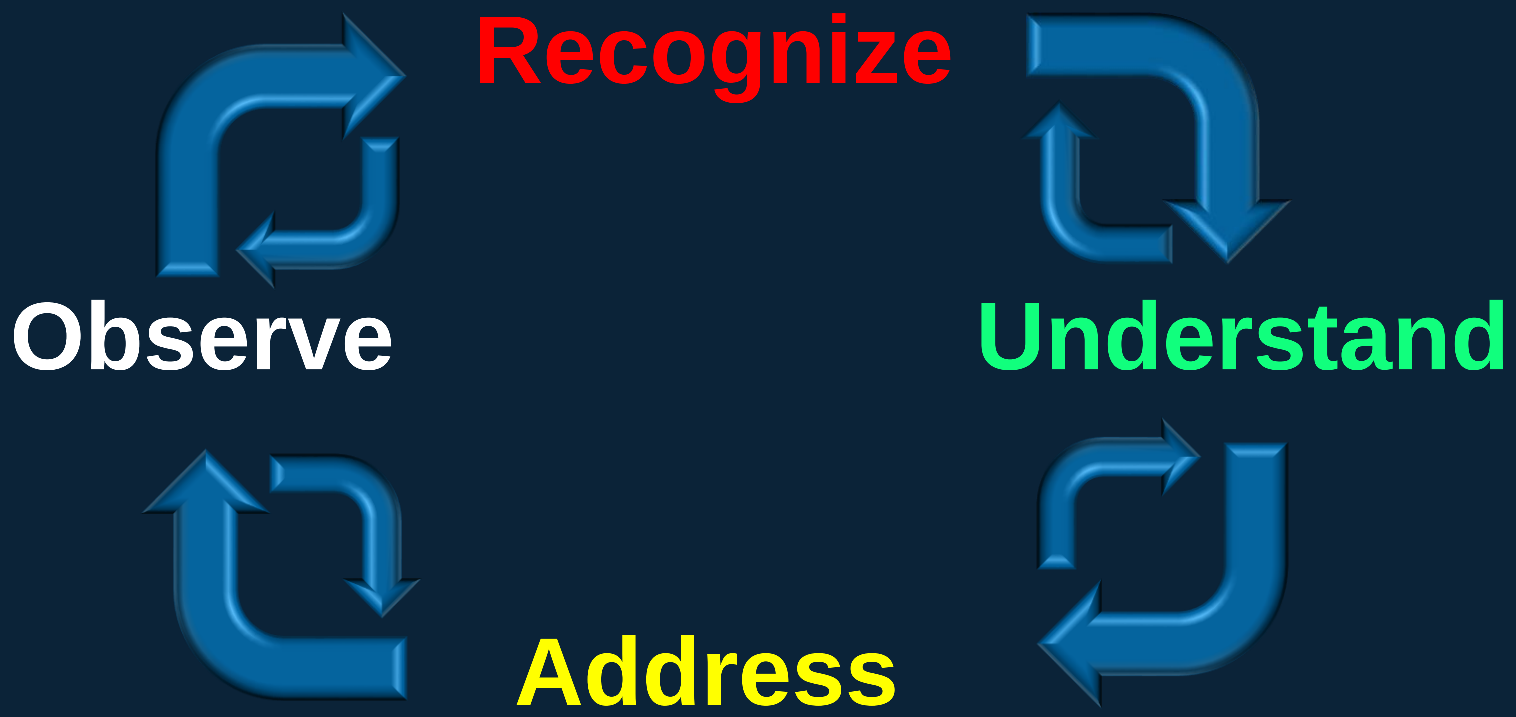
Dynamics of asynchronous development



Complex Operational Dynamics

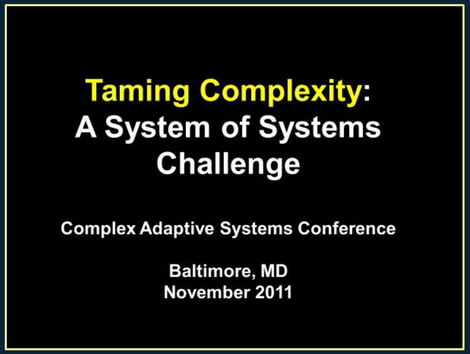
Dynamics of independent operations

Addressing SoS Complexity



Where others see **complexity,** the person of action sees the thing that needs to be done.

Michael Lipsey


Taming Complexity:
A System of Systems Challenge

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Time to go beyond "observe" -- admiring the problem

Partnership with Complexity Working Group

29th Annual INCOSE international symposium
Orlando, FL, USA
July 20 - 25, 2019

Appreciative Methods Applied to the Assessment of Complex Systems

1. Diversity
2. Connectivity
3. Interactivity
4. Adaptability
5. Multiscale
6. Multi-perspective
7. Behavior
8. Dynamics
9. Representation
10. Evolution
11. Emergence
12. Disproportionate effects
13. Indeterminate boundaries
14. Contextual influences

Dimensions of Complexity

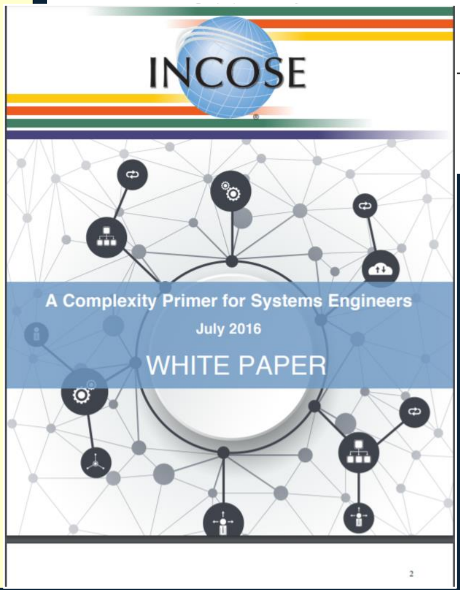
A. COMPLEXITY THINKING: GUIDING PRINCIPLES

1. Think like a gardener, not a watchmaker.
2. Combine courage with humility.
3. Take an adaptive stance.
4. Use free order.
5. Identify and use patterns.
6. Zoom in and zoom out.
7. See through new eyes.
8. Collaborate
9. Achieve Balance.
10. Learn from problems.
11. **Mega-cognition.**
12. Focus on desired regions of outcome space rather than specifying detailed outcomes.
13. Understand what motivates autonomous agents.
14. Maintain adaptive feedback loops.

Guiding Principles

Table 1. Candidate approaches to address complexity in problem context or environment.

	Requirements Elicitation and Derivation	Trade Studies	Solution Architecture and Design	Development Process
Complexity in the environment - General	Use multiple methods for requirements elicitation Elicit requirements from multiple perspectives and at multiple levels of aggregation	Emphasize robustness over local efficiency and performance	Include both positive and negative feedback mechanisms to provide mechanisms to compensate for the effects of higher-than-linear positive feedback and runaway system behavior	Employ soft systems methodologies to surface the nature of the problem space, its internal structure and information flows, and produce simple representations, eg 'rich pictures' to communicate these.
			Early implantation (or at least prototyping) of external interfaces	Early deployment of system functionality with feedback to developers



Candidate Approaches

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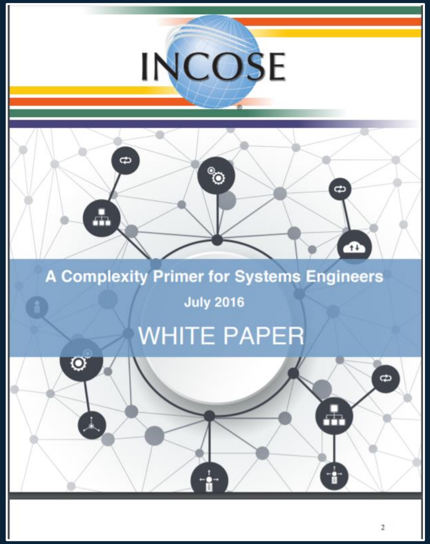
Complexity WG offers foundational material to address SoS Complexity

INCOSE SoS & Complexity Project

Apply Complexity concepts to address Systems of Systems Complexity Challenges



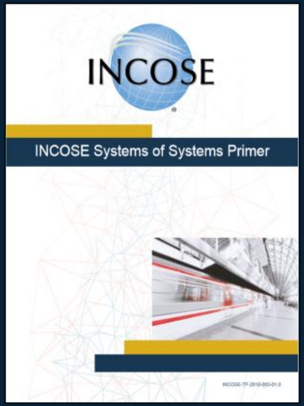
Practical application of

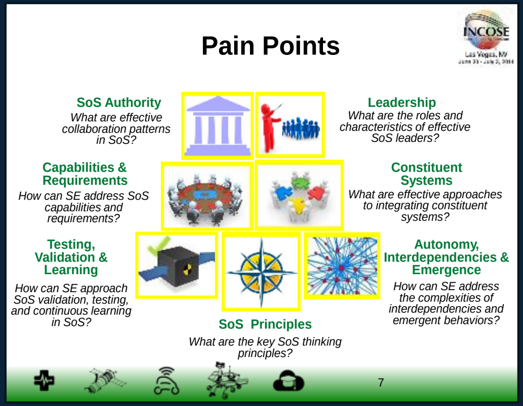
- Complexity dimensions
- *Guiding Principles for complexity thinking*
- *Candidate approaches to addressing complexity*

Practical approaches to

- identifying
- understanding
- addressing

Systems of systems complexity





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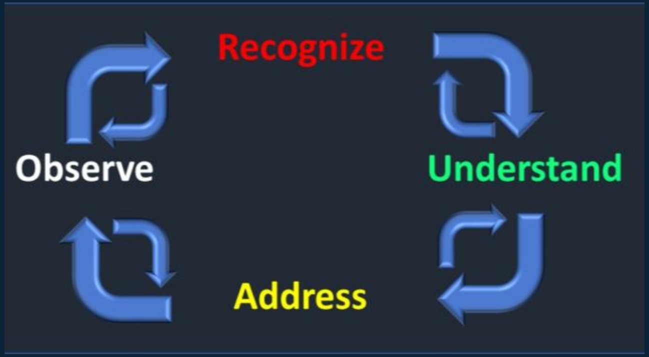
‘Recognize’ and ‘Understand’



How and why are SoS characterized by different dimensions of complexity?

Dimension	Definition[1]	How SoS Exhibit…	Why?
Diversity	*The structural, behavior, and system state varieties that characterize a system and/or its environments*	SoS can exhibit tremendous diversity across the various constituent systems which provide a range of different behaviors, functionality and technical approaches.	By definition, SoS are comprised of multiple independent systems with their own users, management structures, requirements etc. often developed prior to their membership in an SoS, increasing the likelihood that there will be differences among the constituents of an SoS.
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.*	SoS include connectivity within each constituent system, among constituents in the SoS and between the SoS and its environment.	SoS are comprised of “connected” constituent systems, so in addition to the connectivity within each constituent, an SoS by its nature is characterized by additional connectivity among constituents. SoS typically have large numbers of nodes, a diversity of node types, a large number of links, and diversity in link characteristics, as well as multiple layers of connections within the system structure. Discontinuities (breaks in a pattern of connectivity at one or more layers) are often found in SoS.

Guiding Principles to Complexity Thinking Applied in Systems of Systems

Name	Guiding Principles to Complexity Thinking	Relevance to SoS
Use free order	*In architecting and designing solutions, build in “order for free” using self-organization, presuming it has been modeled and can be limited to desired effects. This in particular applies when the system being designed must be resilient*	Particularly in collaborative or virtual SoS, where SoSE may be from within the SoS, understanding (and modeling) the behavior and interactions among constituents may be an effective way to anticipate effects of interest.
Identify and use patterns	*Patterns are exhibited by complex systems, can be observed and understood, and are a key mechanism in the engineering of complex systems. Patterns are the primary means of dealing specifically with emergence and side effects – that is, the means of inducing desired emergence and side effects, and the means of avoiding undesired emergence and side effects.*	Understanding systems, their behaviors and interactions is a core element of SoSE. By modeling these and treating them as opportunities, patterns can be an effective SoSE approach.
Zoom in and zoom out	*Because complex systems cannot be understood at a single scale of analysis, systems engineers must develop the habit of looking at their project at many different scales, by iteratively zooming in and zooming out. Can problems be solved more elegantly by addressing them at a higher or lower hierarchical level? The complex systems engineer must be especially open to solutions that arise from the bottom-up through self-organization, rather than only seeking to impose order from the top-down*	Effective SoSE is often called a ‘middle out’ process, where there is a need to understand the top down drivers for the SoS, but also to respect the bottoms up needs and capabilities of the constituents. The dynamics between these two perspectives reflects the ‘zoom in and zoom out’ principle as reflected in SoSE thinking.

First step was to recognize and understand how complexity dimensions and principles apply to SoS and why

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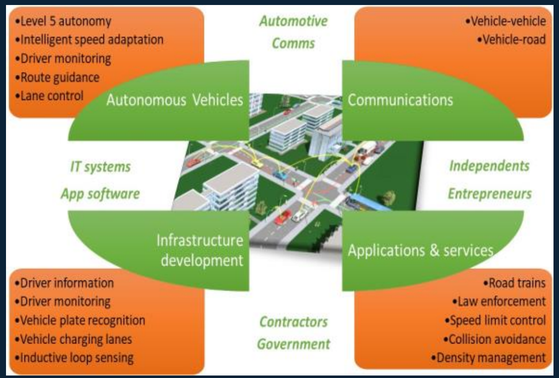
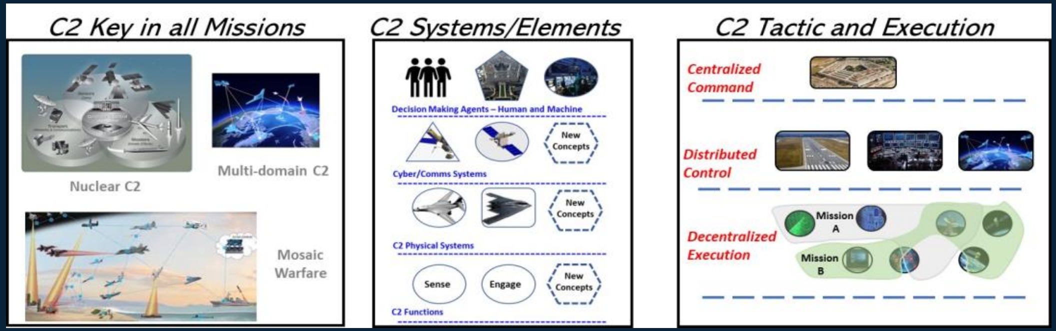
How Do These Complexity Concepts Apply in Context of Selected SoS?

Dimension	Definition	Smart Highways	Defense Command & Control
Diversity	*The structural, behavior, and system state varieties that characterize a system and/or its environments*	▪ **Managing entities live on different planets – different goals, different objectives.** ▪ Humans will not agree. ▪ **System states and state variables highly different but interrelated.** ▪ Vehicle: speed, position, destination ▪ Highway: flow rates, time of day • **Diversity of interfaces** ▪ Independence of the CS managers causes this as a default. • **Some standardization through interoperability.** • **Diverse development methods/processes – infrastructure vs. vehicles vs software** • **Life cycle of the CSs are diverse, ranging from ephemeral (updates in months) to decades** • **Diversity of regulation and laws** • **Diverse incentives**	**Does this apply?** • Yes, by definition, diversity in SoS components/participants is present. • In fact, greater diversity could be an aspiration when putting together the SoS to enrich its capabilities and resilience. **Describe** • Diversity is present from an operational standpoint as well as a composition perspective. • Diversity brings different possibilities to combine different systems in various ways. **Example:** • Search and Rescue: Diversity is present in mission objectives (e.g., going from fire rescue to hurricane). • Training can be diverse as it is difficult to predict all the various mission the ISR will be applied to (e.g., rescue from land slide).



Smart Highways
Eric Honour



Topic of workshops at INCOSE IW 2020 and 2021 IEEE SoSE

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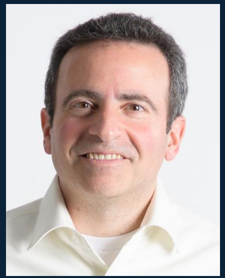


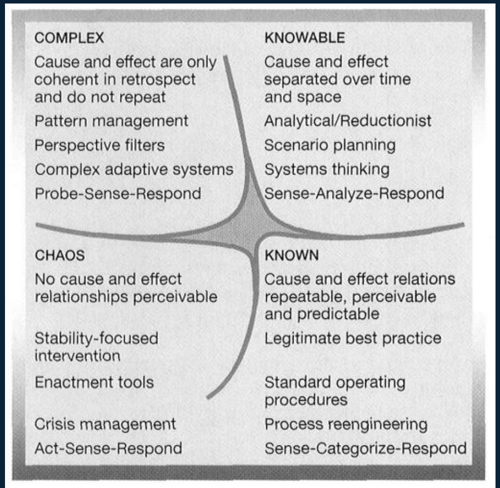
Defense Command and Control
Dan DeLaurentis & Ali Raz

Operationalising our Knowledge of Complexity

Use these ideas to classify the class of SoS challenge and use this knowledge to direct practice

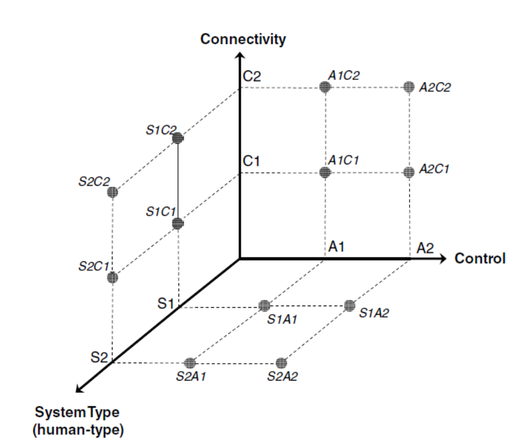
The latter is facilitated through the development of a discipline

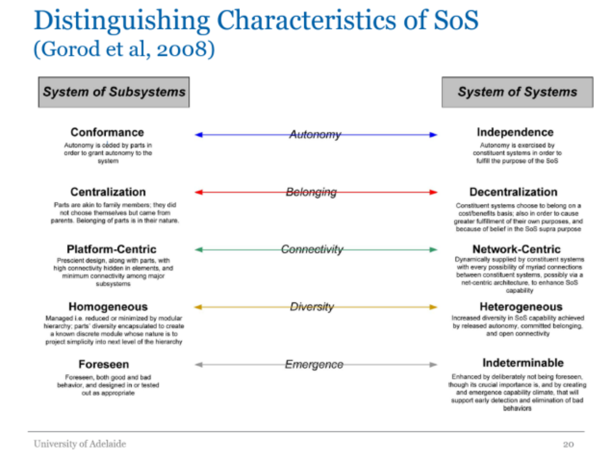
Stephen Cook



Kurtz and Snowden's Cynefin Domains (2003)

Taxonomy to Guide SoS Decision Making (DeLaurentis et al., 2011)



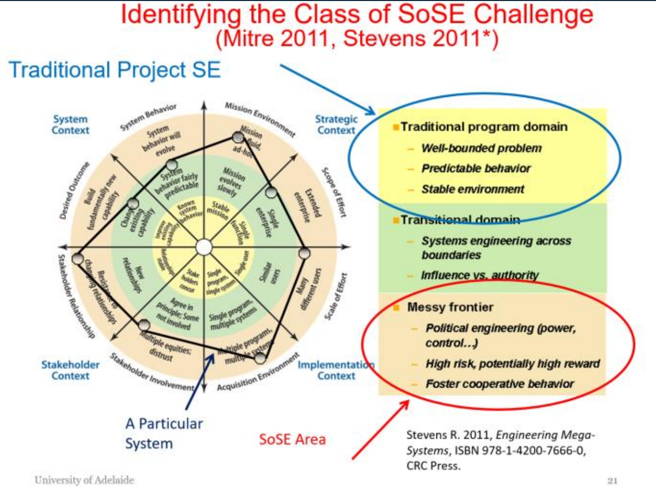


Classifying Dimensions (Cook & Pratt, 2016)

Dimension	Categories
Governance	Virtual, Collaborative, Acknowledged, Directed
Complexity	Based on technical, organizational and system performance complexity. Sets of these can be categorized or the SoS-of-interest can be benchmarked against known SoS, e.g. city transportation system, humanitarian aid deployment, international air traffic control, and the Internet
Degree of Stakeholder Agreement	Unitary, Pluralist, or Coercive
Dynamicity	Benchmark against well-known SoS that compare the dynamicity to constituent system lifetime. Using a change scale such as: slowly, moderately, rapidly
Domain	Key domain area. This need not be a small list e.g. transportation, defence, telecommunications
Level	Start with Hitchins' levels, could make domain specific e.g. business, industry, socioeconomic
Connectivity	Benchmark against well-known SoS, e.g. trucking fleet, global banking system, Internet, air traffic control
Sociotechnical Nature	Benchmark against well-known SoS, e.g. electricity distribution, transportation, international trade
SoS Lifetime	SoS lifetime as a proportion of average life of constituent systems. Scales such as: < 0.1, 0.1-2.0, and > 2.0

Flood and Jackson's Total Systems Intervention (1991)

	Unitary	Pluralist	Coercive
Simple	Operations research Systems analysis Systems engineering Systems dynamics	Social systems design Strategic assumption surfacing and testing	Critical systems heuristics
Complex	Viable system diagnosis General system theory Socio-technical systems thinking Contingency theory	Interactive planning Soft systems methodology	?



SoSE 2021 Panel

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Next Steps