32nd Annual INCOSE international symposium

hybrid event

Detroit, MI, USA
June 25 - 30, 2022

INCOSE Roundtable

Systems of Systems Complexity

www.incose.org/symp2022

Abstract

As part of INCOSE Systems of Systems (SoS) Working Group efforts to work towards development of **practical approaches to address SoS challenges**, there is an ongoing collaboration between the INCOSE Systems of Systems and Complexity Working Groups to identify ways to leverage work coming from the complexity community to address this SE practice area.

In particular, the **INCOSE Complexity Primer** and the recent paper on '**appreciative methods**' provide approaches to characterize and address complexity. In this initiative, these have been viewed through the lens of systems of systems to assess how and why systems of systems exhibit complexity, as the basis for identifying approaches from the complexity community that can guide the application of systems principles to systems of systems. The results of these efforts will be presented in a new **SEBOK article in Emerging Knowledge on 'SoS and Complexity'**

This roundtable will briefly share the results of this working group effort to date and provide a set of perspectives on the nature of SoS complexity addressing a set of questions on the implications of SoS complexity for effective application of systems engineering to SoS and large interconnected systems as presented in the INCOSE SE Vision 2035.

The Panel

Dr. Judith Dahmann

- Technical Fellow, The MITRE Corporation
- Over 25 years experience in modelling and simulation, SE, SoS, and mission engineering
- INCOSE Fellow
- Founder and cochair of INCOSE SoS WG
- jdahmann@mitre.org

Ali Raz

- Asst. Professor Systems Engineering, George Mason University
- Research interests in complex systems, AL/ML, and System of Systems
- Co-Chair Complex Systems Working Group and AI Working Group
- araz@gmu.edu

Dan DeLaurentis

- Professor of Aero/Astro Eng., Purdue University
- Over 25 years experience in research and tech transition in design methods, M&S for aerospace sys., SoS, and mission engineering
- INCOSE Fellow
- Chief Scientist, DoD Sys Eng Res Center (SERC)
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- Over 25 years experience in industrial SE, SE research and teaching, and SoS
- INCOSE Fellow
- Stephen.cook@shoalgroup.com

Jakob Axelsson

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- Research leader, RISE Research Inst. of Sweden
- Research interests in SoS, SE, system architecture, complex systems
- Around 15 years experience from industry, primarily automotive (Volvo)
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Characteristics and Definition of Systems of Systems

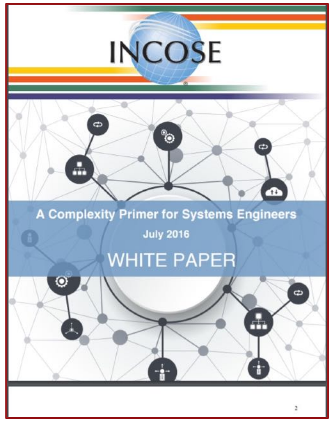
Maier (1998) postulated five key characteristics (not criteria) of SoS: operational independence of component systems, managerial independence of component systems, geographical distribution, emergent behavior, and evolutionary development processes, and identified operational independence and managerial independence as the two principal distinguishing characteristics for applying the term 'systems-of-systems.' A system that does not exhibit these two characteristics is not considered a system-of-systems regardless of the complexity or geographic distribution of its components.

In the Maier characterization, 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. As introduced in the article "Emergence", 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.

Systems of Systems (SoS) - SEBoK (sebokwiki.org)

SoS & Complexity Project

Apply Complexity concepts to address Systems of Systems complexity challenges



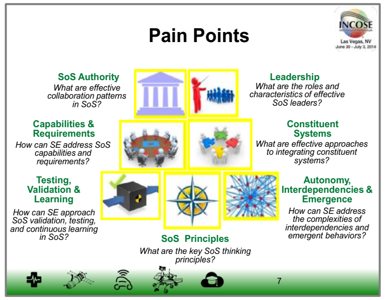
Practical application of

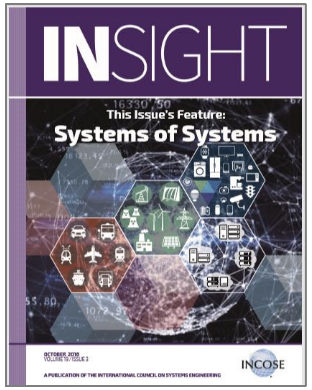
- Complexity dimensions
- *Guiding Principles for complexity thinking*
- *Candidate approaches to addressing complexity*

Practical approaches to

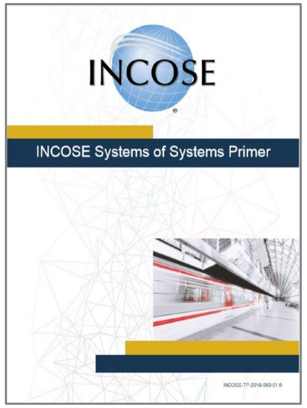
- *identifying*
- *understanding*
- *addressing*

SoS complexity





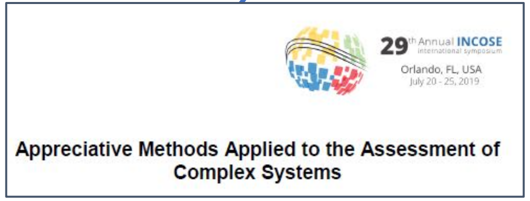
Joint Project of SoS and Complexity WGs



Apply complexity concepts to identify and understand SoS complexity

Appreciative Methods Paper

- Review definitions of the 14 dimensions of complexity
- Provide input on applicability to SoS
  - *How do the complexity characteristics manifests in Systems of Systems and why?*



Complexity Primer

- Review 'Guiding Principles to Complexity Thinking'
- Identify how SoSE incorporates complexity thinking
  - *How do Complexity Principles apply to SoS?*

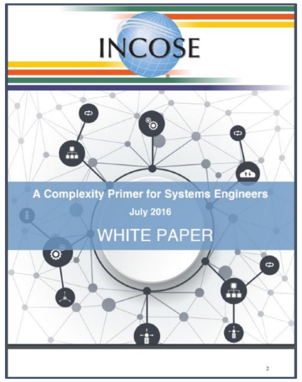
Practical application of

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

Practical approaches to

- *identifying*
- *understanding*
- *addressing*

SoS complexity



Complexity Characteristics from Appreciative Methods Paper

- How do these apply to SoS and why?
- Paper provides definitions and discussions of each characteristic from the perspective of SoS

Characteristic:	How	Why
Diversity		
Connectivity		
Interactivity		
Adaptability		
Multiscale		
Multi-persp		
Behavior (n describable response system)		
Dynamics complex		
Representation difficult		
Evolution		
System Emergence not predictable behavior		
Disproportionate Effects		
Indeterminate Boundaries		
Contextual Influences		

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Appreciative Methods Applied to the Assessment of Complex Systems

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

Provides a starting point for identifying approaches for addressing complexity

Log in

SEBoK GUIDE TO THE SYSTEMS ENGINEERING BODY OF KNOWLEDGE

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Stewards

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- ⊞ Part 2: Foundations of Systems Engineering
- ⊞ Part 3: SE and Management
- ⊞ Part 4: Applications of Systems Engineering

System of Systems and Complexity

System of Systems and Complexity

Lead Author: *Judith Dahmann*

Systems of Systems are generally characterized as complex (Sheard, 2019) (Luzeau et al.,2011) (Simpson, 2009) (DeLaurentis, 2007) (Ireland, 2014) (Magee, 2004), as is noted in the systems of systems (SoS) knowledge area of the SEBoK.

The question for those seeking to perform SoS Engineering (SoSE) then is how to add
complexity? In an ongoing collaboration between the INCOSE SoS and Complexity Wo
work on characterizing complexity has been applied to SoS, to assess how and why So
the basis for identifying approaches from the complexity community to applications of s
systems of systems. This collaboration was spurred by recent work in both communitie
understand how complexity affects systems of systems (Watson, 2020) and guiding principles to complexity thinking can be applied in Systems of Systems Engineering. (INCOSE, 2016)

Contents [hide]

Provides a starting point for identifying approaches for addressing complexity

https://www.sebokwiki.org/draft/System_of_Systems_and_Complexity

Dan DeLaurentis

- Professor of Aero/Astro Eng., Purdue University
- Over 25 years experience in research and tech transition in design methods, M&S for aerospace sys., SoS, and mission engineering
- INCOSE Fellow
- Chief Scientist, DoD Sys Eng Res Center (SERC)
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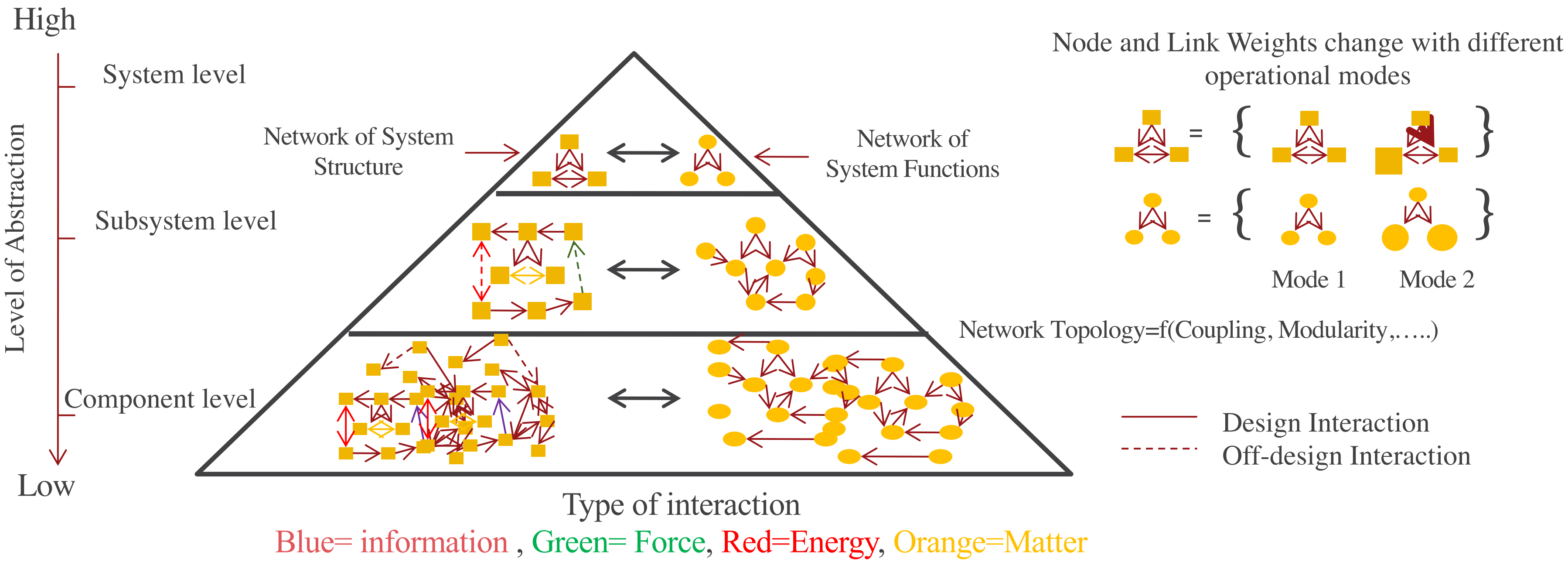
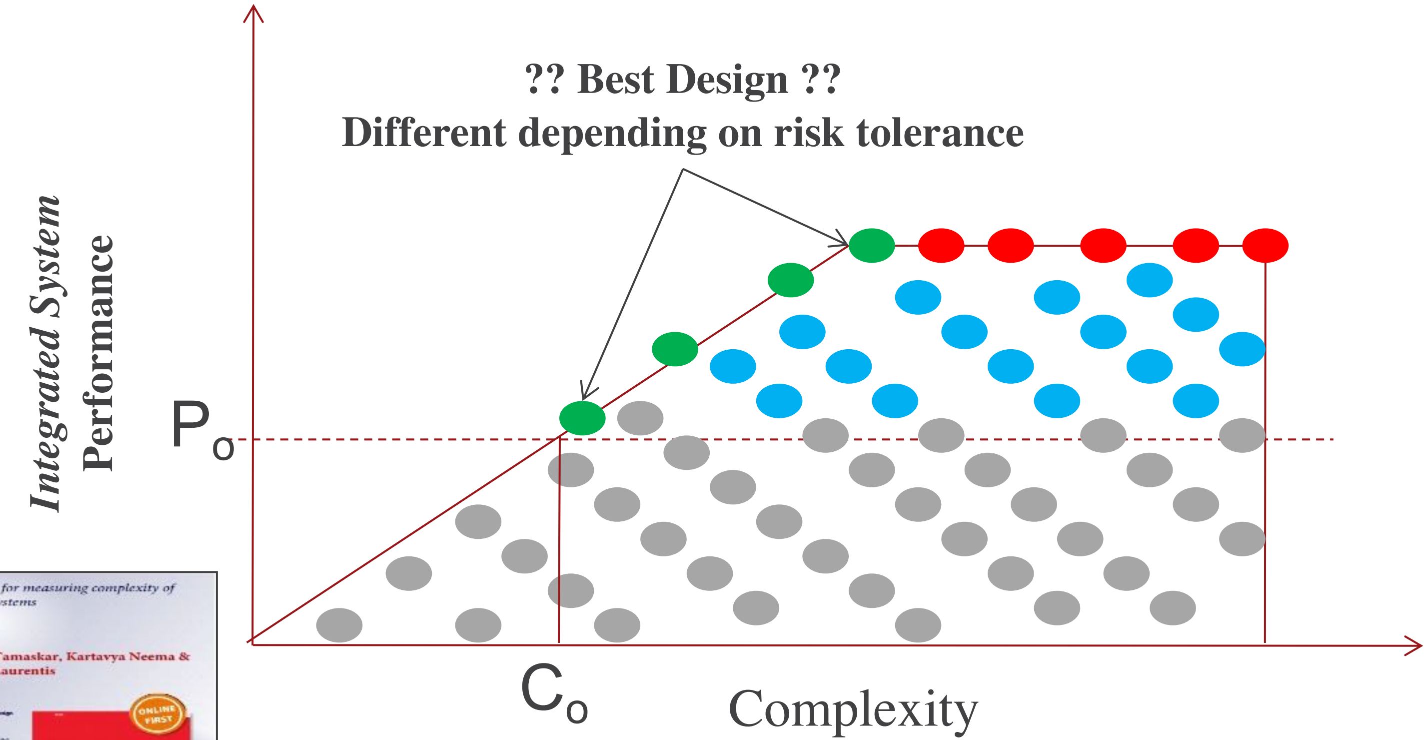
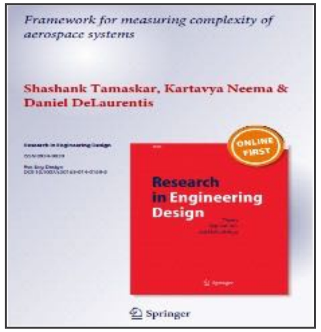
The Science of Systems Integration

*Complex Systems exhibit integration at multiple levels of hierarchy and must be studied as such, marrying structural and functional representations of the system, addressing cross-domain interactions and **seeking appropriate allocations of complexity and autonomy**.*



Useful complexity metrics are those that, when combined with the right performance metrics, assist human designers & architects to reason about design alternatives cognizant of risk tolerance.





Tamaskar, S., Neema, K., DeLaurentis, D., "Framework for measuring complexity of aerospace systems", *Research in Engineering Design* , February 2014.

Ali Raz

- Asst. Professor Systems Engineering, George Mason University
- Research interests in complex systems, AL/ML, and System of Systems
- Co-Chair Complex Systems Working Group and AI Working Group
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Traits of Complex Systems*

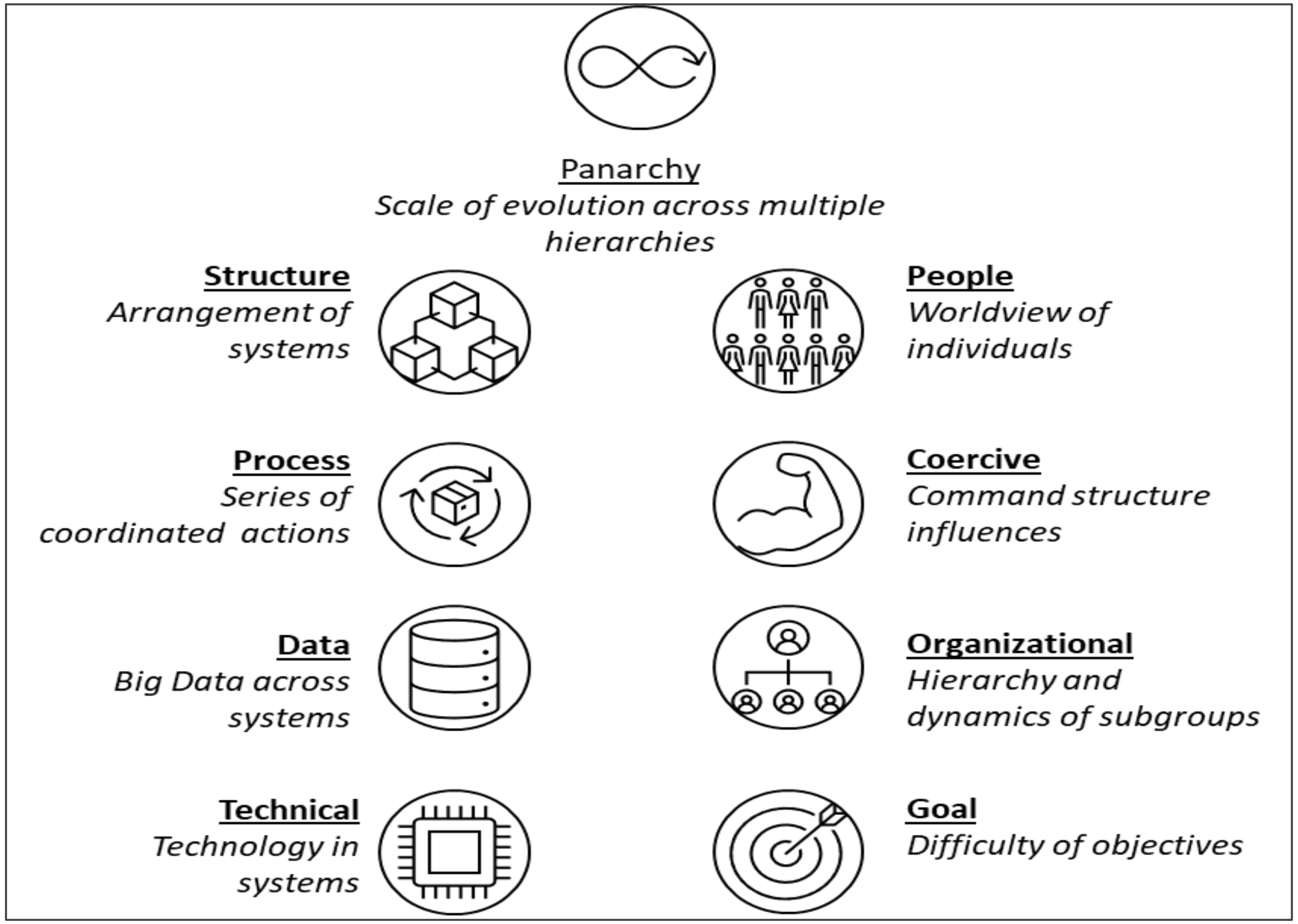
- 14 distinguishing traits of complex systems

Diversity	Dynamics
Connectivity	Representation
Interactivity	Evolution
Adaptability	Emergence
Multi-Scale	Disproportionate Effects
Multi-Perspective	Intermediate Boundaries
Behavior (unpredictable)	Contextual Influences

- Complexity Management Strategies
  - **Balance** instead of optimization
  - **Tension** between large-small, agile-planned, centralized-distributed
  - **Bounded** within simpler structure
  - **Architecture** to understand interactions
  - **Social-Political Complexity** relationship between engineered, natural & governance environment

* Watson et. al., “Appreciative Methods Applied to the Assessment of Complex Systems”, INCOSE IS 2019

Beyond technical complexity, the "other dimensions" of complexity are as important, if not more, for understanding complex systems



- While complexity is most often thought to pertain to technical aspects and technicality of functions, our study findings indicate that other dimensions of complexity (e.g., organizational complexity, process complexity, data complexity, and environment complexity) may be as important, if not more, for understanding (and designing) systems
- Our research uncovered eight different viewpoints of complexity and one overarching concept of Panarchy to tie it all together

Technical Complexity

Technical Complexity occurs when one seeks to "design a system to achieve a predefined purpose by organizing the various components and subsystems in the most efficient way possible"

Systems Engineering

Operations Research

Systems Analysis

Methods to manage complexity

Process Complexity

Process Complexity "arises when we have to put together a series of interdependent actions to achieve a purpose"

The Vanguard Method

Methods to manage complexity

Coercive Complexity

Coercive complexity is "associated with the exercise of power, which can operate to ensure some individuals or groups have the capacity to control the behaviors of others and benefit as a result"

- Team Syntegrity
- Critical Systems Heuristics

Methods to manage complexity

Data Complexity

Data complexity is associated with the collection, storage, processing, and use of large amounts of data

- 5V's of Big Data

Methods to manage complexity

Structure Complexity

This type of complexity is based on the arrangement and dynamic relationships between different system elements

Network Theory

System Dynamics

Methods to manage complexity

Organizational Complexity

Organizational complexity is seen as driven both by the internal interactions of the parts of a system and by the interactions between the system and its turbulent environment.

Socio-Technical Systems Thinking

Organizational Cybernetics

Methods to manage complexity

People Complexity

People complexity is rooted in differences in the worldviews, perspectives, and assumptions of individuals, and its larger impacts through culture, politics, religion, and other social constructs.

Strategic Assumptions Surfacing and Testing

Soft Systems Thinking

Methods to manage complexity

Goal Complexity

This complexity arises when different parts necessary to perform a task or reach a goal interact or conflict

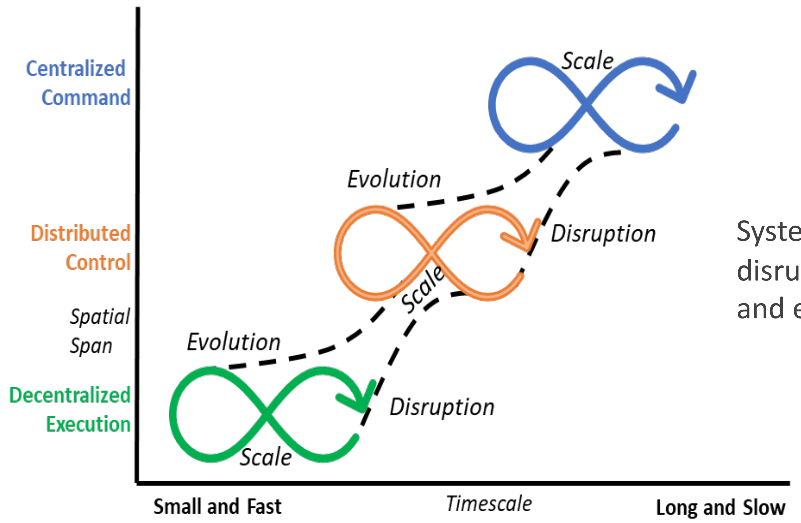
Task Complexity Framework

Methods to manage complexity

Panarchy

Panarchy is a "conceptual model that describes the ways in which complex systems of people and nature are dynamically organized and structured across scales of space and time"

Panarchy proposes that adaptive cycles within a complex system are connected via multi-scale hierarchies and remain interdependent on one another across both spatial and temporal scales (i.e., spatial spans and timescale).



Systems will inevitably change, driven by disruption and evolution from internal and external sources

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- Research leader, RISE Research Inst. of Sweden
- Research interests in SoS, SE, system architecture, complex systems
- Around 15 years experience from industry, primarily automotive (Volvo)
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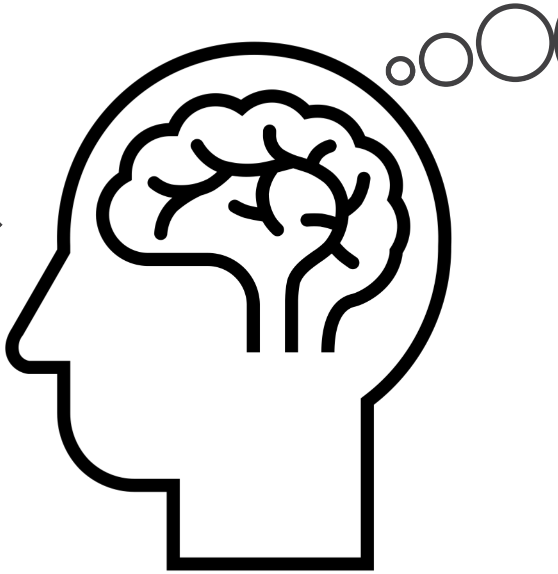
Systems and complexity

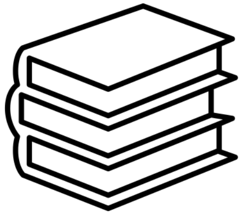
Reality

Perception of reality

System

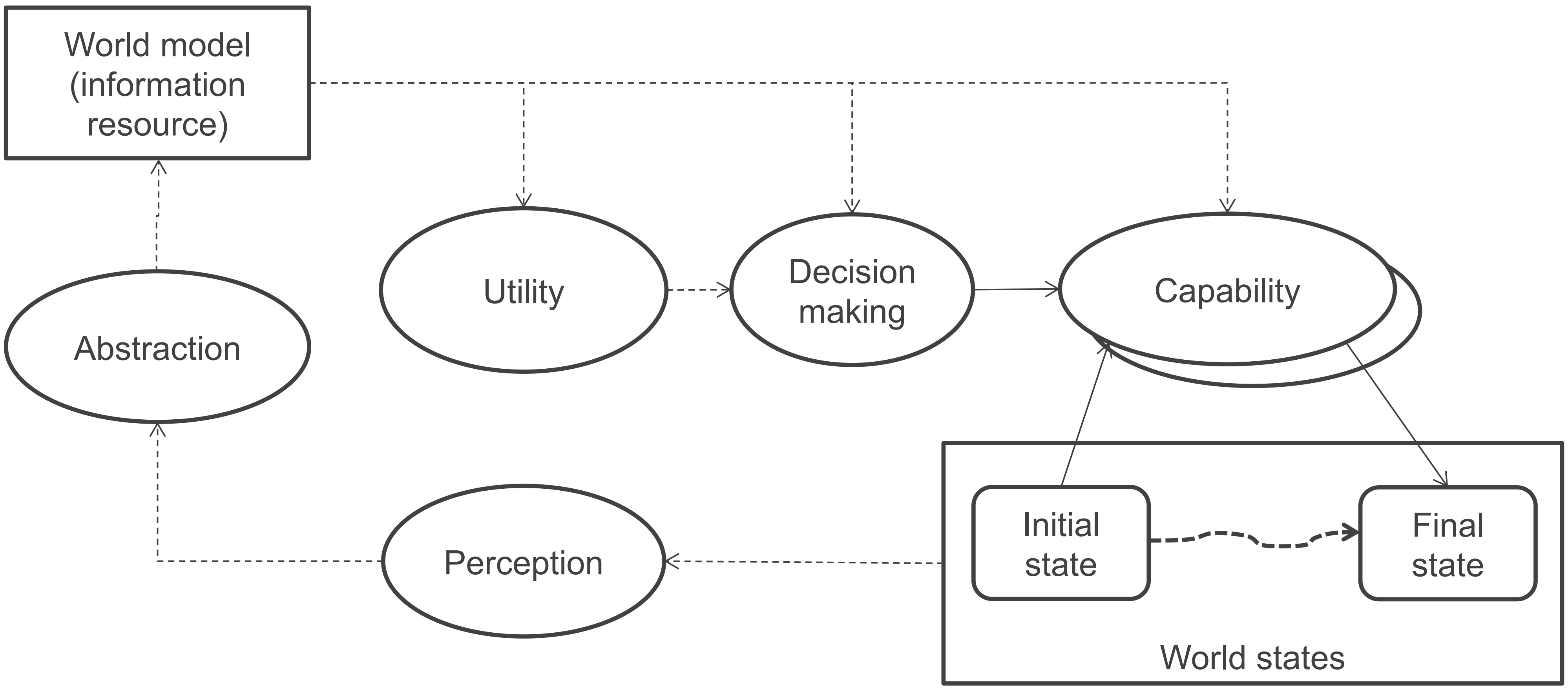


Cognitive agent



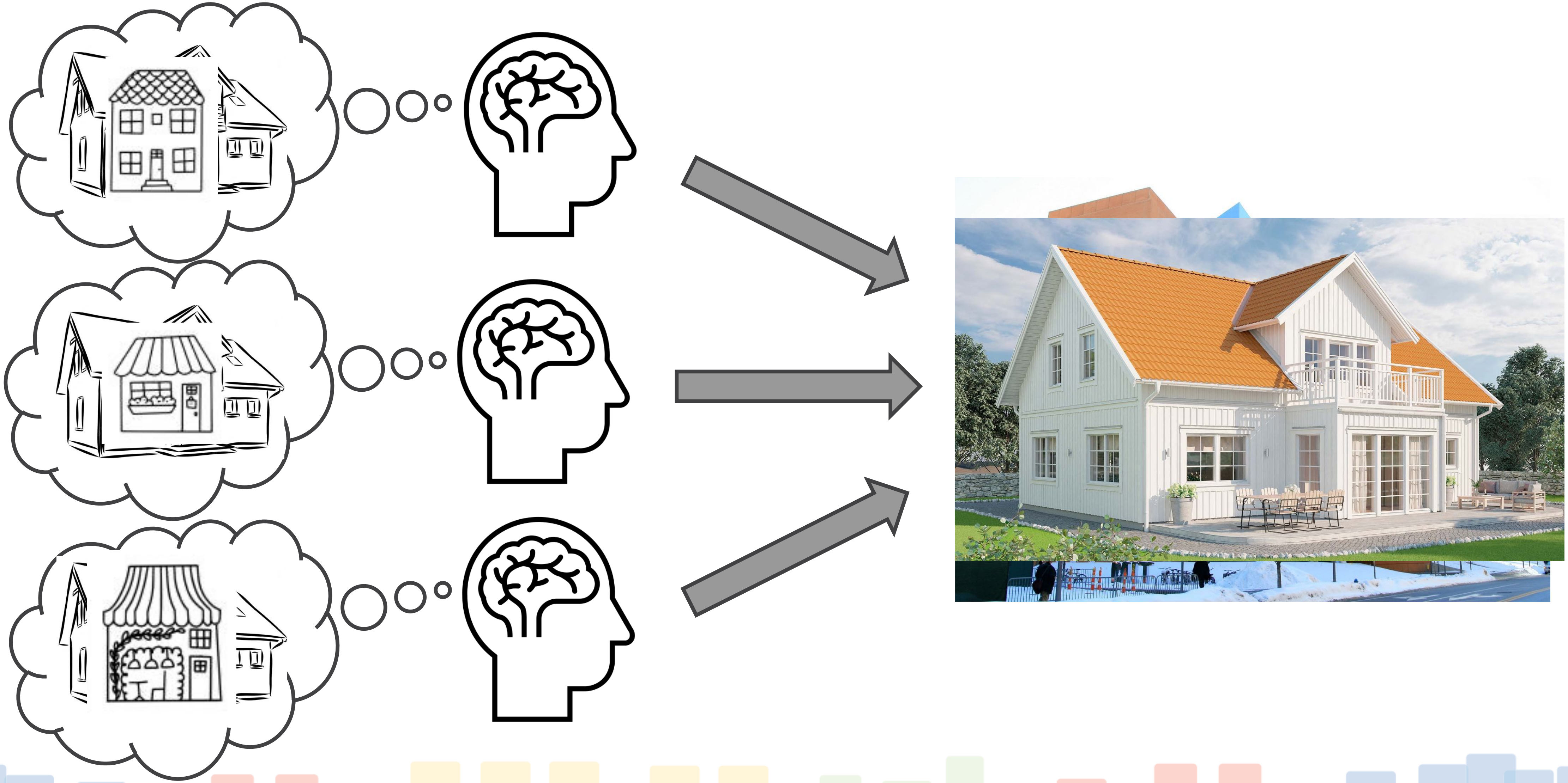
Complexity

Cognitive agents

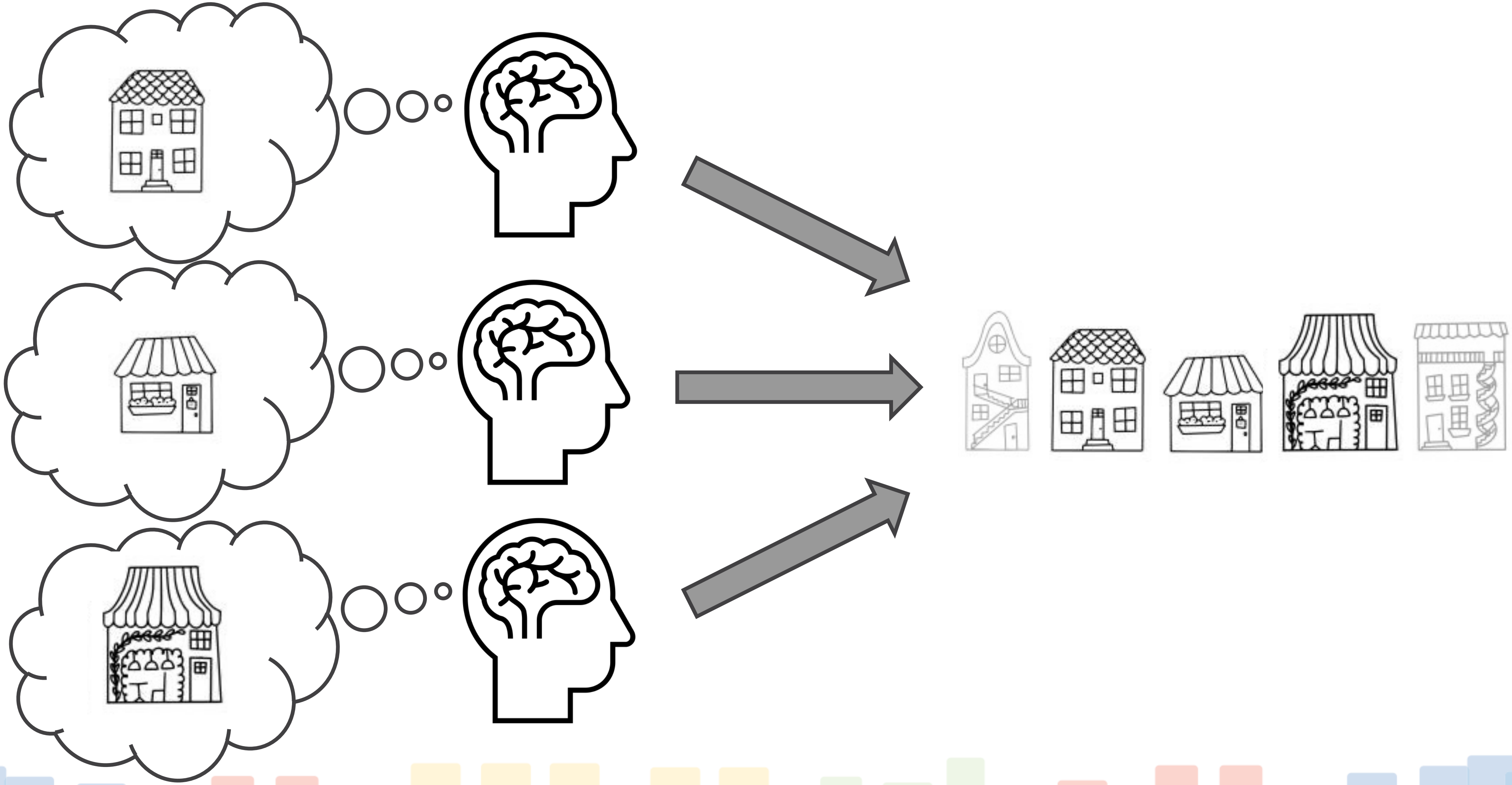


J. Axelsson & P. Svenson. "On the Concepts of Capability and Constituent System Independence in Systems-of-Systems". Proc. IEEE System of Systems Engineering Conf., 2022.

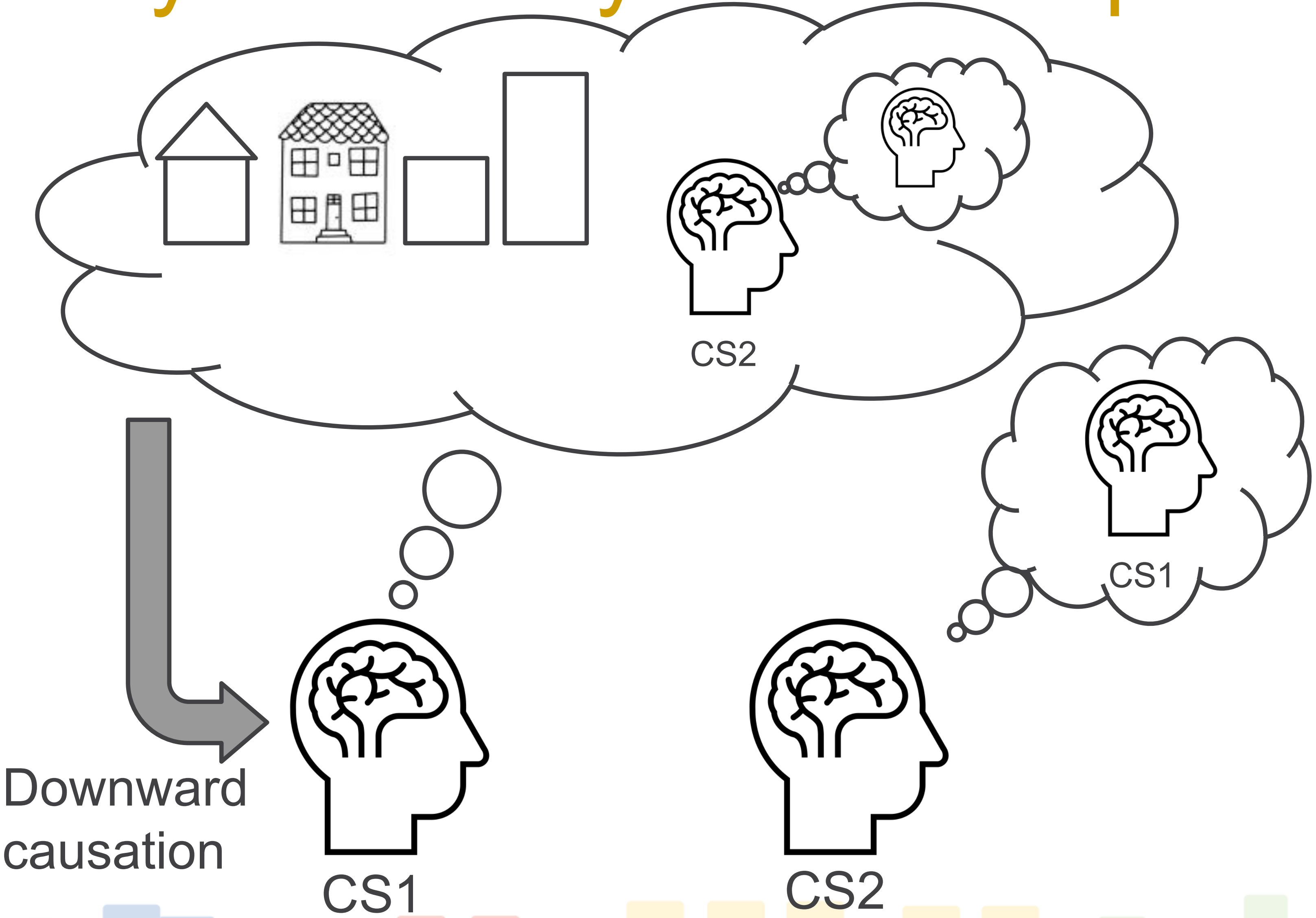
Reconciling world views: Integrated systems

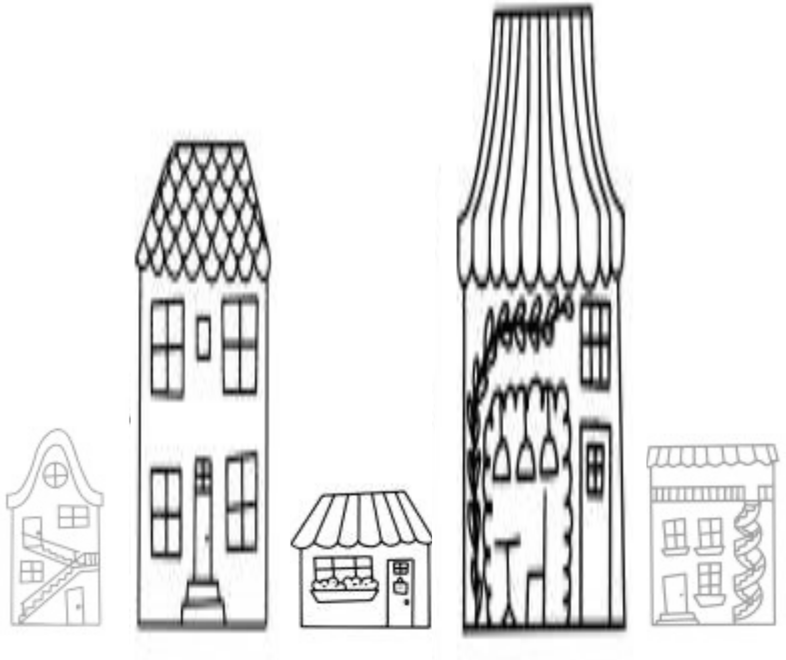


Reconciling world views: SoS



System-of-systems complexity





Stephen Cook

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  Professor of Defence Systems, The University of Adelaide
- Over 25 years experience in industrial SE, SE research and teaching, and SoS
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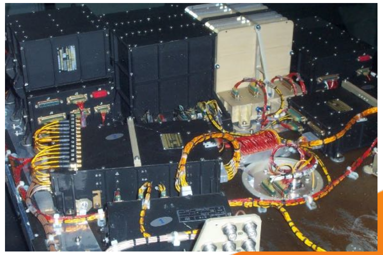
An Engineering View of SoSE

- In broad terms, SoSE has been seen by the INCOSE community as a practice area of SE
- Indeed, SEBoK covers SoSE in *Part 4: Applications of Systems Engineering*
- SoSE is employed where the differentiating characteristics of SoS are apparent: managerial and operational independence of the constituent systems, eg:
  - Transportation systems
  - Defence C5ISREW systems
  - National health systems
  - Market-based energy systems
  - The Internet
  - The international exploitation of space
- As complexity increases, the competencies and disciplines need to change

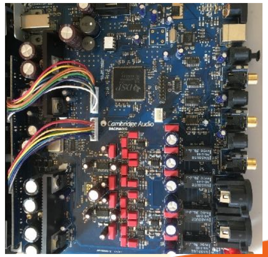
International exploitation of space

An orbital vehicle

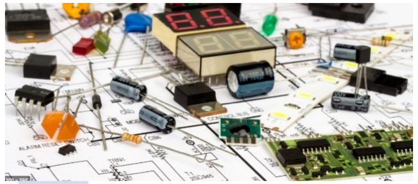
A sensing subsystem



A circuit card assembly



Electronic components



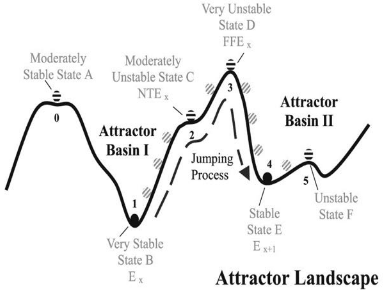
Complexity

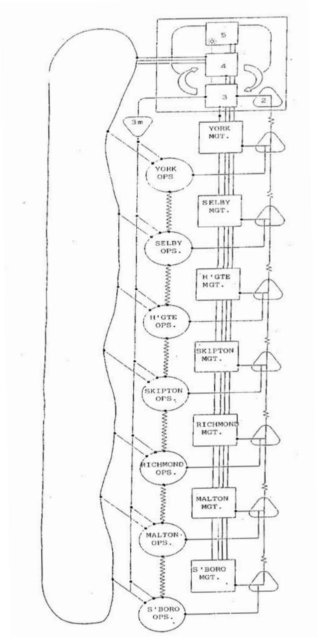
Complexity Hierarchies are Not a New Idea! – (Boulding, 1956)

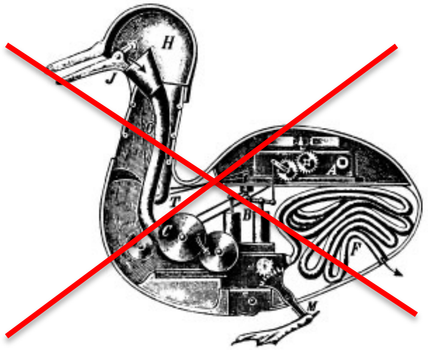
Level	Characteristics	Examples	Relevant disciplines
1. Structures	Static	Crystals, bridges	Description, verbal or pictorial, in any discipline
2. Clock-work	Predetermined motion	Clocks, machines, the solar systems	Physics, classical natural science
3. Control mechanisms	Closed-loop control	Thermostats, homeostasis mechanisms in organisms	Control theory, cybernetics
4. Open systems	Structurally self-maintaining	Flames, biological cells	Theory of metabolism (information theory)
5. Lower organisms	Organised whole with functional parts, 'blue-printed' growth, reproduction.	Plants	Botany
6. Animals	A brain to guide total behaviour, ability to learn.	Birds and beasts	Zoology
7. Man	Self-consciousness, knowledge of knowledge, symbolic language	Human beings	Biology, psychology
8. Socio-cultural systems	Roles, communication, transmission of values	Families, the Boy Scouts, drinking clubs, nations	History, sociology, anthropology, behavioural science
9. Transcendental systems	'Inescapable unknowables'	The idea of God	Unknown

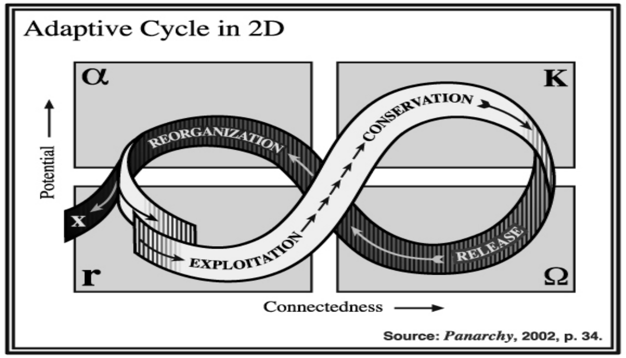
Notes: (1) Emergent properties are assumed to arise at each defined level.
(2) From level 1 to level 9: complexity increases; it is more difficult for an outside observer to predict behaviour; there is increasing dependence on unprogrammed decisions.
(3) Lower level systems are found in higher level systems- eg man exhibits all the distinguishing properties of levels 1-6, and emergent properties at the new level.

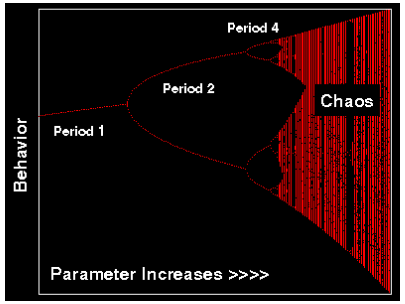
Complexity Science is a Mainstream Influence in Business and Management



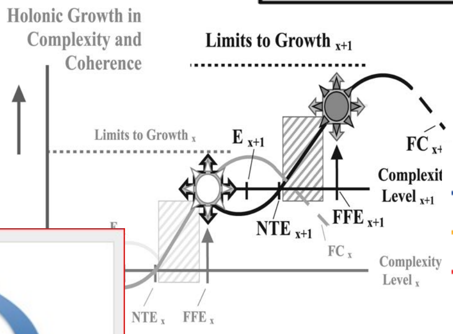


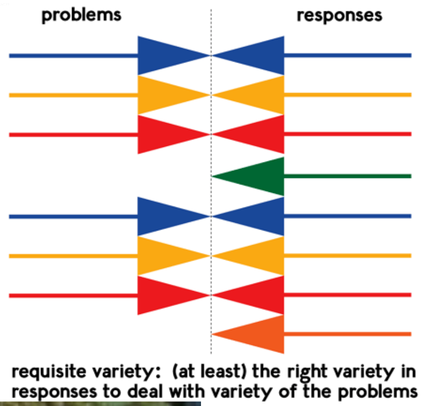


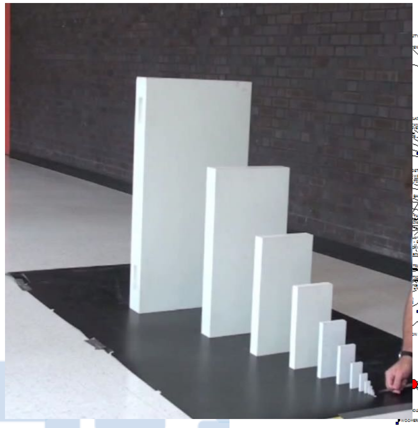


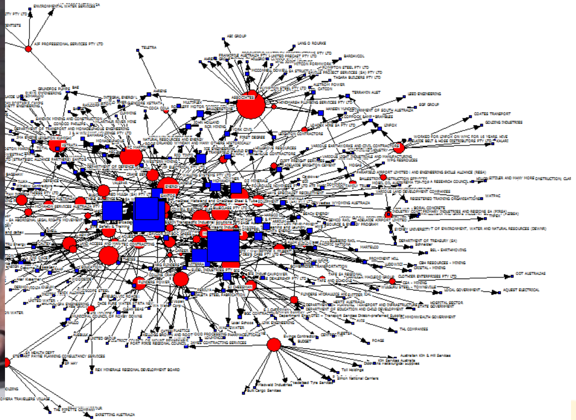


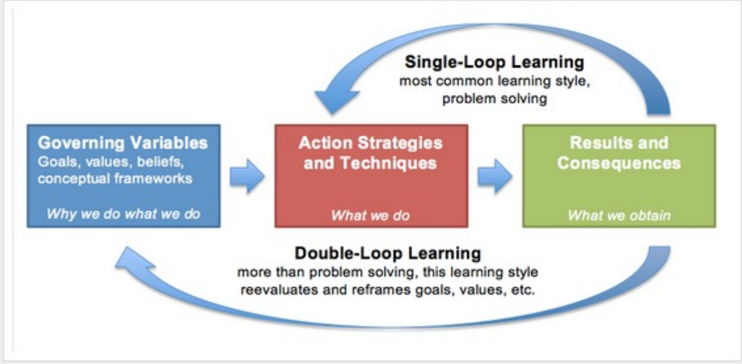
- Management science has drawn on a broad base of systems and complexity theory for strategic management and organisational interventions
- Their language is focused on dealing with the flux of life and continual improvement to achieve outcomes that are systemically desirable and culturally feasible



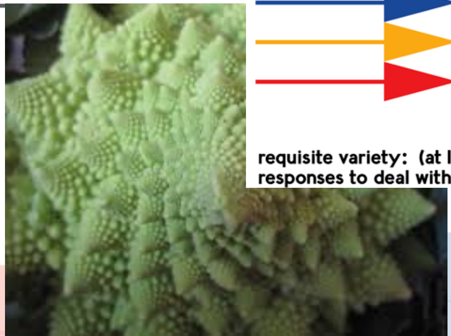








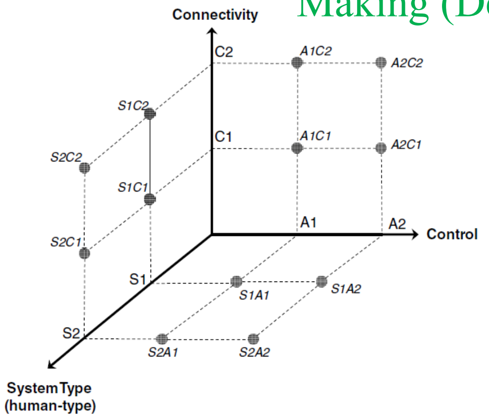
– Adapted from interpretations of Argyris's writings: http://www.infed.org/thinkers/argyris.htm and http://bsix12.com/double-loop-learning/



Operationalising our Knowledge of Complexity

- Use these ideas to classify the SoS challenge and use this knowledge to direct practice
- The latter is facilitated through the development of a discipline

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



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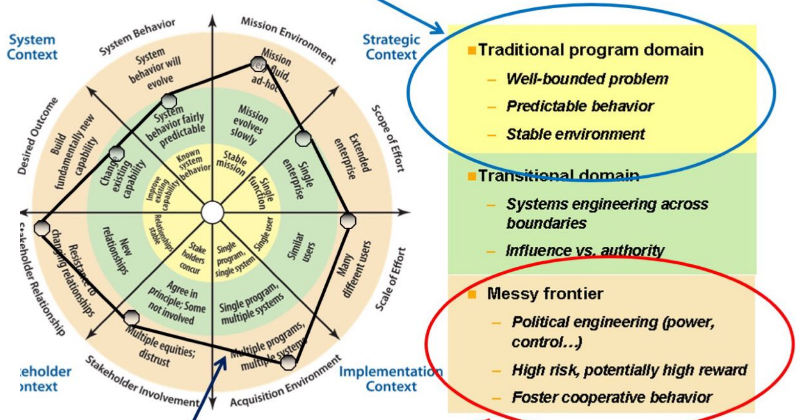
Identifying the Class of SoSE Challenge
(Mitre 2011, Stevens 2011*)

Traditional Project SE



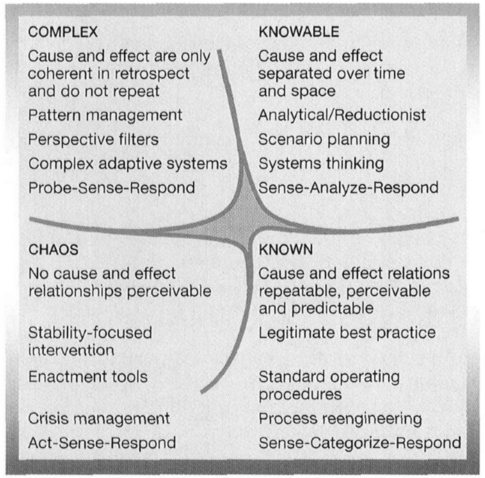
A Particular System

SoSE Area

Stevens R. 2011, *Engineering Mega-Systems*, ISBN 978-1-4200-7666-0, CRC Press.

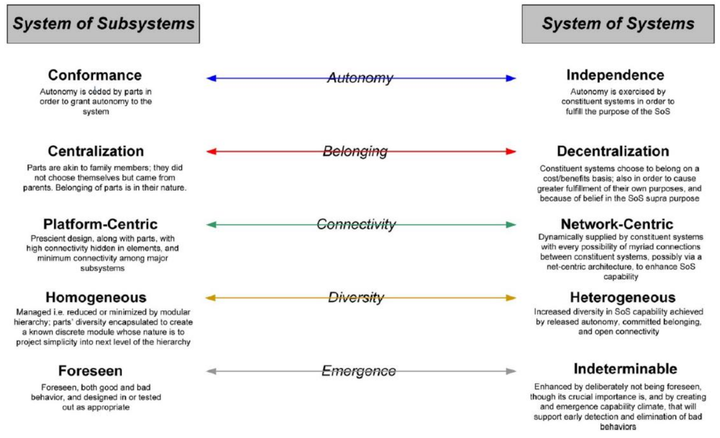
rsity of Adelaide 21

Kurtz and Snowden's Cynefin Domains (2003)



Appreciative Methods Applied to the Assessment of Complex Systems Watson et al (2019)

Distinguishing Characteristics of SoS
(Gorod et al, 2008)



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Flood and Jackson's Total Systems Intervention (1991)

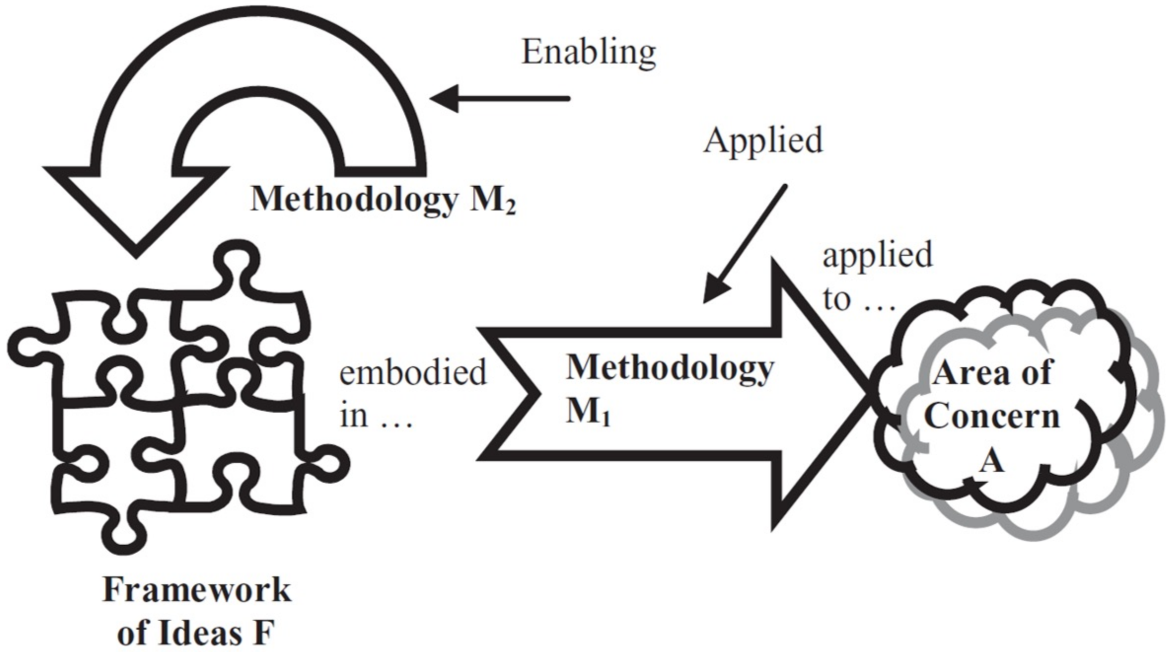
	Unitary	Pluralist	Coercive
Simple	Operations research Systems analysis Systems engineering Systems dynamics	Social systems design Strategic assumption surfacing and testing	Critical systems heuristics
Complex	Viable system diagnosis General system theory Socio-technical systems thinking Contingency theory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

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

Elements of a Discipline

- Cook & Ferris (2007) describe the elements necessary for a discipline (after Cropley et al, 2005; Checkland and Holwell 1998 & Kline, 1995)
  - F = framework of ideas
  - M_1 = methodology applied to problems that embodies F – marshals methods, tools, and techniques
  - M_2 = agreed methodology for developing F
  - A = area of concern. Covers problem, discipline, domain, and real-world problem situation.
  - Also need a community of paid scholars ☺



See also Rousseau et al, (2016)

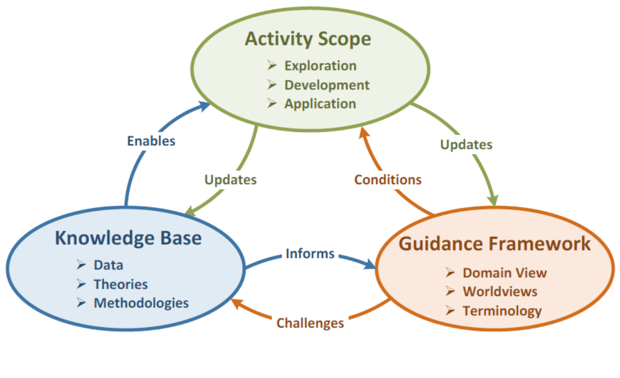
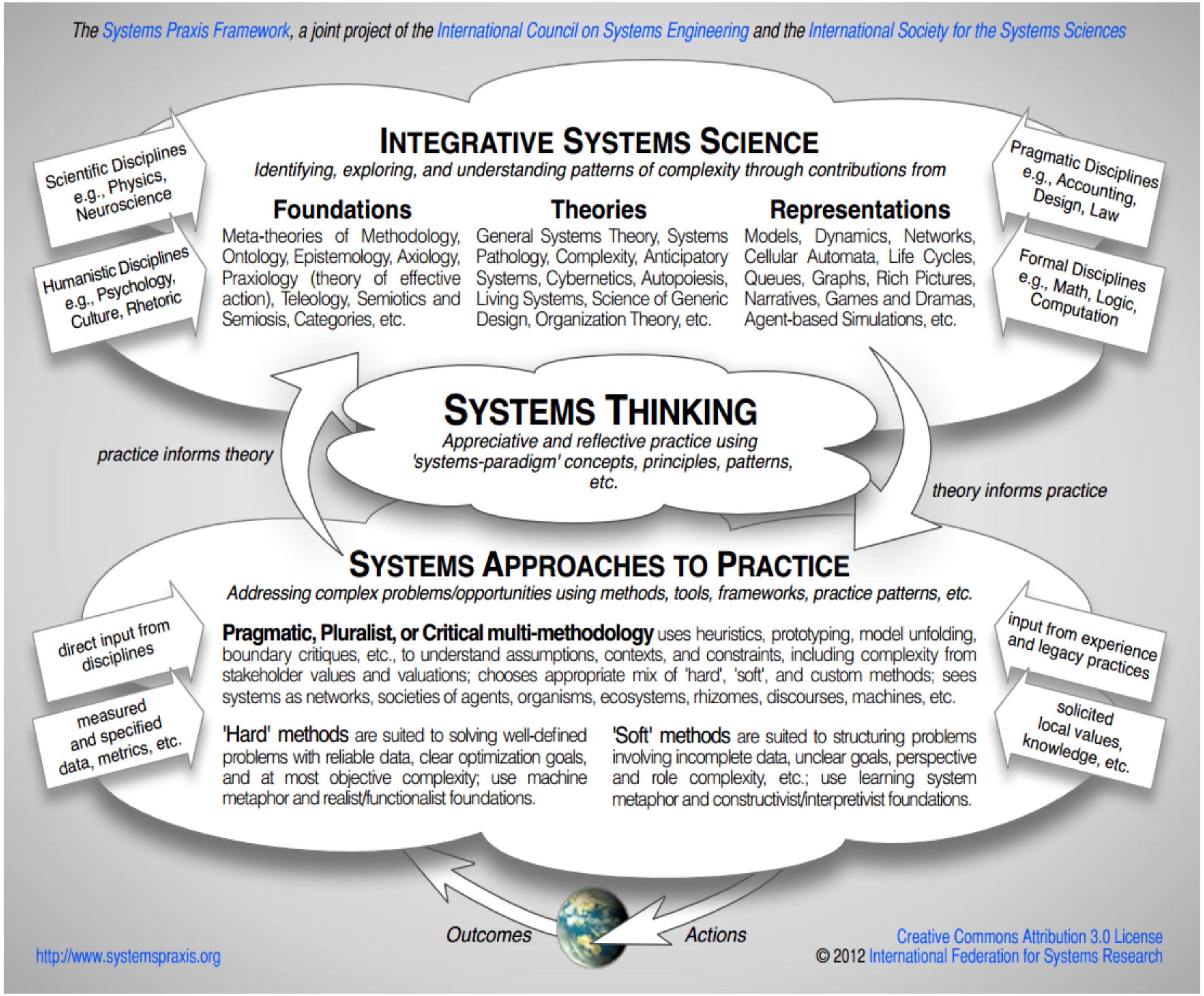


Figure 4: The AKG Model of a Discipline

A Helpful Construct

- The INCOSE/ISSS System Praxis Framework (Martin et al, 2013) helps show that all systems practice draws on systems sciences (which includes complexity science) via systems thinking
- In SoSE, influencing and shaping take precedence over directing
- Need to employ a pluralistic approach
  - Socially aware “soft” approaches
  - Critical systems approaches to include all the stakeholders
  - Engineering and scientific methods to engineer the technical solution
  - Project management to drive progress
- Thus, SoSE practice is informed by multidisciplinary systems science



Getting Started on an SoSE Challenge

- The Business and Mission Analysis Process of ISO/IEC/IEEE 15288:2015 is useful to understand the context, commercial drivers, social and political aspects, and value models

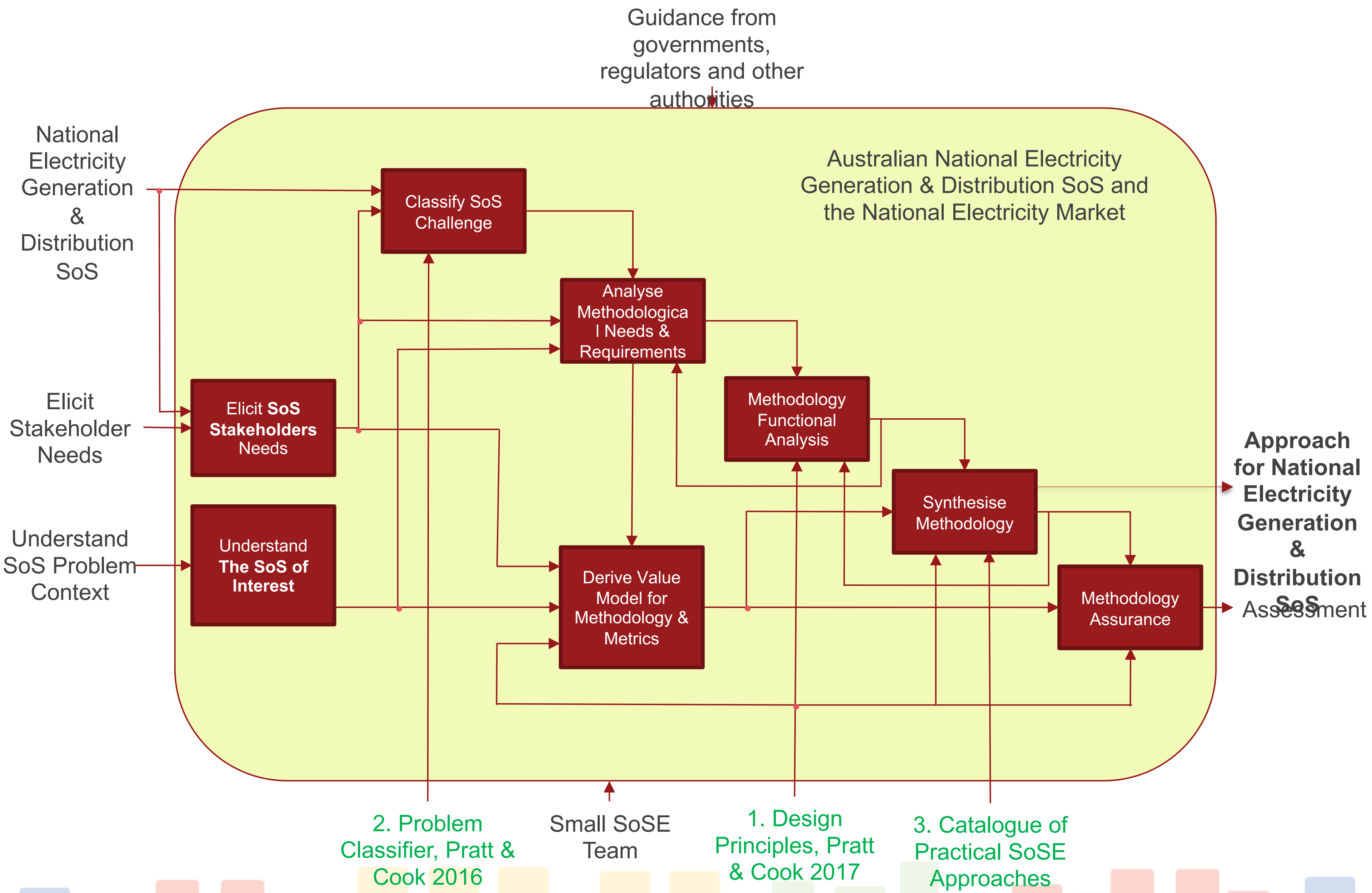
- Classifiers can surface the:
  - Nature of the SoS of Interest
  - Role of the actors
  - The problem context

- Use these findings to identify relevant systems approaches and their associated Frameworks of Ideas

- Design the detailed, specific SoSE approach

- Undertake the SoSE methodology and learn and refine it over the iterations

A Design Process for a SoSE Approach (Cook, Pratt & Unewisse 2015)



Key Needs for the SoSE Methodology Design Process

- Classifiers – already discussed
  - Also lifecycle focus e.g. strategic planning, portfolio management, acquisition, asset management
- Catalogue of practical SoSE approaches – see right
- Catalogue of SoSE methods, processes, tools, & techniques – see *Complexity Primer*
- Principles for the design of SoSE approaches
- Key personnel with competencies in:
  - Design of SoSE approaches
  - Systems Engineering
    - In particular systems thinking and systems theory
  - Broader systems approaches and underpinning systems philosophy, science/engineering and practice

In Summary

- Systems and Complexity theory along with Systems Thinking underpins practice in SoSE

SoSE Approach	Description	Good for …
US Department of Defence SE for SoS: The Wave Model	The wave model is an evolutionary model comprising five main process elements with experiential learning from many SoSE programs. It was originally designed for acknowledged SoS with a small SoSE team; however, it has also been applied to collaborative SoS challenges. It is a meta-methodology, i.e. it guides the design of SoSE methodologies, and is extensively documented. Key references: OUSDA (2008), Dahmann et al. (2011), Lane et al. (2010), Dahmann and Heilmann (2012).	• Directed and acknowledged SoS with a small SoSE team (has been applied to collaborative SoS)
Dynamic Optimization of SOS using Value Measurement (DOSVM)	*DOSVM draws on complexity theory and recognizes Constituent System Project Offices (CSPO) have the resources and means to change, and that in many SoS, the actual authority and resources of any central element is insufficient to do more than guide the evolution of the SoS. In DOSVM, each CSPO views the SoS in terms of its utility to itself, seeking to "optimise" the SoS (from its point of view) through the influences available to it. DOSVM is ideal for collaborative SoS in which there is little or no central control. Key references: Honour (2016), Honour and Browning, (2007).*	• *Collaborative SoS with little or no central control*
The Modified Wave Model	*Cook and Unewisse (2017) concluded that the wave model is well suited to the Australian Defence program level of SoSE effort and proposed a simplified Modified Wave Model for programs. Aspects of the methodology and its supporting tools and techniques have been trialled in Defence and industry to good reviews (Jusaitis and Cook 2018; French and Heard 2018). Subsequently, a compatible, austere integration and interoperability assurance methodology was developed and trialled successfully. Key References: Cook and Unewisse (2018).*	• *Programs to co-ordinate many Projects using modest resources*
SoS Governance (SoSG)	*SoSG, through its origins in complexity theory, seeks to expand SoSE away from the "technology first and technology only" perspective of earlier versions of SoSE. It includes appreciating the context to determine what initiatives might be feasible, identifying areas that can improve the SoS, and adopting a "long-term view" of the evolutionary development of the SoS. SoSG appreciates that de-centralized control can be expected and is suited to a wide range of collaborative and acknowledged SoS challenges. Key references: Keating (2015), Morris et al. (2006).*	• *A wide range of collaborative and acknowledged SoS* • *Appreciates that de-centralized control can be expected*
Systemic Strategic Planning and Execution (SSPE)	*SSPE is a comprehensive but austere multi-methodology inspired by strategic planning, systems theory, CBP, and BSTA to achieve inclusivity and stakeholder engagement in a systemic way. Later versions include ideas from system engineering to achieve structured abstraction and trade-offs between candidate force structures. SSPE is ideally suited to force design and has been used successfully in Australia; additional technical approaches are needed to cover technical integration aspects. References: Hodge and Cook (2013), Hodge and Cook (2014a, b).*	• *Force design* *** additional technical approaches are needed to cover technical integration aspects*

Fragment of a table on SoSE approaches (Cook & Pratt, 2020)

Discussion

32nd Annual INCOSE international symposium

hybrid event

Detroit, MI, USA

June 25 - 30, 2022

www.incose.org/symp2022