System of Systems Engineering

The What, Why, and How

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Is it a system? What is it made of?

Defining a system

What is a system?

“A system is **an assemblage or combination** of **functionally related elements** or parts forming a unitary whole, such as a river system or a transportation system.” – Blanchard and Fabrycky

“A system is **a set of elements** so **interconnected** so as to aid in driving toward **a defined goal**.” – Gibson, Scherer, and Gibson

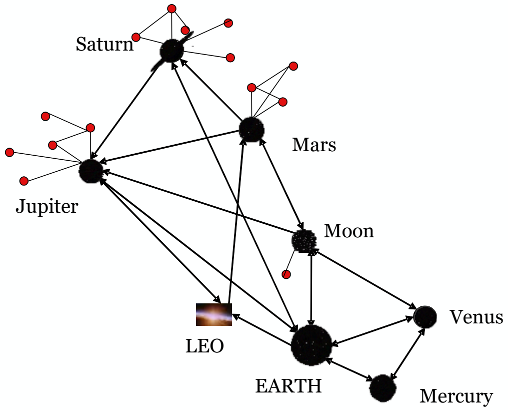
“A **set of different elements connected or related** so as **to perform a unique function** not performable by the elements alone”. – Rechtin and Maier

→ **Collection of elements**

→ **Interdependence of elements**

→ **Goal**

What is a System of Systems (SoS) ?



SoS is a "special kind of system"

So, first of all it possesses all the attributes of a system

Spoiler of the "special-ness" of SoS (more on this in a couple of slides):

- Looser, and more fluid, connection between component systems
- The components have twin purposes: their own and that to fulfill the SoS

Many attempts at universal definition of SoS, never with much success

Early systems thinking

Pre-history of SoS

"The whole is more than the sum of its parts."

So said Aristotle, Methaphysics, Book 8, 1045a, 9-10.

Systems approach formally arose after WWII

Ludwig von Bertalanffy, Kenneth Boulding, William Ross Ashby, etc. were some of the early researchers

Systems engineering (SE) also arose after WWII

Bells Labs first used the term in 1940s

Mr. G. W. Gilman offered first SE course at MIT in 1950

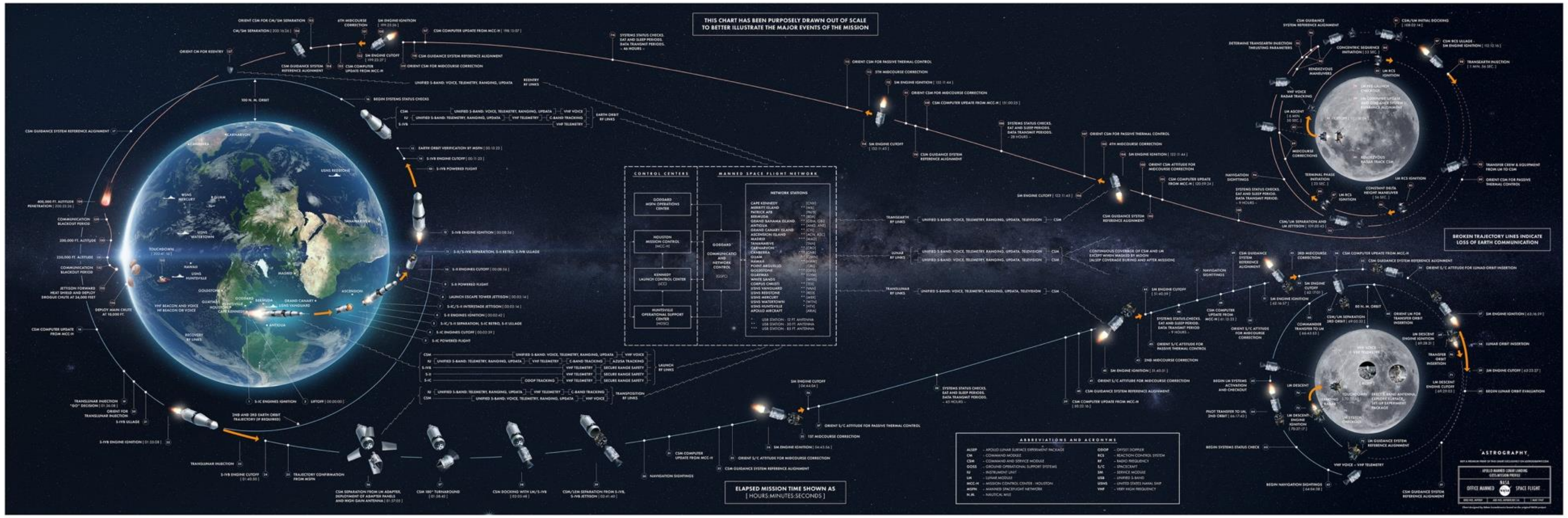
RAND Corp. too was an early contributor of the discipline

From Bell Telephone Magazine, 1922

First notions of System of Systems

Getting there without knowing it yet

- Early ideas similar to SoS appeared in 1960s (perhaps sooner too!), e.g., Apollo missions
- Considered SoS as collection of theory rather than engineered systems
  - Boulding: considered it as a “gestalt” or a “spectrum of theories” greater than the sum of parts
- First use of term SoS for engineered systems was in the Strategic Defense Initiative in 1989



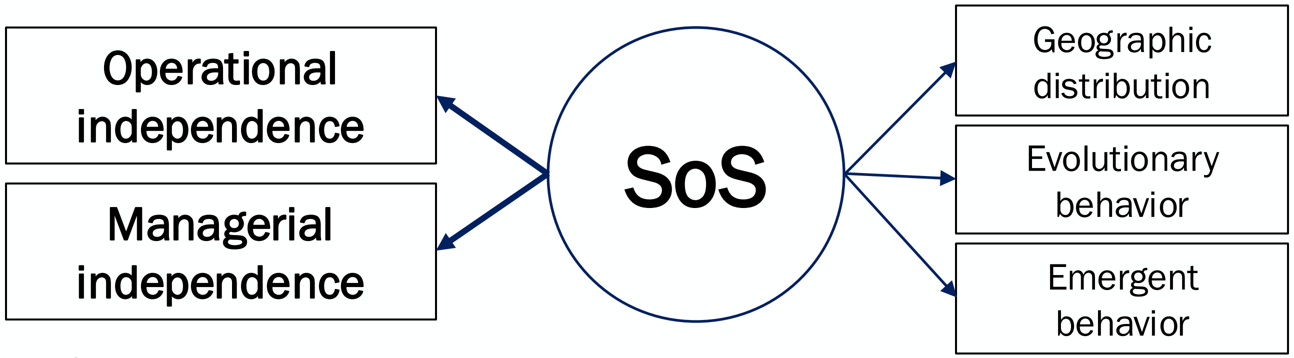
System of Systems in the 1990s

The What

Two approaches to understanding What is an SoS emerged:

1. By definition
   a. Eisner was one of the first to define SoS in 1991. Quickly followed by Shenhar, Holland and others
   b. Problem is that many researchers focused on their domain of expertise to define SoS: Kotov for IT, Owens for military, Manthorpe for Command, Control, Communications, Computers, and Intelligence (C4I)
2. By characterization, using distinguishing criteria
   a. Maier is considered one of the most influential researchers characterizing SoS. His five distinguishing criteria for SoS are widely recognized: **operational and managerial independence, geographic distribution, evolutionary and emergent behavior**

Later, he emphasized that **operational and managerial independence are key**



System of Systems in the 2000s

From the What to the Why

Industry and academia began playing stronger role in research

US DoD:

- ‘Defense Acquisition Guidebook’ (2004)
- ‘Systems of Systems, Systems Engineering Guide’ (2007)

Two books, primarily collection of views and applications:

- ‘System of Systems Engineering - Innovations for the 21st Century,’ Mo Jamshidi, Editor (2008)
- ‘Systems of Systems Engineering: Principles and Applications,’ Mo Jamshidi, Editor (2010)

Conferences:

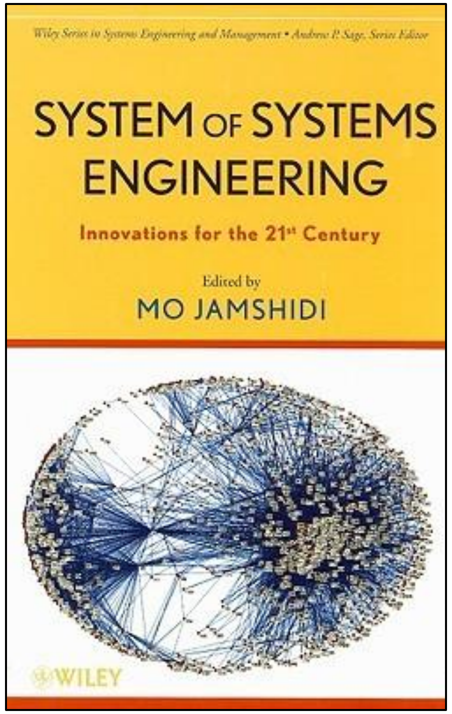
- IEEE (SMS) / INCOSE SoSE Conference (since 2006. Latest in Tirana, Albania, in June 2025)

Societies:

- INCOSE SoS Working Group, IEEE SoS Technical Committee

SoS journal articles:

- IEEE Systems Journal, INCOSE Systems Engineering, International Journal of SoSE

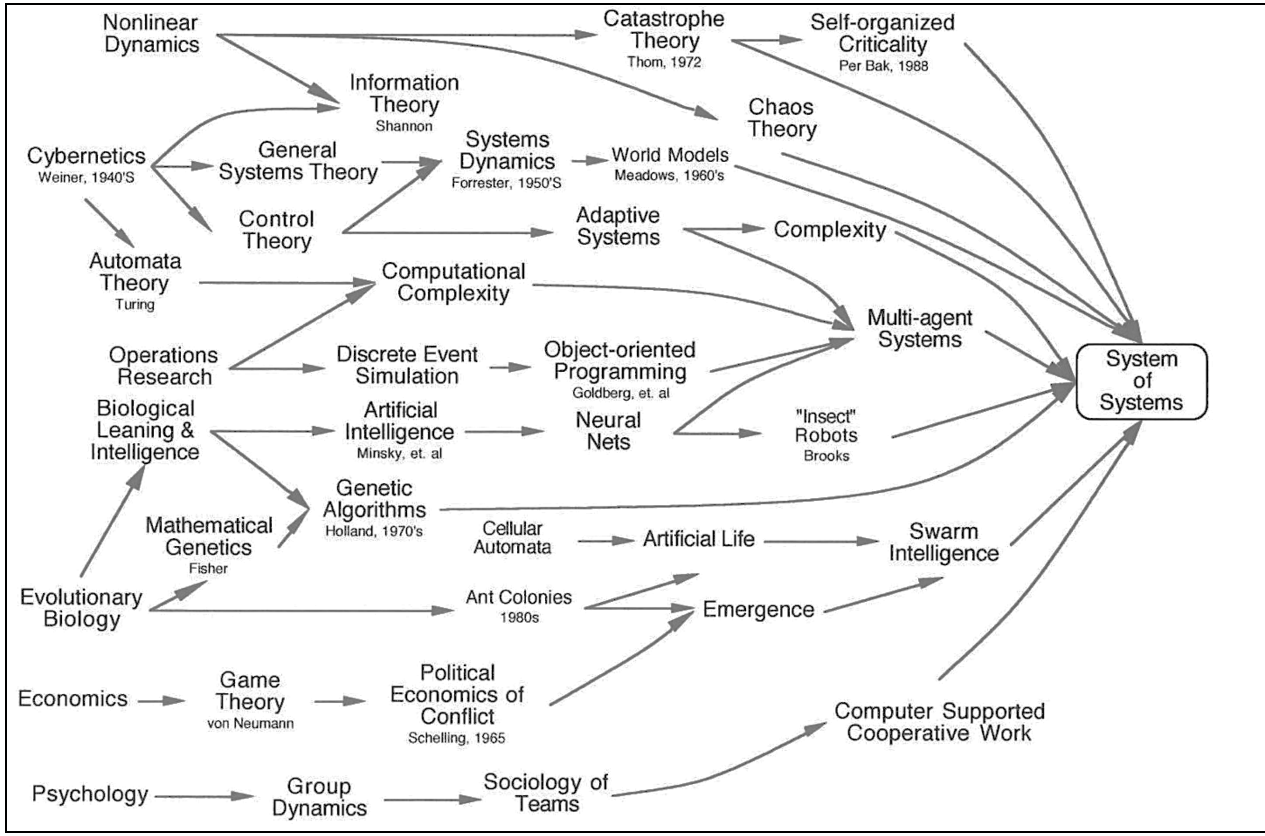


System of Systems in the 2000s (2)

From the What to the How

Research and practice by government, industry and academia established that:

- SoS is a distinct type of system
- SoS has distinct challenges, mostly based on:
  - o locus of control (autonomy) over the SoS
  - o architecture of the components
  - o interdependence amongst constituent systems
- SoS merits treatment as a separate type of problem



Many SoS challenges are intermixed with other fields, as in Solberg Chart to the right. Most recently, also:

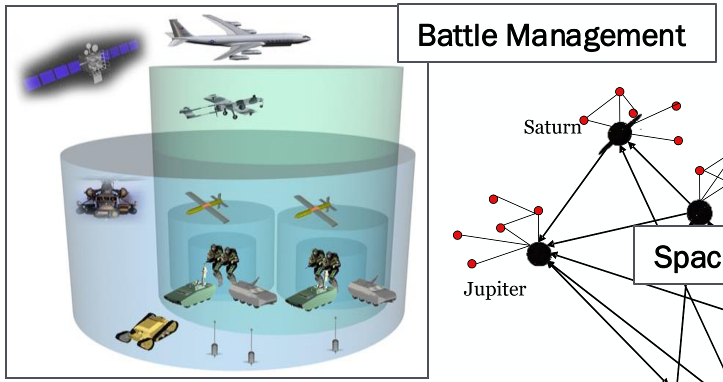
- UQ, XAI
- Mission Engineering
- SoS ontology
- Interoperability
- SoS policies

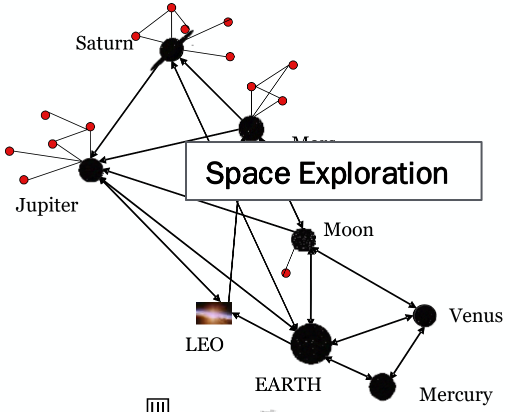
Systems Engineering AND (not vs.) System of Systems Engineering

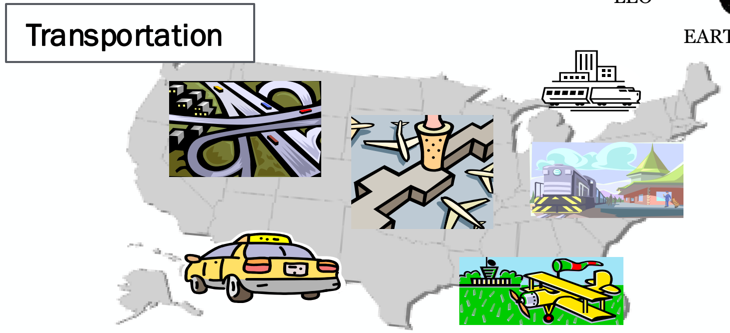
Systems Engineering

- Typically, a single product or system
- Well-defined requirements :)
- Still hard – Complex Systems
- e.g., aircraft, tower, rocket

System of Systems Engineering







- Network of independently operating systems that may collaborate
- Emergent Behavior (good or bad)
- Very high consequences (cost and capability)

Practical Challenges of System of Systems

The Why

System of Systems Integration is the bringing together of systems to ensure that the systems will interact in order to satisfy the user's needs. But

- SoS stakeholders have managerial and operational independence.
- Plus, we can have heterogeneity of components and domains, complexity, geographical distribution, emergence (more in this shortly), complicated dynamics.

Maier proposed to adhere to guiding principles when architecting SoS:

1. **Stable intermediate forms** – do not architect the most intricate SoS in one step
2. **Policy triage** – a SoS architect is not in control of everything. Decide what can and what cannot be done
3. **Leverage at the interfaces** – the most important aspect of a SoS, and the way components interact
4. **Ensure cooperation** – a SoS architect is not in control of other stakeholders... Or is he/she?

Practical Challenges (2): "System of Systems Pain Points"

More challenges of SoS, still very present today

From: Dr. Judith Dahmann, INCOSE Webinar Series on Systems of Systems, 22 Feb 2013

Pain Points	Question
SoS Authority	*What are effective collaboration patterns in systems of systems?*
Leadership	*What are the roles and characteristics of effective SoS leadership?*
Constituent Systems	*What are effective approaches to integrating constituent systems into a SoS?*
Autonomy, Interdependencies & Emergence	*How can SE provide methods and tools for addressing the complexities of SoS interdependencies and emergent behaviors?*
Capabilities & Requirements	*How can SE address SoS capabilities and requirements?*
Testing, Validation & Learning	*How can SE approach the challenges of SoS testing, including incremental validation and continuous learning in SoS?*
SoS Principles	*What are the key SoS thinking principles, skills and supporting examples?*

An underlying challenge in SoS: emergence

Where does it come from?

"It takes two to tango"… and to produce emergence

Strong and weak emergence

For SoS, weak emergence arises from the interactions among semi-independent systems

Herbert Simon's perspective: strong and weak emergence

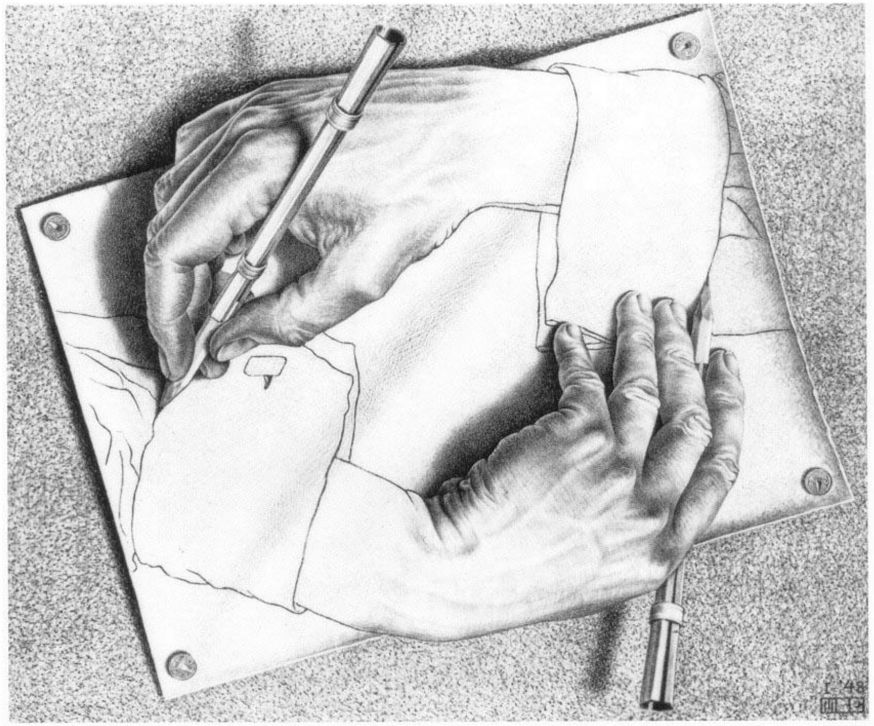
- Strong: "putting together their parts will not produce them" (J. Smuts)
  - Thinking is more than just arrangement & behavior of neurons--- *anti-reductionist*
  - A "creative" principle is at work: mechanistic explanations of emergence rejected.
- Weak: Parts of complex system have relations that do not exist for parts in isolation
  - Emergence is a "relative" entity; we need two bodies interacting to understand gravity; also "inertia mass" in mechanics, and "voltage" in electrical circuits
  - Weak emergence poses no problem for reductionism because the interaction can be explained in terms of known properties

Question: Can emergence be detected, designed, or controlled?

How is it possible?

I have always loved Escher diagrams

- Hofstadter's Strange Loops and Tangled Hierarchy:
  - Emergent phenomena can occur via a Strange Loop, where the top level reaches back down towards the bottom level and influences it, while at the same time being itself determined by the bottom level.



M.C. Escher- "Drawing Hands", 1948

D. R. Hofstadter, "Gödel, Escher, Bach: an Eternal Golden Braid," Basic Books,1999

How is it possible? Solution --> Hierarchy

Deciphering hierarchical relationships to see the true situation

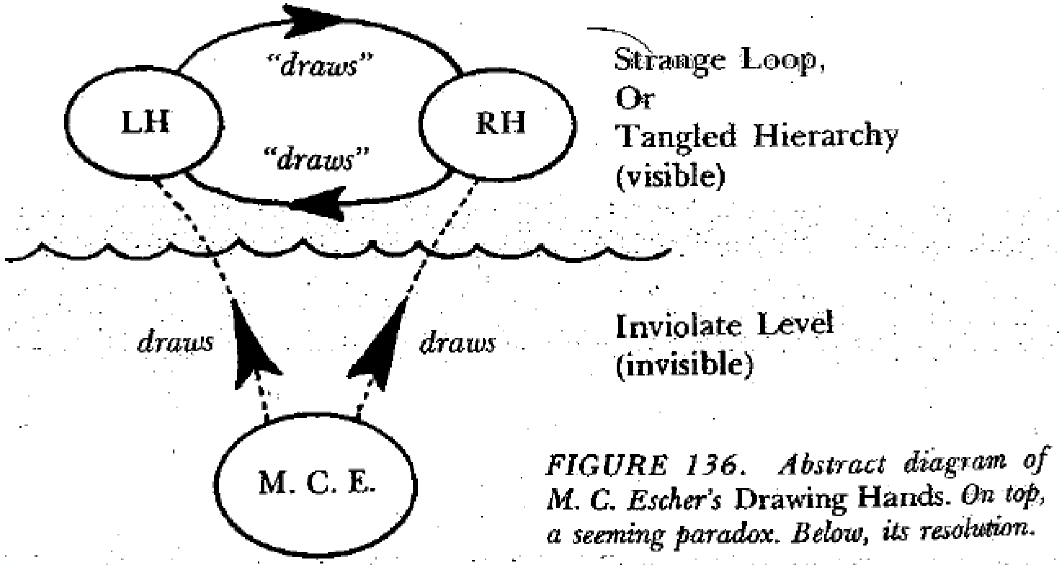
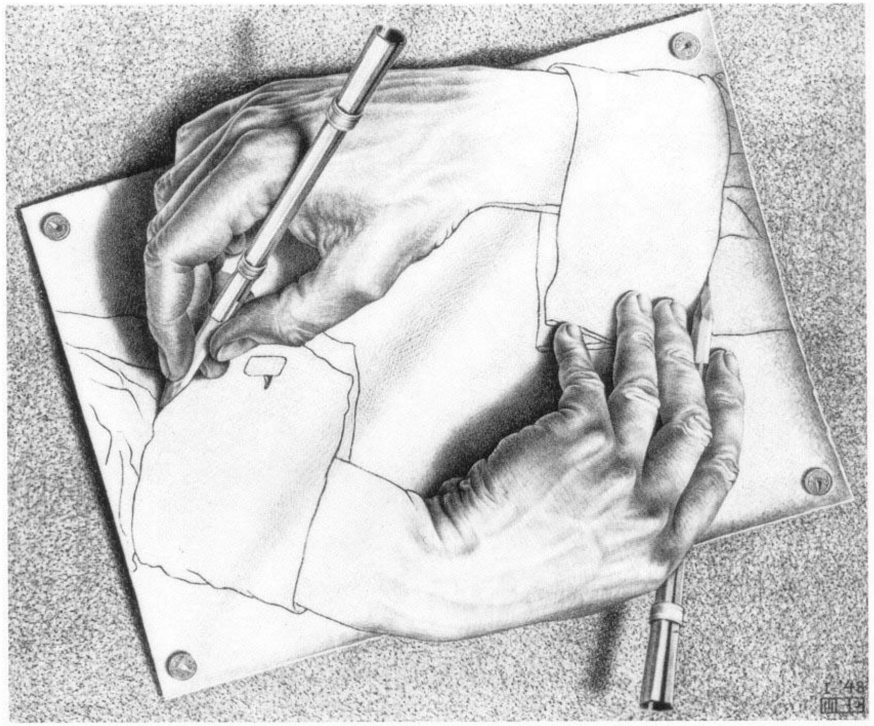


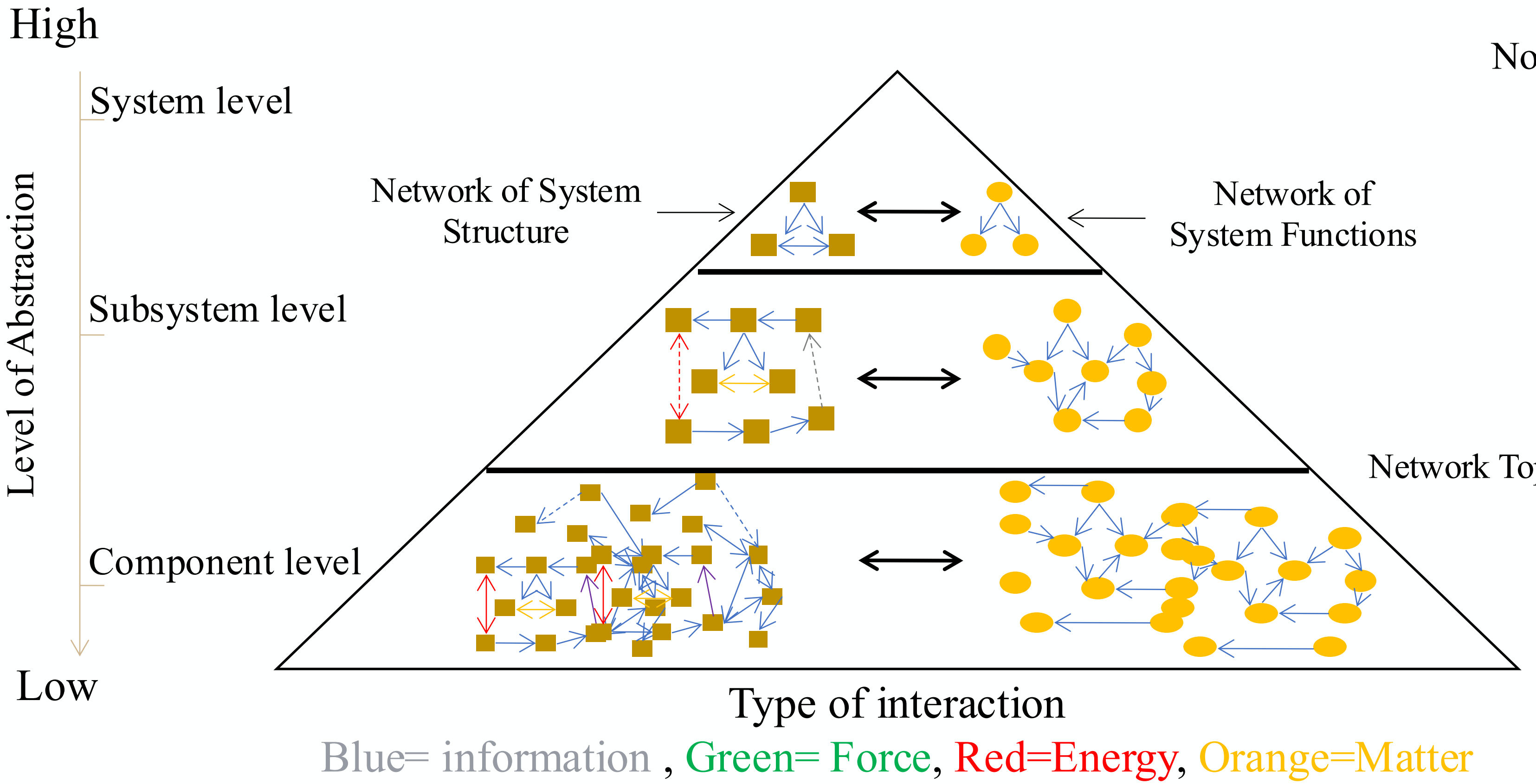
FIGURE 136. Abstract diagram of M. C. Escher's Drawing Hands. *On top, a seeming paradox. Below, its resolution.*

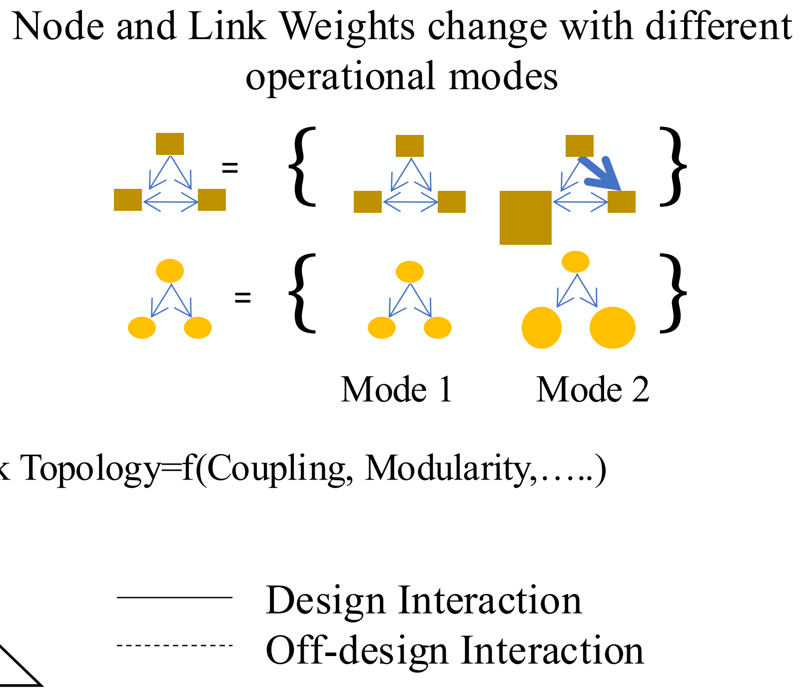


M.C. Escher- “Drawing Hands”, 1948

Towards the Science of System of System Integration

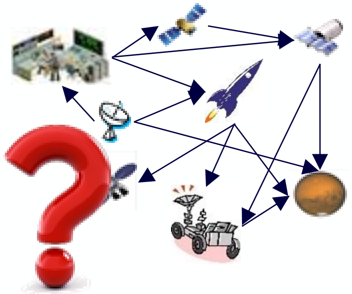
Complex Systems (of Systems) exhibit integration at multiple levels of hierarchy and must be studied as such, marrying structural and functional representations of the system, addressing cross-domain interactions and seeking appropriate allocations of complexity & autonomy.





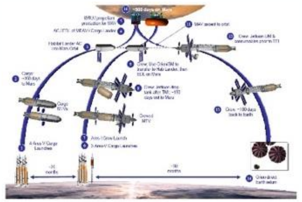
System Engineering Modeling Methods and Tools Tailored for SoS

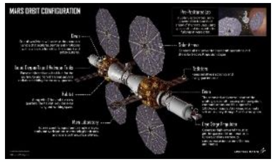
The How (at Purdue)

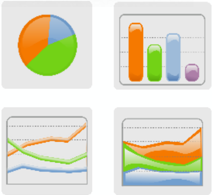


1. Build tools and methods for **quantitative evaluation of criticalities and impact of interactions** between systems/capabilities

2. Build tools and methods to **evaluate risks and robustness of different technological choices**, and their impact on complex architectures



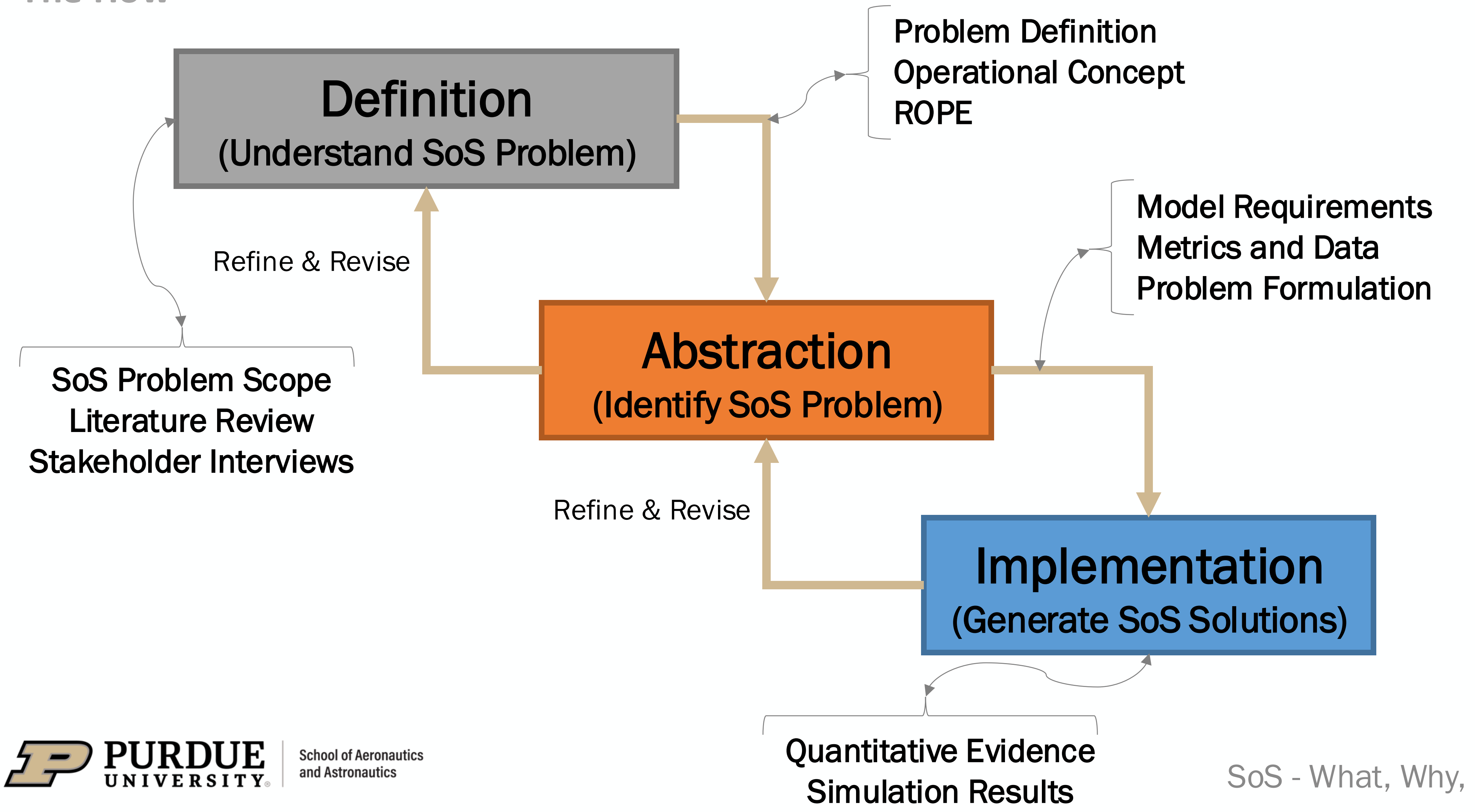




3. Build tools and methods for **to support architecture-level trade-off decisions for cost, risk, and performance**

One approach to these challenges: DAI Modeling & Analysis Phases

The How



From Definition to Abstraction

Recognizing Complexity in Hierarchy and "Beyond the Physics" in Representation: ROPE

Resources	Operations	Policy	Economics
Laws of Physics	*Human & Machine Activities, Processes*	*Rules, Constraints & Regulations*	*Human/Org Behaviors & Incentives*

Delta ← etc →

Gamma ← Network of Networks →

Beta ← Network of Collaborating CESs and human organizations →

alpha ← Complex engineered systems (CES) and humans →

The gist is socio-technical thinking…and modeling…but in a SoSE specific manner. Aspects of complexity and its role in judicious choices in representation of a system, network, or behavior matter quite a bit.

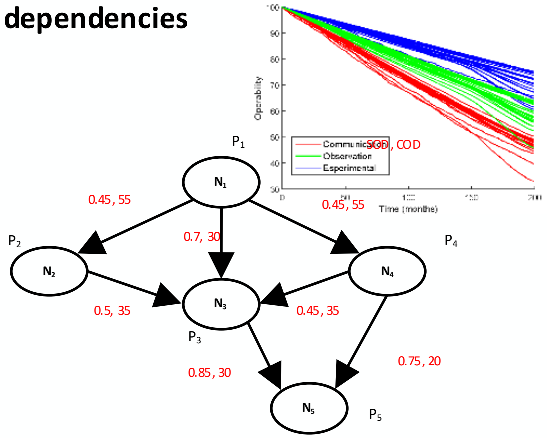
SoS Analytic Workbench: Created under the Systems Engineering Research Center (SERC)

A history of success in How to "do" SoSE

System Operational Dependency Analysis (SODA)

Assess impact of technical dependencies

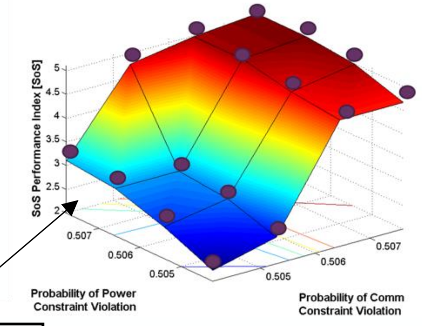
- Which systems are critical to SoS performance? SoS risks?
- What is the impact of partial/total system disruptions during operations?
- How do/should partial capabilities evolve over time?



Robust Portfolio Optimization (RPO)

Optimal System Selection and Architecture Design

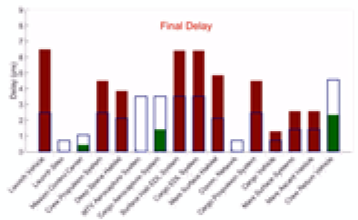
- Treat SoS as a portfolio of systems
- Model individual systems as nodes
- Represent as mathematical programming problem
- Determines "best" architecture based on
  - Stakeholder objectives
  - Architecture robustness
  - Cost and budget constraints



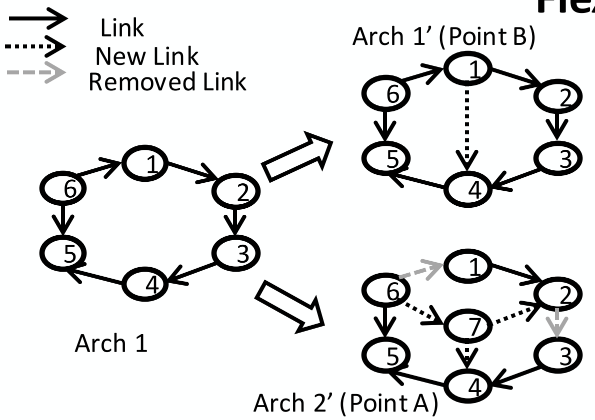
System Developmental Dependency Analysis (SDDA)

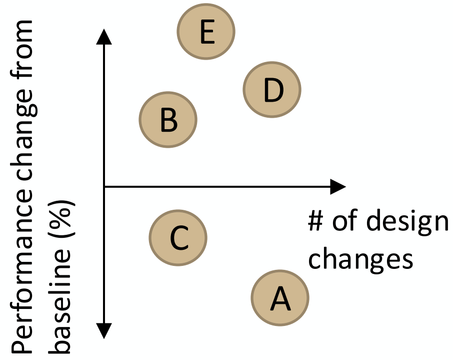
Assess impact of schedule dependencies

- How do/should partial capabilities evolve over time?
- What is the impact of development delays in an interdependent network?



Flexibility





SoS Example: Operational Limits in Urban Air Mobility

A recent example of independent stakeholder collaborating to a SoS

Motivation

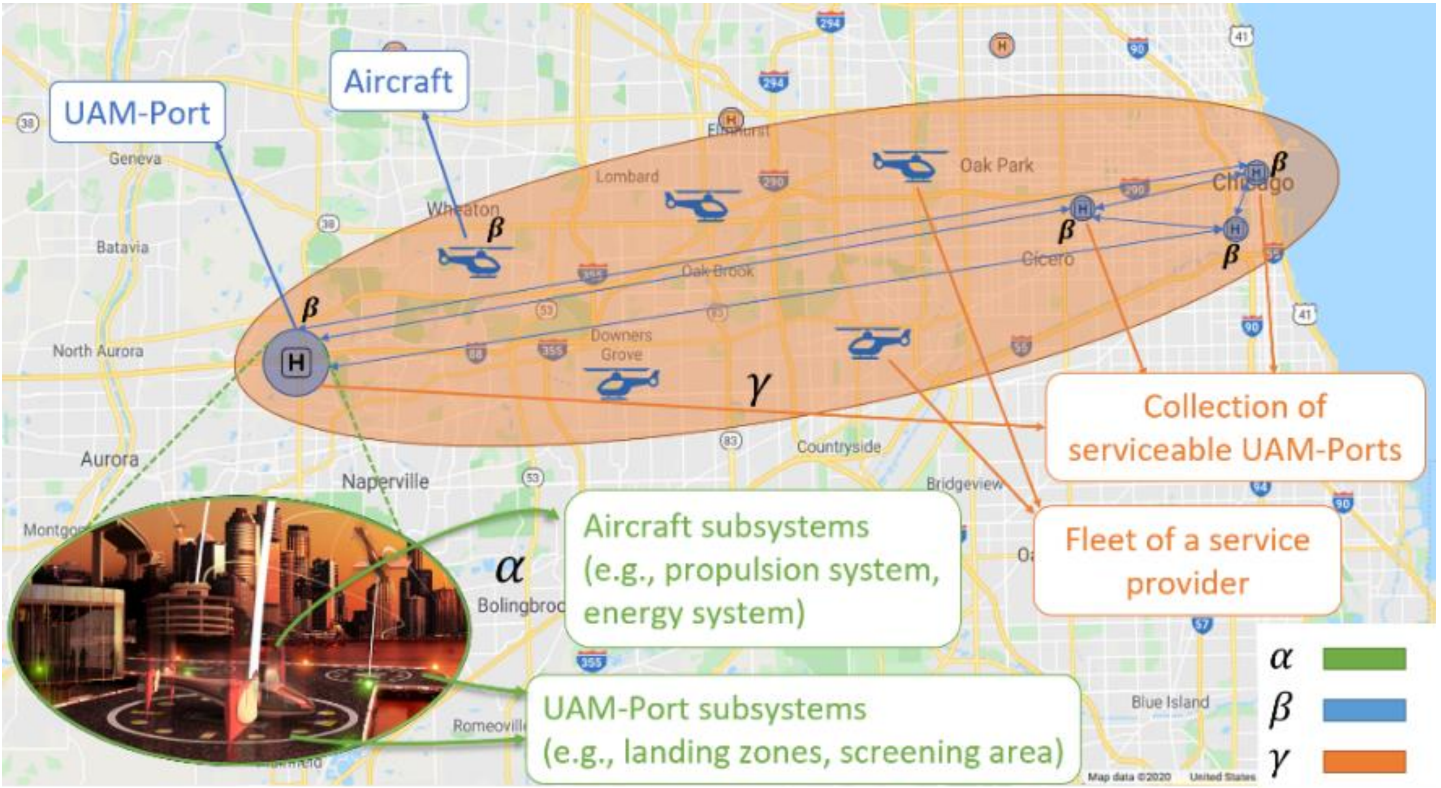
Convergence of new technologies and new business models leading to emergence of new aviation markets, e.g., passenger-carrying ***Urban Air Mobility (UAM)***

Important to assess the evolution of technology, infrastructure, societal acceptance, airspace integration, and many other factors to take us from the current state-of-the-art to the envisioned large-scale operations

For near-term applications of passenger-carrying UAM, identify **"bottlenecks" limiting the scalability of early UAM operations ("Op Limits")**

Create computer model, driven by appropriate data & scenarios, to analyze significance of key Op Limits

*System of System Modeling Approach**



Background Map data © 2020 Google

*Initial Metro Studies: Chicago and Dallas; Current work examines 5 more

Beyond the Basics: A Sample of Current Challenges in SoS

How do you know what is the appropriate modeling fidelity for SoS-level analysis?

- Multi-fidelity modeling in classic engineering systems provides some clues…but "its all physics"; in SoS, its "physics and beyond"
- How do you discover the right questions to ask in order to determine scope, model (or data) appropriateness
- Need benchmarks and use cases- have people exchange only models that are expressive enough for others to use them effectively

What kind and how much data do you need to answer a particular question, e.g. acquisition decision in a Mission Engineering (ME) context?

- This question is perhaps recast best as an uncertainty quantification (UQ) question
- Managerial independence – Service-level decision may satisfy local program objective but exacerbate gap in the joint portfolio
- Approaches:? "Keep your Options Open"- Set-based design; Robust Decision-making – robust to modeled uncertainty, or missing data, for given risk tolerance

How to <u>model, simulate, predict, explain, learn</u> in a future multi-domain, complex (commercial or military) scenarios?

- **Designing future Missions** is a tough SoS problem- operational and managerial independence of the components…fast-paced multi-domain battle with unknown techs → Perhaps AI/ML and Missions as Games
- Focus on optimizing incentives and levers - gaming, mechanism design
- Focus on Flexibility and Adaptability- How many solutions can be obtained in relatively few changes/enhancements- Hamming distance and the flexibility /cost ratio; Far beyond today's "War Gaming"

Thank You

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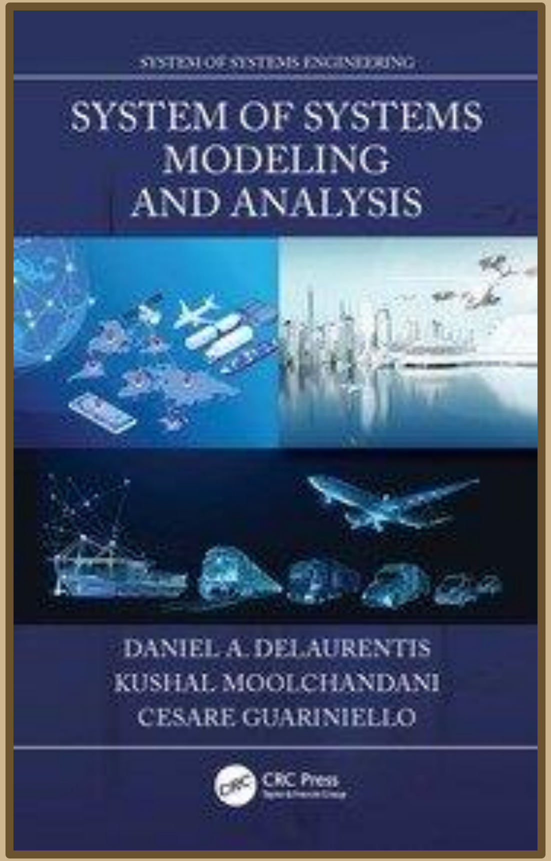

DeLaurentis, Moolchandani, Guariniello "System of Systems Modeling and Analysis" (CRC press, 2022)

The first System of Systems college textbook