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Presenter, Eric B. Dano, Ph.D.
BAE Systems, Electronic Systems (ES)
eric.b.dano@baesystems.com

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Introducing System Thinking Techniques into an Undergraduate Engineering Education

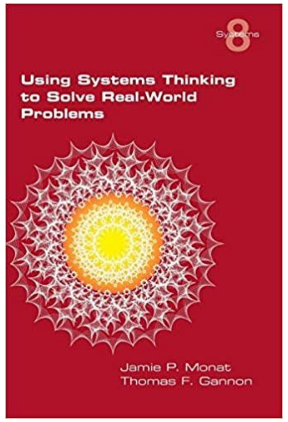
Outline

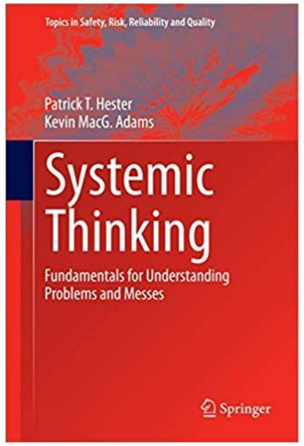
- Systems Thinking Overview
- System Thinking for the architectural development of complex engineered systems
- Integrating System Thinking aspects into undergraduate engineering curricula

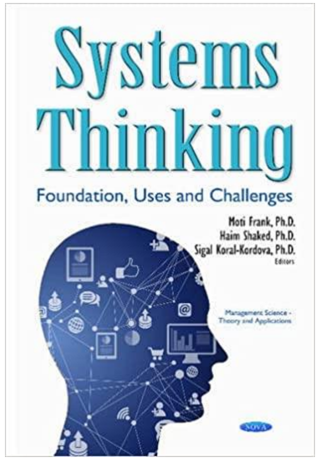
Definitions

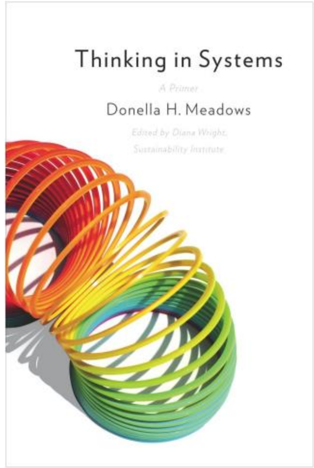
Systems Thinking - "A set of synergistic analytic skills used to improve the capability of identifying and understanding systems, predicting their behaviors, and devising modifications to them in order to produce desired effects," [1,2]

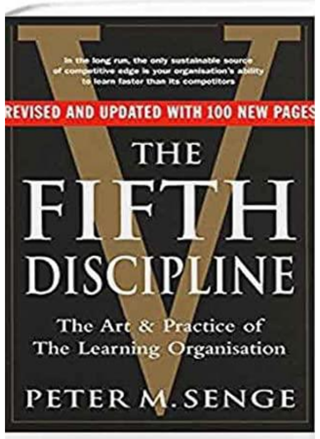
"**Systems Thinking** focuses on the relationships among system components and the interactions of the system with its environment, as opposed to focusing on the components themselves," [3]







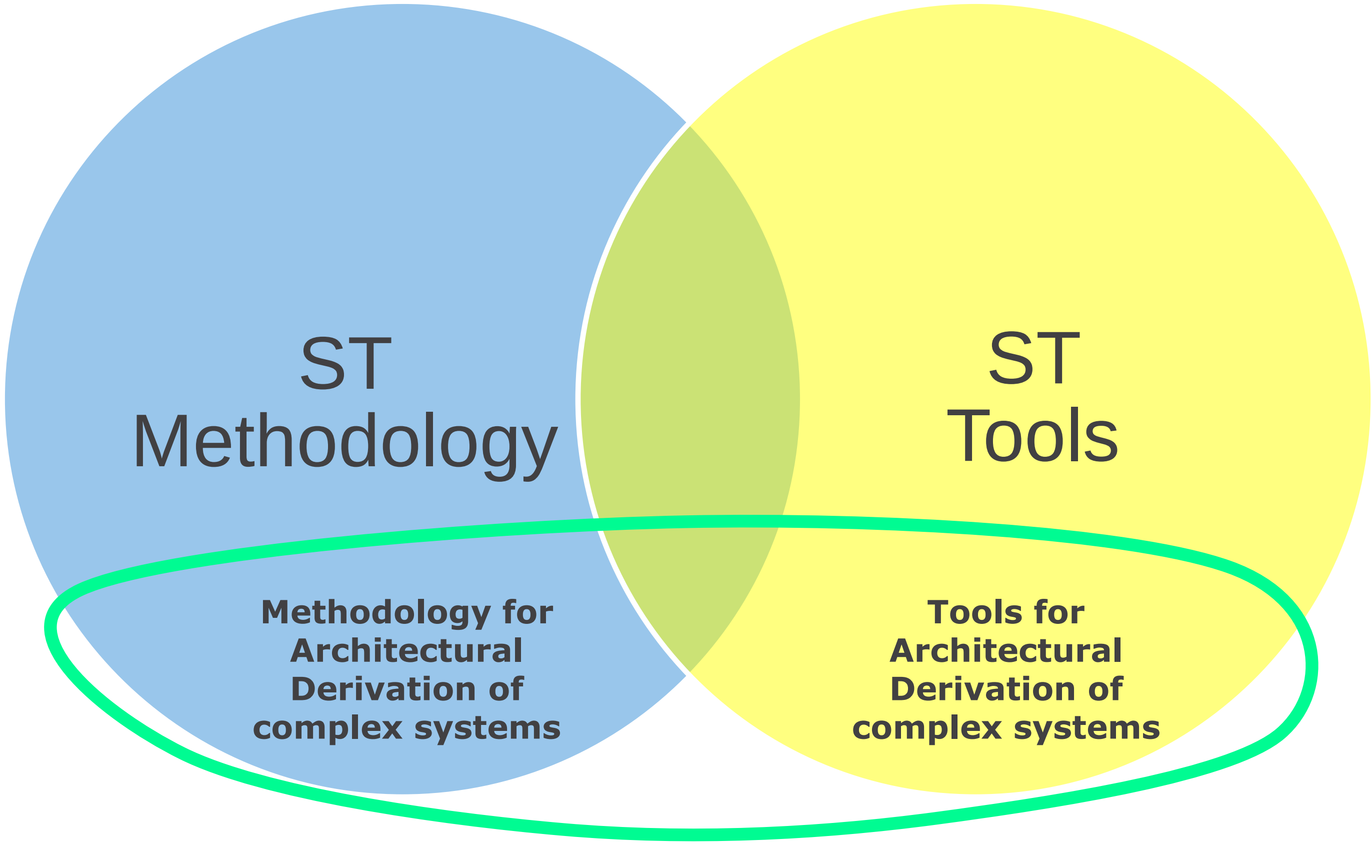




System Thinking (ST) Ontology

ST Methodology from Monat & Gannon [3]

1. "Develop and articulate problem statement
2. Identify and delimit the system
3. Identify the elements and patterns
4. Discover the structures
5. Discover the mental models
6. Identify and address archetypes
7. Model (if appropriate)
8. Determine the systemic root causes
9. Make recommendations
10. Assess improvements"



ST Tools from Monat & Gannon [3]

- "Iceberg" Model
- Causal Loop Diagrams
- Behavior Over Time Plots
- Stock and Flow Diagrams
- System Dynamics Modeling
- Archetype identification
- Root cause analysis
- Systemigrams
- Interpretive Structural Models

Specific tools used will depend on application

We will focus on the ST methods and tools used in the architectural derivation of engineered systems, as the architecture drives ~75% of the system cost and realized capabilities

Why System Thinking?

- "Technological advancement spawns system after system, each increasing in interdependence on other systems that have come before (Internet, GPS, power grid, etc.). These systems feed into each other to produce extremely complex, unpredictable effects. Through the use of systems thinking, one can hope to better understand the deep roots of these complex behaviors in order to better predict them and, ultimately, adjust their outcomes [1]."
- The INCOSE 2025 SE Vision states that systems engineering education must be advanced such that, "systems thinking is formally introduced in early education, systems engineering is a part of every engineer's curriculum, and systems engineering at the university level is grounded in the theoretical foundations that spans the hard sciences, engineering, mathematics, and human and social sciences [25]."

Complex Systems

- **Complex system -** "A system made up of a large number of parts that interact in a non-simple way" [4].
  - In a complex systems it becomes difficult to predict the emergent behavior of the complex system, whether it be desired (good) or undesired (bad).
  - System Thinking methods and tools are required to understand and reduce the complexity
- **Architecture –** "An abstract description of the entities of a system and the relationship between those entities" [5].
  - System Thinking methods and tools are required to understand and reduce the complexity
    - System complexity, and potentially emergent properties, can be reduced by using architectural derivation tools
    - Architecture must take a transdisciplinary approach to option generation in order to address complex systems [6].
  - Architecture Development Models (ADMs) are aligned with system thinking characteristics
    - Concept of Operations → Functional Decomposition → Allocation → Aggregation → Partitioning

System thinking is key to architectural derivation of engineered systems and is directly relevant to engineering students

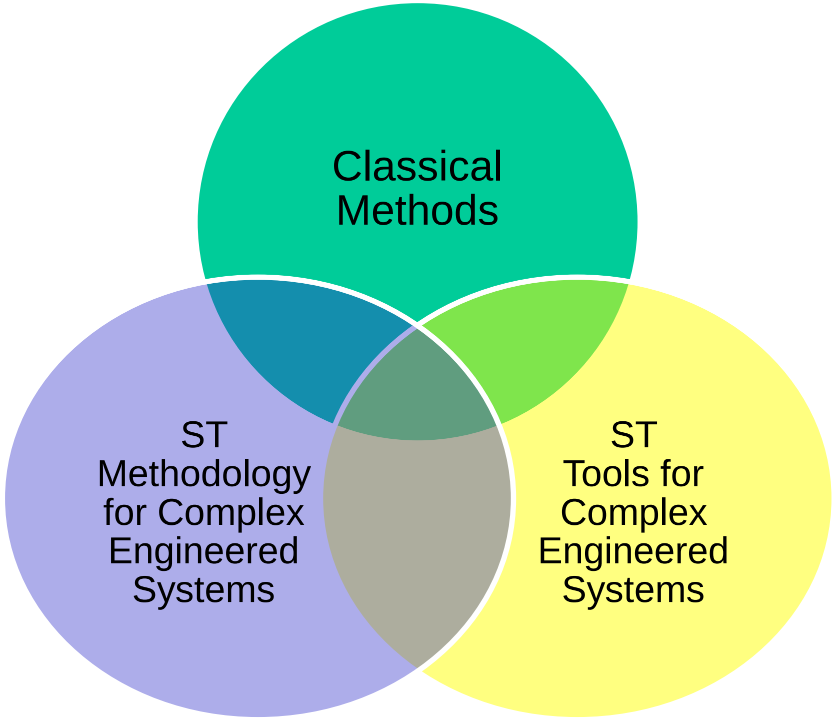
System Thinking (ST) Ontology

Classical Methods:

- Ability to perform sensitivity and error analysis
- Ability to use mathematical and statistical tools of analysis
- Ability to perform trades/analysis, and make data driven decisions

ST/Architecture Development Methodology :

1. Concept of Operations (ConOps)
   - Operational/Support/Cyber, etc.
   - Stakeholder Identification
2. Functional Architecture
   - Define/decompose top level functionality and define functional interdependencies
3. Logical Architecture I
   - Allocate functionality based on heuristics and required performance. Aggregate the allocated functions to create logical groupings of functions
4. Logical Architecture II
   - Define/document systems threads required to meet the top-level system functionality
5. Physical Architecture
   - Partition aggregated functions to specific system configuration items



ST Tools:

- As described in [3] and in addition . . .
- Option generation/brain storming/ conceptual design [5, 8]
- Perform holistic thinking/finding highest level objectives [5, 8]
- Using heuristics/design patterns [5, 8]
- Using analogies to create options [5, 8]
- Model based engineering [9]
- Digital system modeling [9]

And

- Softskills (leadership, team building, motivation, agile thinking, ethics, etc.)

All methods and tools are implementable in an undergraduate engineering education

System Thinking Competencies

Basic System Thinking [10]

- Option generation/brain storming/ conceptual design/Stakeholder ID
- Perform holistic thinking/finding highest level objectives
- Using analogies to create options
- Digital system modeling and simulation
- Understanding System Structure/ Scalability
- Recognizing Interconnections

Advanced System Thinking [1]

- Identifying feedback
- Differentiating types of stocks, flows, variables
- Understanding Non-Linear Relationships
- Understanding Dynamic Behavior
- Reducing Complexity

Basic Systems Thinking lends itself to undergraduate education

Advanced Systems Thinking lends itself to organizational training

Can System Thinking be Taught?

- Some say that system thinking can not be taught because of its abstract nature, or because human practitioners are unable to grasp the complexity of modern systems, and therefore a “natural reductionist” approach is defaulted to [22].
- Researchers have surveyed multiple engineers to determine their capacity for system thinking. Their findings include:
  - System thinking can be taught but will develop slowly in practitioners. [23]
  - System thinking development time was more correlated to the diversity of systems a practitioner was exposed to, than time spent on a given system. [24]
  - The current educational system is an inhibitor to systems thinking because schools are structured for students to find the correct answer over possibility exploration, and for memorization over problem solving. [22]
  - There was a correlation between personality traits of practitioners and their systems thinking capacity. [23]

Introducing Basic Systems Thinking into Undergraduate Education

Lecturing/Mentoring

Class projects

Case studies/Heuristics

Experimental Systems Engineering (ESE)

Exposure to the various multi-discipline system stakeholders

Conducting background research

System Thinking elements should be integrated directly into all engineering undergraduate courses

Incorporating System Thinking – Lecture/Mentoring

- Core courses should include mathematics, and computer science to build the necessary knowledge base for system thinking
- Humanities should also be taught to broaden cross domain/discipline thinking
- Integrate basic system thinking techniques in course lectures, homework and exercises with a focus on [11, 12, 14]:
  - Looking at problems holistically
  - Performing option generation
  - Formal Trades/Analyses
  - Modeling and Simulation
  - Stakeholder Identification
  - Error Analysis/Statistical Analysis
- Introduce the use of heuristics to the students (e.g. design patterns [13])

Incorporating System Thinking – Projects/Experiments

- Engineering Labs/Projects/Experiments are a key opportunity to introduce basic system thinking/classical methods [11, 12]:
  - Modeling and Simulation of system to predict expected performance
  - Big data collection and processing/Hypothesis Testing
  - Perform statistical analysis/report generation
  - Perform error analysis to understand accuracy of results and find error drivers
  - Documenting labs (early engineering process)

- The more detailed experiments also have additional advantages of [15, 16]:
  - Provides direct hands-on domain experience
  - Develops critical reinforcement of scientific method (analysis vs results)
  - Sharpens problem solving and resolution skills
- Projects provide leadership and team building experience

Incorporating System Thinking–Case Studies/Background Research

- Case Studies provide the ability examine system thinking in various domains/applications (e.g. [14, 15])
  - Successful Applications
  - Unsuccessful Applications
  - Introduction to System Thinking Methods/Tools [3]

- Background Researching improves the student's basic research skills, as well as building system thinking skills:
  - Well Defined Systems (simple systems)
    - Multi-Domain [18]
  - Ill-Defined systems (complex systems with emergence)
    - System of Systems [19]
    - Complex socio-technical [20]
    - Humanitarian Engineering [21]

Incorporating System Thinking–Multi-Discipline/Capstone Projects

- Multi-discipline capstone projects introduce students to aspects of system development they would not normally be exposed to, as well as advanced analysis tools/models [6, 17]:
- Holistic/Multi-Discipline Learning:
  - EE: Is a circuit card testable? Producible? Reliable? Cost Drivers?
  - SE: What are the interfaces and data flows between system elements? Dependencies?
  - SWE: How will the software be coded for debug? Security? HMI?
- Tools include: MagicDraw/Cappella, AutoCAD, Fortify, ANSYS …
- Projects provide leadership and team building experience

The student's research should purposely be selected to cover multiple domains, and include both well-defined and ill-defined systems

Advanced Systems Thinking in Organizations

Continue systems thinking learning/mentoring:

- Experience on assigned projects
- Performing trades/analyses
- Professional development
- In-house training courses
- Experience in multiple domains/technologies
- Experience with multiple stakeholders
- Graduate Certificates/Degrees

Learning the art and science of deriving and documenting a complex system architecture:

- Functional architecture
- Logical architecture
- Physical architecture
- System model
- System Artifacts

Organizational system architecture training:

- Concept of Operations
- System Architecture
- Frameworks (e.g. UML, SysML, DoDAF)
- Modular Open System Approach (MOSA)
- Model Based Engineering (MBE)
- Adv Degrees & Certs.

Relevant Tools and Processes will be given to the practitioners:

- Modeling and simulation tools
- System architecture /engineering tools
- Applicable processes
- Applicable Standards that systems must adhere to

Organizations will also put individuals in positions to hone both their leadership, communication and management skills. This provides the requisite “soft skills” needed to complement system architecture/system thinking effectiveness

Proposed ST Education Path

	High School	Undergraduate	Organization
Classical Methods	• Scientific method • Basic Math, Science and Humanities • Basic Computer Skills • Basic data analysis	• Trade Studies/Analysis • Adv. Math and statistics • Sensitivity analysis, Data analysis, error analysis • Scientific documentation • Advanced Computer Skills	• Architecture synthesis (functional, logical and physical architectures) • Multi-discipline aptitude • Architecture documentation • Big data processing

System Thinking (Tools & Methods)	• Holistic Thinking
	• Option generation
	• Simple systems
	• Reductionism
	• Simple tools and simulations
		• Basic System Thinking
		  • Option generation
		  • Conceptual design
		  • Heuristic use
		  • Complex systems
		  • Holism
		  • Stakeholder Identification
		• Formal lectures/mentoring
		• Multi-domain projects, and case studies
		• System simulations
		• Modeling languages/tools
			• Adv system thinking
			  • Recognizing Interrelations
			  • Understanding feedback and dynamic behavior
			  • System hierarchy , stock, flows and behavior
			  • Complexity reduction
			• SA/SE Process
			• Formal lectures/mentoring
			• Adv Multi-domain projects
			• Adv Modeling languages/ tools

Enablers	• Early Leadership experience • Communications skills	• Early Leadership experience • Communications skills	• Rotations/Leadership • SE process over lifecycle • Domain Training/Projects • Enabling Environment

Conclusions

- System thinking methods and tools were described for the purpose of architectural derivation
  - Directly relevant to engineering architecture and design in multiple-disciplines
- Integrating system thinking into an undergraduate engineering education develops:
  - Holistic Thinking – The ability to focus on the system and system elements simultaneously, and to see complex interactions internal/external to the system
  - Option Generation – The ability to define and assess a complete set of options for a given problem space
  - Stakeholder Identification – The ability to understand the various domains required to create a successful system, and the importance of including all stakeholder views in decisions
  - Dynamic Modeling – The ability to use modeling and simulation to predict dynamic performance for a system
  - Recognizing Interconnections – The ability to recognize interactions between system elements

System Thinking exercises provide a great opportunity to develop student's leadership, problem solving teamwork skills, and also reinforces classical methods

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www.incose.org/symp2022

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