INSIGHT

This Issue's Feature:

Advancing Systems Engineering in the Face of Complexity

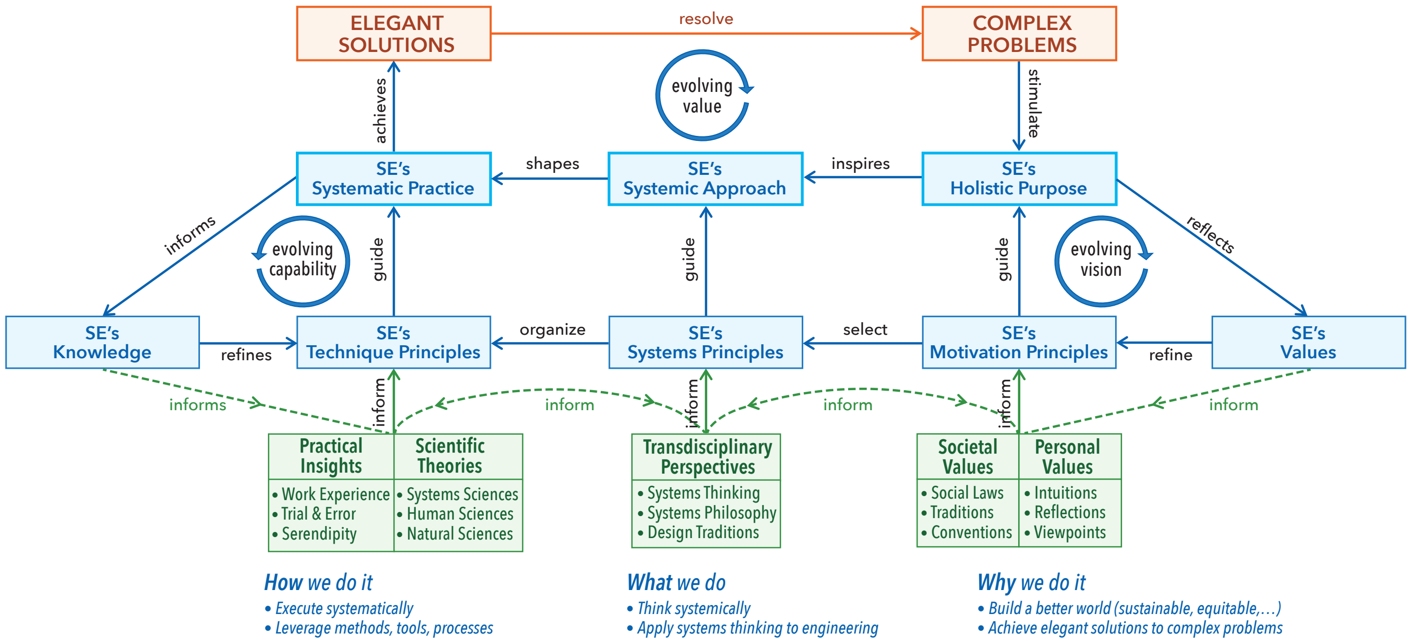

Illustration credit: from the article
Systems Engineering and the Pursuit of Elegance: A Transdisciplinary Approach to Complex Problems
by Michael Pennotti, Peter Brook, and David Rousseau (page 8)

APRIL 2024
VOLUME 27 / ISSUE 2

INCOSE

A PUBLICATION OF THE INTERNATIONAL COUNCIL ON SYSTEMS ENGINEERING

CALL FOR PAPERS

Special Issue on Advancing Systems Engineering in the Face of Complexity

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OBJECTIVES

Systems Engineering Journal in collaboration with INCOSE's Future of Systems Engineering (FuSE) Program invites submissions for a special issue focusing on the evolution and advancement of Systems Engineering (SE) in addressing the engineering of increasingly complex systems.

BACKGROUND

Historically, Systems Engineering has been pivotal in the development of methods for designing large technical systems. This legacy of success has positioned SE at the forefront of disciplines sought to provide effective methodologies for engineering complex systems in our rapidly evolving world. However, we recognize that current SE approaches face limitations when applied to the multifaceted nature of social, technical, and ecological systems of systems – areas that are increasingly recognized as being in critical need of innovative engineering solutions.

SCOPE

This special issue seeks to address these challenges by advancing both the theoretical and practical dimensions of Systems Engineering. We are calling for papers that offer groundbreaking insights, methodologies, and applications that can enhance the capacity of SE to effectively engineer complex systems. Topics of interest include, but are not limited to:

- Innovative theoretical frameworks in SE for non-traditional domains.
- Case studies demonstrating novel applications of SE in social, technical, and ecological domains.
- Cross-disciplinary approaches integrating SE with other fields, such as Systems Science, to address complex challenges.
- Analysis and critique of current SE methodologies in the context of increasingly complex systems.
- Demonstrations of new tools, techniques, and practices in SE that can be applied to many kinds of systems.
- Empirical studies that validate the value of new theories, methods, and tools.

SUBMISSION GUIDELINES

We invite authors to submit papers that push the boundaries of our current understanding and practice of Systems Engineering. Submissions should be original, well-researched, and provide significant contributions to the field. Both theoretical and applied research papers are welcome. Detailed submission guidelines, including formatting and length requirements, can be found on the Systems Engineering journal's website.

IMPORTANT DATES

- **Submission Deadline:** Nov. 1, 2024
- **Notification of Acceptance:** Jan. 1, 2025
- **Final Manuscripts Due:** March 1, 2025
- **Publication Date:** April 1, 2025

SUBMISSION PROCESS

Manuscripts should be submitted through the Systems Engineering Journal's online submission portal. Please indicate in your submission that your manuscript is intended for the special edition on "Advancing Systems Engineering in the Face of Complexity."

GUEST EDITORS

- **Dr. Erika Palmer**, Cornell University (USA)
- **Prof. Peter Brook**, FREng, INCOSE Fellow, Dashwood Systems Engineering (UK)
- **Dr. Michael Pennotti**, PhD, INCOSE Fellow, Stevens Institute of Technology (USA)
- **Dr. David Rousseau**, PhD, FRSA, INCOSE Fellow, Centre for Systems Philosophy (UK), & Oregon State University (USA)
- **Dr. Javier Calvo-Amodio**, PhD, ASEM Fellow, Oregon State University (USA)

INSIGHT

A PUBLICATION OF THE INTERNATIONAL COUNCIL ON SYSTEMS ENGINEERING

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About This Publication

INFORMATION ABOUT INCOSE

INCOSE's membership extends to over 20,000 members and CAB associates and more than 200 corporations, government entities, and academic institutions. Its mission is to share, promote, and advance the best of systems engineering from across the globe for the benefit of humanity and the planet. INCOSE charters chapters worldwide, includes a corporate advisory board, and is led by elected officers and directors.

For more information, click here:
The International Council on Systems Engineering
(www.incose.org)

OVERVIEW

INSIGHT is the magazine of the International Council on Systems Engineering. It is published four times per year and features informative articles dedicated to advancing the state of practice in systems engineering and to close the gap with the state of the art. ***INSIGHT*** delivers practical information on current hot topics, implementations, and best practices, written in applications-driven style. There is an emphasis on practical applications, tutorials, guides, and case studies that result in successful outcomes. Explicitly identified opinion pieces, book reviews, and technology roadmapping complement articles to stimulate advancing the state of practice. ***INSIGHT*** is dedicated to advancing the INCOSE objectives of impactful products and accelerating the transformation of systems engineering to a model-based discipline.
Topics to be covered include resilient systems, model-based systems engineering, commercial-driven transformational systems engineering, natural systems, agile security, systems of systems, and cyber-physical systems across disciplines and domains of interest to the constituent groups in the systems engineering community: industry, government, and academia. Advances in practice often come from lateral connections of information dissemination across disciplines and domains. ***INSIGHT*** will track advances in the state of the art with follow-up, practically written articles to more rapidly disseminate knowledge to stimulate practice throughout the community.

PERMISSIONS

ARTICLE SUBMISSION insight@incose.net

Publication Schedule. ***INSIGHT*** is published six times per year. Issue and article submission deadlines are as follows:

- June 2024 issue – 1 March 2024
- August 2024 issue – 1 May 2024
- October 2024 – 1 July 2024
- December 2024 – 1 September 2024
- February 2025 issue – 1 November 2024
- April 2025 issue – 2 January 2025

For further information on submissions and issue themes, visit the INCOSE website: www.incose.org

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FROM THE EDITOR-IN-CHIEF

William Miller, insight@incose.net

We are pleased to announce the April 2024 *INSIGHT* issue published cooperatively with John Wiley & Sons as the systems engineering practitioners' magazine. The *INSIGHT* mission is to provide informative articles on advancing the practice of systems engineering and to close the gap between practice and the state of the art as advanced by *Systems Engineering*, the Journal of INCOSE also published by Wiley.

The focus of this April issue of *INSIGHT* is advancing systems engineering in the face of complexity. We thank INCOSE technical products & services director Erika Palmer for engineering the collaboration of both *INSIGHT* and the *Systems Engineering* journal with the future of systems engineering (FuSE) program (www.incose.org/fuse) to realize the *Systems Engineering Vision 2035* (www.incose.org/publications/se-vision-2035). This issue of *INSIGHT* is to be followed with a special issue of the *Systems Engineering* journal having the same focus scheduled for publication in April 2025 with the support of the journal's editor-in-chief Clifford Whitcomb. The call for papers for the journal was announced at the INCOSE 2024 International Workshop in Torrance, CA, US in January with the paper submission deadline 1 November 2024.

We thank theme editor and INCOSE fellow David Rousseau for shepherding the first four coupled articles and technical products manager Christian Sprague for technical editing. The inspiration for advancing systems engineering in the face of complexity came out of the spontaneous networking of INCOSE fellows Peter Brook, Michael Pennotti, and David Rousseau, collectively named the *bridge team*, interacting with and supporting two FuSE projects: 1) the systems engineering principles action team led by current INCOSE president-elect Michael Watson developing the *Systems Engineering Principles* (https://portal.incose.org/commerce/store?productId=INCOSE-SEPRINCIPLE), and 2) the group of the INCOSE fellows led by Dorothy McKinney developing the *systems engineering heuristics* (https://www.incose.org/learn/incose-pdp/supporting_pages/pdp-heuristics). The *bridge team*, now including INCOSE systems science working group chair Javier Calvo-Amodio (https://www.incose.org/communities/working-groups-initiatives/systems-science), came to the realization from supporting the principles and heuristics developments that systems engineering needs to go beyond process and methodology to recognize that it must leverage it's being a transdisicipline to devise elegant solutions to the complex challenges we face in the engineering of systems and systems-of-systems. This collective collaboration of systems engineers from industry, academia, and government(s), networking both within INCOSE and within the broader systems community, demonstrates the unique value that INCOSE brings towards a better world through a systems approach.

"Systems Engineering and the Pursuit of Elegance: A Transdisciplinary Approach to Complex Problems" by Michael Pennotti, David Rousseau, and Peter Brook addresses the challenge for systems engineering to remain relevant given the increasingly complex landscape of advanced technologies. Systems engineering originated with a pragmatic focus on achieving technical objectives but shifted towards process and methodology. They argue for a return to its roots as a transdiscipline necessary for devising elegant solutions to today's complex challenges. The authors present a comprehensive framework around the nature of systems engineering, detailing its principles, methods, and purposes, thereby demonstrating its links to numerous disciplines and social institutions, showcasing its multifaceted impact. The intent is to foster a common recognition of systems engineering's value, ensuring its continued significance in a rapidly evolving world.

"Advancing System Engineering's Relevance in a Changing World" by Peter Brook, Michael Pennotti, and David Rousseau state that to be relevant, systems engineering must expand its scope beyond the technical realm by addressing today's most pressing and complex problems, which span technical, social, and ecological domains. They propose collaborative strategies with other disciplines to enhance and broaden systems engineering's foundational base, crucial for realizing its potential as a transdisciplinary field in an increasingly complex world.

"Five Perspectives on Transdisciplinary Systems Engineering" by Peter Brook, Azad Madni, Michael Pennotti, David Rousseau, and Hillary Sillito offers insights from five INCOSE fellows on the evolution and significance of transdisciplinary in system engineering. Michael Pennotti reviews the origins of systems engineering, emphasizing its inherent transdisciplinary nature and the need for continuous evolution. Azad Madni considers transdisciplinarity as systems engineering's true calling, crucial for the 21st century, and highlights his TRASEE™ program at the University of Southern California as pivotal for systems engineering's advancement. Hillary Sillitto sees the climate crisis as systems engineering's most critical and complex challenge, asserting transdisciplinarity's crucial role in addressing it. David Rousseau examines the cultural and scientific underpinnings of transdisciplinarity, presenting systems engineering as a prime example. Peter Brook envisions the joint evolution of systems sciences and systems engineering to confront future challenges, advocating for transdisciplinarity as an essential role in systems engineering leadership for addressing global challenges.

"The Spectrum and Evolution of Systems Engineering's Guiding Propositions" by David Rousseau, Michael Pennotti, and Peter Brook observe that systems engineering has numerous guiding propositions scattered across various publications and classified under different schema, leading to confusion and inconsistency. They present a framework for understanding the origin and evolution of a guiding proposition and developing a guiding proposition into a principle to meet the challenges of Industry 4.0 and Society 5.0. They argue that following this process will enhance the elegance and transdisciplinary value of systems engineering principles and aid in solving complex problems.

The additional contribution beyond the first four coupled articles in the April 2024 *INSIGHT* by Stuart Harshbarger and Rosa Heckle is titled "Transitioning Science to Practice". National security challenges require a new approach to collaborative problem solving to address emergent challenges or opportunities. Development of artificial intelligence (AI) technologies including machine learning (ML) and deep learning (DL), is underway. Advancing AI/ML capabilities requires transdisciplinary research encompassing the fusion of technology and emergent scientific discovery. Achieving this requires a departure from traditional research and development (R&D) methods. New development processes need to support the understanding that research progresses iteratively, technology insertion is incremental, and the final capability is evolutionary. The authors propose a novel systems engineering/research model called the vortical model, illustrated with a case study applying machine learning based computer vision research to improve optical character recognition (OCR) capabilities.. The vortical model introduces an iterative framework through which emerging advances in research outcomes are effectively demonstrated and validated for integration, as new capabilities, at varying technology insertion points. The goal is to facilitate the transfer of knowledge from emerging research for swift, effective integration into the organization's mission capabilities.

We hope you find *INSIGHT*, the practitioners' magazine for systems engineers, informative and relevant. Feedback from readers is critical to *INSIGHT*'s quality. We encourage letters to the editor at insight@incose.net. Please include "letter to the editor" in the subject line. *INSIGHT* also continues to solicit special features, standalone articles, book reviews, and op-eds. For information about *INSIGHT*, including upcoming issues, see https://www.incose.org/products-and-publications/periodicals#INSIGHT. For information about sponsoring *INSIGHT*, please contact the INCOSE marketing and communications director at marcom@incose.net. ■

INSIGHT Special Feature

Systems Engineering and the Pursuit of Elegance: A Transdisciplinary Approach to Complex Problems

Michael Pennotti, Peter Brook, and **David Rousseau**
Corresponding Author, david.rousseau@systemsphilosophy.org

ABSTRACT

In an increasingly complex landscape of advanced technologies, the question of how systems engineering can retain its relevance is more pertinent than ever. Originating with a pragmatic focus on achieving technical objectives, systems engineering has shifted towards process and methodology. We argue, however, that it's time for this discipline to return to its roots and embrace its nature as a transdiscipline. Transdisciplinarity is not just a characteristic of systems engineering; it's necessary for devising elegant solutions to today's complex challenges. In this article, we present a comprehensive framework around the nature of systems engineering, detailing its principles, methods, and purposes. This framework demonstrates how systems engineering is linked to numerous disciplines and social institutions, showcasing its multifaceted impact. By understanding and using this framework as a lens on the discipline, we can foster a common recognition of systems engineering's value, ensuring its continued significance in a rapidly evolving world.

INTRODUCTION

Systems engineering, though relatively young, is a rapidly evolving discipline due to the increasing recognition of the need for a systems approach. A systems approach aids in the successful engineering of complex systems and creative solutions to intricate problems. The need for a systems approach arises from various factors:

- Explosive growth in technical capabilities driven by scientific and technological advancements.
- Escalating financial and performance risks in complex, interdependent development projects.
- Acknowledgment of the systemic complexity in urgent human and ecological issues.
- Growing awareness of the necessity for cross-disciplinary collaboration, especially for global-scale challenges.
- Recognition of the immaturity of systems engineering's theoretical foundations, particularly in understanding and designing for cross-disciplinary interests.

Amidst these challenges, members of the systems engineering community have begun to compile lists of heuristics, principles, and guiding propositions, seeking to learn from past experiences and avoiding rigid adherence to outdated 'best practices.'

These guiding propositions help gauge the maturity of systems engineering as they compress and organize insights on efficient engagement with complexity. However, the challenge lies in the lack of coordination and standardization in current efforts, introducing complexity into education and practice.

This article arose in the context of a project initiated by the International Council on Systems Engineering (INCOSE) under the collective name "Bridge Team," to explore the relationship between heuristics and principles. That project investigated how systems engineering discovers and applies diverse guiding propositions, contributing to the evolution of systems engineering. This article presents a framework for understanding systems engineering's architecture in the context of its ongoing evolution, driven by clarification and enhancement of its guiding propositions.

With this framework, organizations like INCOSE can accelerate the discipline's evolution to support their mission of building a better world through a systems approach. This involves curating guiding propositions, guiding systems engineering's development as a disciplined profession with clear standards and unique value, inspiring future practitioners, and actively and purposefully engaging other disciplines.

BACKGROUND

This research project is part of INCOSE's "Future of Systems Engineering" (FuSE) initiative, which was initiated in late 2020 with the aim of establishing insights and a framework to connect two other projects: one focusing on compiling "systems engineering heuristics" based on the work of Maier and Rechtin (2009), the other refining a smaller set of "systems engineering principles" drawing from the NASA Systems Engineering Consortium (Watson 2022). The distinction between principles and heuristics and their relationship to other guiding propositions like axioms, rules, and tenets was initially unclear. This ambiguity extended to how these insights should inform one another and be operationalized. To investigate these issues, the authors conducted a comprehensive review of diverse guiding propositions and the evolution of systems engineering practices and purposes.

Progress and discussions took place in various forums, including quarterly meetings with related FuSE projects and presentations at the INCOSE International Workshops in 2021, 2022, and 2023, at the INCOSE International Symposiums in 2021 and 2022, to the Royal Academy of Engineering in October 2021, and to the Enchantment Chapter of INCOSE in March 2022, and to INCOSE's Europe, Middle East and Africa Sector Systems Engineering Conference 2023. These interactions played a crucial role in shaping the research scope and findings.

This research yielded two main themes:

First is a framework for relating guiding propositions. This framework clarifies the origins, types, refinement mechanisms, and generalization processes of guiding propositions. It suggests that all types of guiding propositions can be termed "principles" when supported by rational evidence, such as scientific theory or simulation. The present article adopts this terminology.

Second is a framework on the trajectory of systems engineering, the subject of the present article. It conceptualizes the evolution of systems engineering from its inception in the 1940s to the present day. It highlights the shift from a focus on 'objectives to be achieved' to an emphasis on formal techniques and processes, sometimes to the detriment of systems engineering's impact and potential. Recent efforts aim to bring systems engineering back to its roots, focusing on elegant solutions to complex problems. The paper presents a framework that describes systems engineering as an evolving transdiscipline with enduring impact and relevance. It emphasizes systems engineering's role in various disciplines and social institutions. Additionally, it discusses how systems engineering is evolving to embrace its transdisciplinary nature and leadership in practical transdisciplinarity. Finally, it emphasizes the value of this framework in fostering a common understanding of the significance and potential of systems engineering, supporting INCOSE's broader mission of creating a better and more sustainable world.

EVOLUTION OF SYSTEMS ENGINEERING'S FOCUS: FROM COMPLEXITY TO DESIGN

To better understand the nature of systems engineering we began by looking at its history. Systems engineering emerged as a recognized discipline in the 1940s, driven by the escalating complexity of technology during World War II and the rapid expansion of the US telecommunications network (Pennotti, n.d.). Initially, it represented a systemic approach to problem-solving, essentially applying systems thinking to engineering. At this stage, systems engineering lacked a structured methodology, and its effectiveness was measured by the quality of the systems it produced.

For instance, a seminal paper by Engstrom (1957) outlined two essential requirements for successful systems engineering: "First, a determination of the objective that is to be reached; and second, a thorough consideration of all the factors that bear upon the possibility of reaching the objective and the relationships among these factors." Notice that Engstrom told us what we have to do to be successful but not how to do it. The reason for this is evident: the objective depends on the specific problem at hand, requiring a deep understanding of the user's needs, the system's context, and the desired system functionality. Identifying the factors affecting the objective's attainment demands comprehensive knowledge of the evolving system design, underlying technology, interdependencies with other systems, and ongoing discoveries. These considerations are problem-specific and lack universal applicability. During this era, systems engineers were domain specialists deeply immersed in their respective fields, such as communications, aerospace, or radar systems. While case studies from this period described their practices, they served as illustrations rather than strict guidelines.

This situation posed challenges for traditional engineers accustomed to disciplines grounded in objective science and mathematics. SE, as a novel discipline, diverged significantly, prompting some to develop prescriptive processes and standards to systematize it. However, this abstraction led to a disconnect between systems engineering and its applied domains, diminishing its practical relevance (Pennotti 2022).

As early as 1969, Robert Frosch, then Assistant Secretary of the US Navy and later NASA Administrator, expressed concerns about systems engineering's shift towards valuing tools over judgment and prioritizing meeting management processes over delivering satisfactory systems. Frosch (1969) emphasized that engineering is an art, not just a technique, and questioned whether systems engineering was producing elegant solutions to real problems. This sentiment was echoed in the view of another former NASA Administrator, Mike Griffin, who emphasized that systems engineering's purpose should be attaining elegant designs, not just satisfying requirements and processes. Griffin (2010) went on to propose four criteria for design elegance:

- Does the system work?
- Is it robust? If the context changes, does it degrade gracefully or fail catastrophically?
- Is it efficient? … not only in terms of financial resources, but also human resources, energy resources, environmental resources, etc.
- Does it minimize unintended actions, side effects, and consequences?

It's essential to clarify that both Frosch and Griffin were addressing the rising number of project failures and advocating against blind reliance on processes and techniques. Frosch called for elegant solutions to complex problems, considering multiple value criteria beyond immediate problem-solving. Griffin extended this idea by emphasizing the creative aspect of systems engineering and the attainment of elegant designs. In essence, they encouraged a holistic approach, incorporating tacit knowledge, intuition, aesthetics, and systems thinking to balance a wide range of value criteria in the pursuit of elegant solutions.

For present purposes, we succinctly describe Griffin's idea as "the purpose of systems engineering is to attain elegant solutions to complex problems." This concept has led to a burgeoning 'elegant design paradigm' in systems engineering, inspiring significant research and discussion. Key questions include how systems engineering's use of 'elegance' compares to its application in fields like

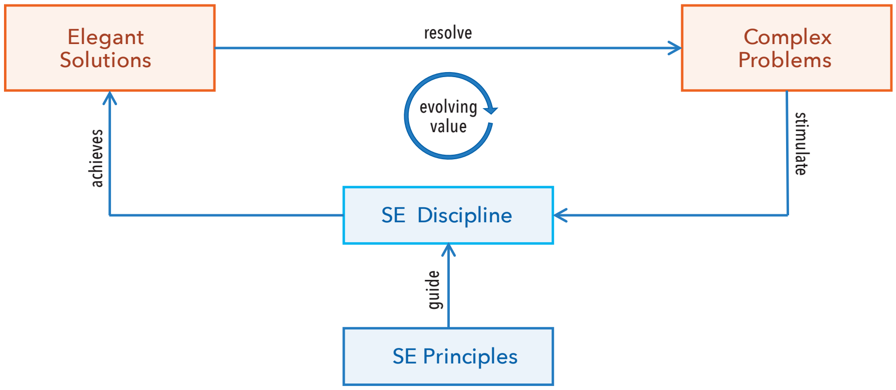

Figure 1. The discipline's relationship to purpose and principles

mathematics or art, and the implications and value of 'elegant' designs in systems engineering.

Griffin's definition of elegance in systems engineering, widely debated and expanded upon, is now termed "Griffin elegance" to distinguish it from broader uses of the term. This is similar to how 'entropy' has various specific forms, like Shannon entropy and thermodynamic entropy. Systems engineering's version of elegance is thus a distinct perspective.

The importance of elegance is highlighted by its practical and strategic benefits. Elegant designs simplify implementation and are seen as indicators of 'systemic virtues', akin to personal and theoretical virtues, leading to longevity and community value.

Reconciling Griffin's view with other authoritative systems engineering definitions shows that while there are multiple expressions of systems engineering's purpose, they essentially expand on Griffin's concise framing. For example, it well aligns with INCOSE's vision of a better world through a systems approach, and it's adaptable to various project contexts.

The Frosch and Griffin inspired definition of systems engineering's purpose – the purpose of systems engineering is to attain elegant solutions that resolve complex problems – focuses on elegance. This emphasis on value over tools and procedures is crucial for systems engineering's continued relevance, especially as problem complexity grows. That is, the more complexity increases the more we need competent system engineers to ensure not only that these systems do not overwhelm the stability of our societies, but moreover that make progress towards "a better world."

This growth in system complexity demands an equal growth in systems engineering's power and relevance, a virtuous cycle that we call the value loop, see Figure 1. Fundamentally, these principles guide the discipline through the value loop. These principles are defined as fundamental ideas for achieving elegant solutions.

We categorize the systems engineering principles into three kinds: technique, systems, and motivation principles, see Figure 2. Technique principles guide the systematic practice of *how* we do what we do. Systems principles guide the systemic approach, which is *what* it is we do. Motivation principles guide our holistic purpose: *why* we do what we do. While systems engineering has largely focused on technique, we seek to broaden and revisit systems and motivation principles to encourage systems engineering's ongoing evolution and value.

THE EVOLUTION OF SYSTEM ENGINEERING'S PRINCIPLED ARCHITECTURE

Examples of principles supporting systems engineering

Systems engineering principles are numerous and varied, with ongoing efforts within INCOSE to collate and organize them. While there is no definitive collection yet, we provide examples in Table 1 to illustrate the range of principles, though they are not exhaustive or definitive.

Technique Principles (Table 1, column 1) address 'how' systems engineering is practiced. This category, the focus of most projects outlining systems engineering principles, includes a mix of scientific

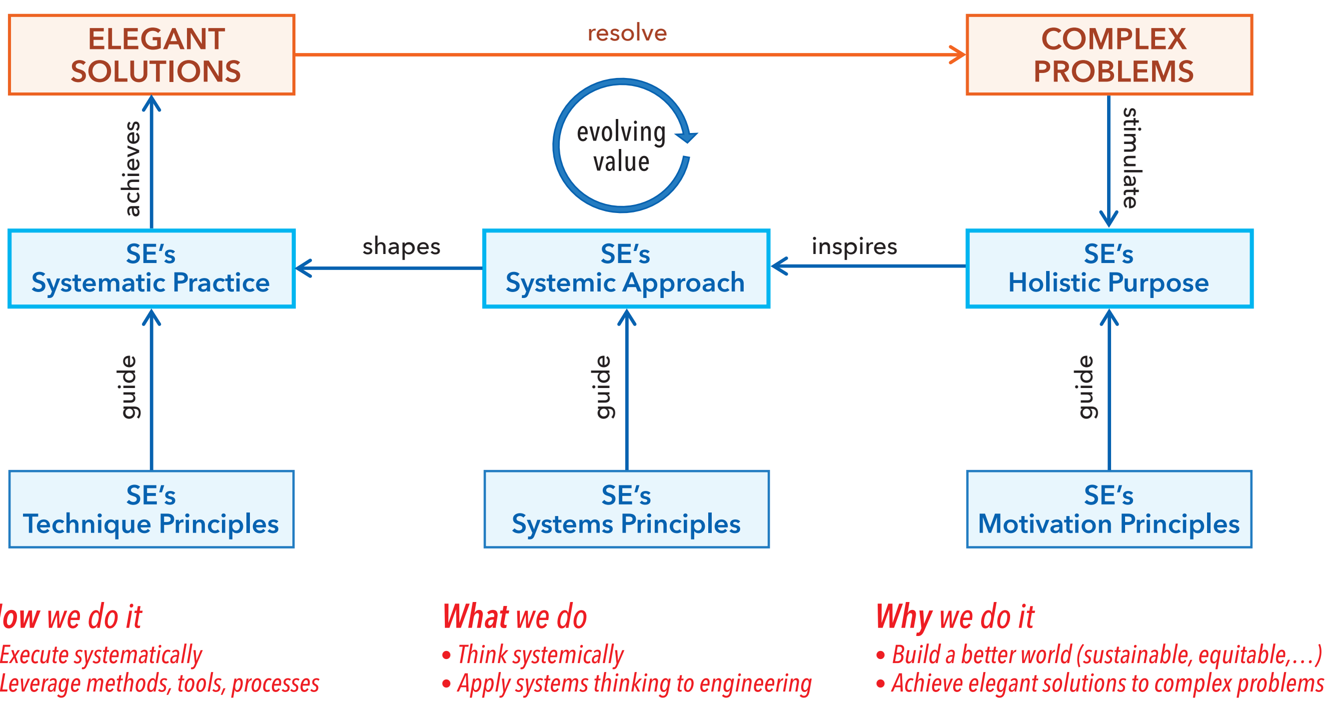

Figure 2. The systemic relationships between value and principles

Table 1. Examples of kinds of SE principles

SE's Technique Principles	SE's Systems Principles	SE's Motivation Principles

• State the problem in solution-independent terms
• Focus early effort on creating one or more feasible designs
• Identify the impact of variations in objectives and solution options on performance, cost, schedule and risk
• Understand interactions across both external and internal systems and incorporate into the solution.
• Base critical decisions on information gathered from analysis of models of various kinds
• Design with the whole solution in mind, test and integrate progressively via its parts
	• Recognize that every complex thing is both a system and part of one
	• Recognize that systems principles apply to physical, social and conceptual systems
	• Recognize that our systems and designs evolve
	• Recognize that system patterns are at the root of handling complexity, sustainability and elegance
	• Employ the principles of system thinking, including:
	  ◦ Think why before how
	  ◦ Think outside before inside
	  ◦ Think relationships not just elements
	  ◦ Think loops not lines
	  ◦ Think long term not just initial capability
		• Help build a better world because the present situation is unsustainable
		• Ensure SE rapidly evolves because rising complexity is imperilling the success of our society and our projects
		• Master a systems approach because complexity and sustainability are systems phenomena
		• Create elegant solutions to our complex problems because elegance reduces complexity and supports sustainability
		• Aim for solutions which serve the widest range of society, because diversity reinforces resilience

findings and practical heuristics, as well as insights from systems thinking. These principles highlight both the scientific and creative aspects of systems engineering.

Systems Principles bridge systems engineering's goals and practices, defining 'what' systems engineering does. These principles differ from those in specialized engineering disciplines (Table 1, column 2).

Motivational Principles (Table 1, column 3) explain 'why' we engage in systems engineering, articulating its purposes and values. These principles capture the overarching goals and rationales of systems engineering as a whole, rather than specific projects.

Each type of principle contributes uniquely to systems engineering's evolution and distinctiveness.

The evolution of systems engineering's capability

Systems engineering's core capability is shaped by the evolution of its technique principles, creating a virtuous loop with systems engineering's practice and knowledge. This dynamic is illustrated in Figure 3, which expands on Figure 2's left-hand side.

Figure 3 shows that systems engineering's technique principles stem from various sources, including practical insights and scientific theories. These insights are gathered from multiple fields, not just SE, and emerge from experiences, trial-and-error, and serendipity. Principles also evolve from scientific theories spanning natural, hu-

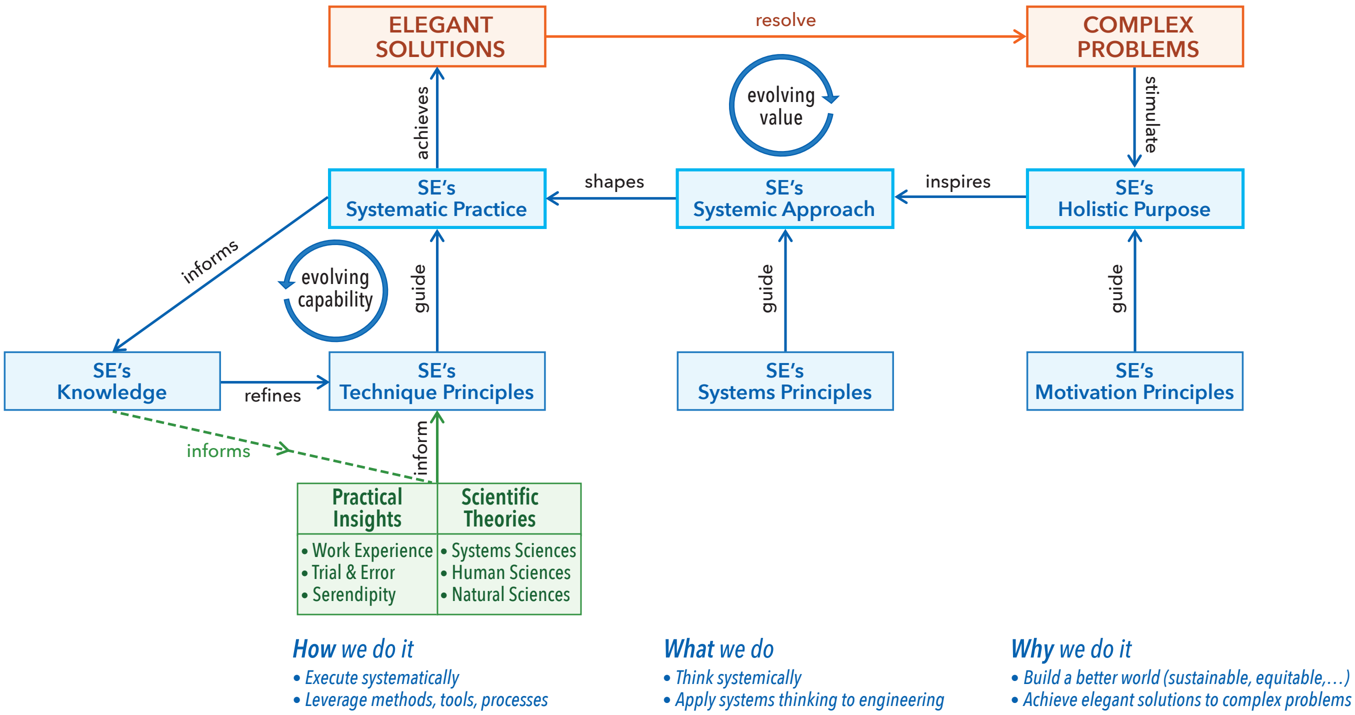

Figure 3. Systemic relationships in evolving core capabilities

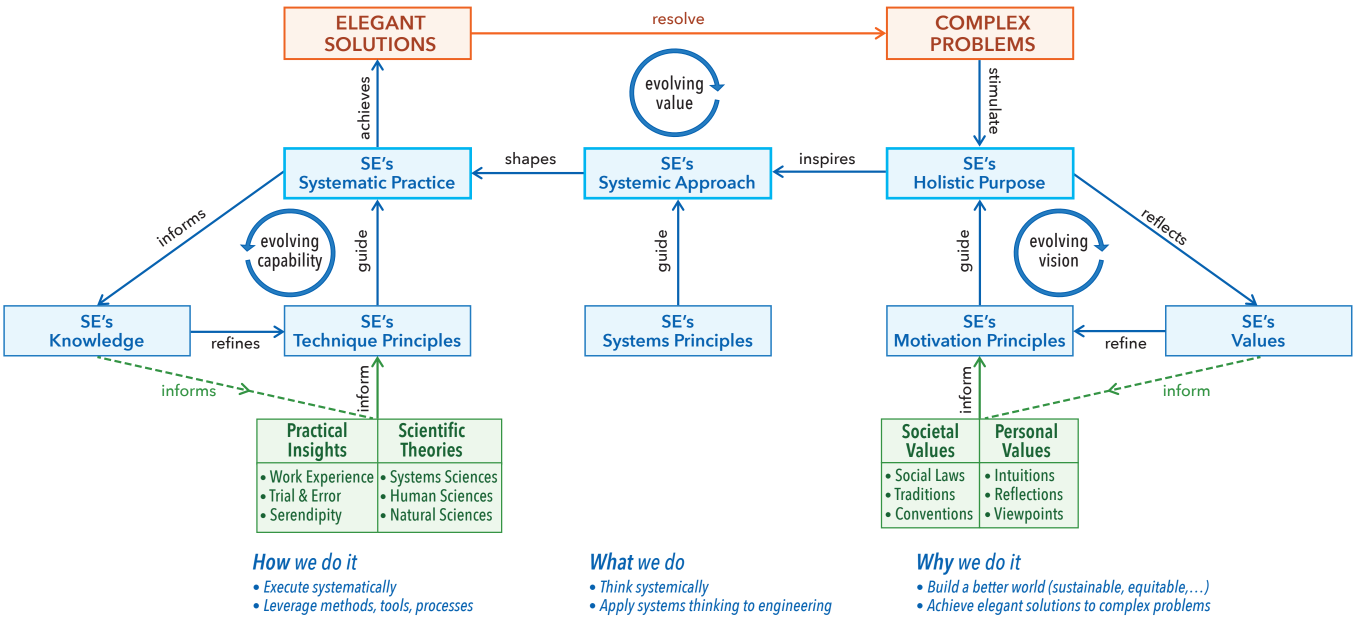

Fig. 4. Systemic relationships in evolving the discipline's vision

man, and systems sciences. Together, these elements contribute to the development of systems engineering's technique principles.

In practice, these principles are applied, tested, and refined, enhancing systems engineering's knowledge. This growth in knowledge not only improves systems engineering's technique principles but also informs the broader realm of practice and theory, from which many principles originate. This process highlights both the evolution of systems engineering's capability and its symbiotic relationship with the advancement of science and practical applications more broadly.

The evolution of systems engineering's vision

Systems engineering is motivated by its vision of potential value and positive impact. This vision evolves through a virtuous loop involving the development of systems engineering's holistic purpose, values, and motivation principles, as diagrammatically represented in Figure 4, expanding on the right-hand side of Figure 3.

Figure 4 illustrates that systems engineering's motivation principles are influenced by a blend of societal and personal values. Society contributes through laws, traditions, and conventions. Additionally, individual insights, intuitions, and perspectives play a crucial role. Influential figures like Augustine, Griffin, Senge, and Meadows, along with institutions like the UN with its human rights declaration and sustainability goals, have significantly shaped systems engineering's vision.

Systems engineering's purpose is steered by its motivation principles, but it also adapts in response to evolving understandings of complex global challenges. Thus, systems engineering's purpose dynamically balances learning from faced problems and aligning with the changing values of the communities it serves. This balance is vital for maintaining systems engineering's self-image, reflecting both courage and humility in problem selection, and demonstrating commitment and responsiveness to societal needs, thereby giving meaning to its duties and services.

The evolution of systems engineering's approach

Systems engineering's unique value is in delivering elegant solutions to complex problems, realized through a systems approach that aligns with its purpose. This approach shapes systems engineering's practice to address complexity effectively.

Systems engineering's systems approach, guided by systems principles (referenced in Table 1, middle column), is selected based on motivational principles. These principles structure the use of technique principles, ensuring relevant application. This interplay, illustrated in Figure 5, demonstrates the systemic relationship between systems engineering's purpose, approach, and practice.

The approach connects values with technology, drawing on transdisciplinary principles from systems thinking, design thinking, and others (for example., (McDermott and Salado 2017, Smuts 1926, Koestler 1967, Rousseau and Billingham n.d., Wade et al. 2017, Lidwell et al. 2010, Alexander et al. 1977, and Cabrera 2008). Applied principles are refined and occasionally lead to new discoveries, with feedback loops enriching other fields and promoting a broader transdisciplinary evolution, as depicted in Figure 5.

Systems engineering's foundation in systems principles sets it apart from other disciplines, emphasizing its role in addressing contemporary challenges like Industry 4.0 and Society 5.0. In an era of rapid technological advancement, the constancy of systems principles ensures systems engineering's capability to continually devise elegant solutions for humanity's complex and evolving challenges.

The Significance of Systems Engineering's Transdisciplinary Evolution

Systems engineering's significance in tackling complex challenges lies in its foundation in systems science and systems thinking. Holonism posits that everything is both a system and part of larger systems, making systems principles universally applicable. Systems engineering, inherently based on these principles, is a transdiscipline, useful across various fields for addressing human problems and ambitions. Unlike abstract disciplines like logic and mathematics, systems engineering is practical, offering tangible solutions and methods for complex issues. As Rousseau et al. (2018) describe, it "adds something new to the disciplines it generalizes over, rather than combining or merging disciplinary resources. Its value is realized when it is used in conjunction with these other disciplines to address problems originating in those disciplines."

Systems engineering serves as a unifying platform for multiple disciplines, facilitating holistic solutions to complex problems. This leadership role in problem-solving is increasingly recognized, as stated by Hillary Sillitto and INCOSE Fellows (2018):

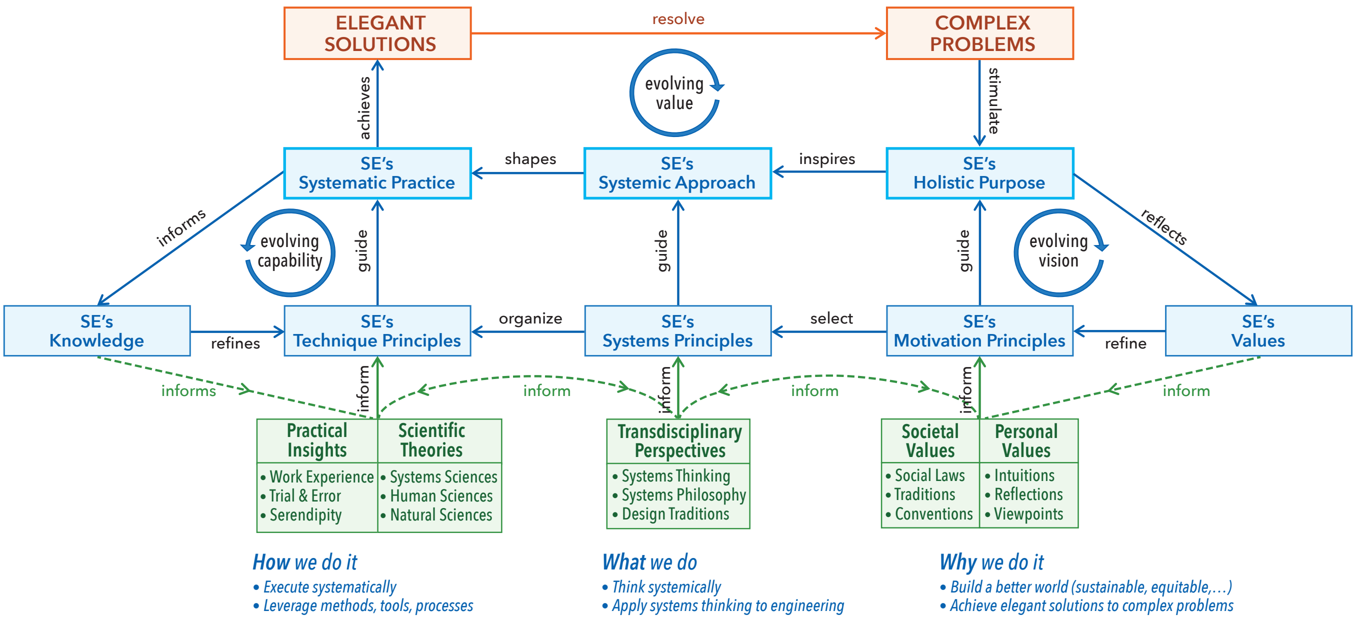

Figure 5. Systemic relationships in evolving the systems approach

"We envisage that systems engineering can be transformed into a truly transdisciplinary discipline – a foundational meta-discipline that supports and enables collaboration between all the disciplines that should be involved in conceiving, building, using and evolving a system so that it will continue to be successful and fit for purpose as time passes."

The past century's exponential rise in problem complexity necessitates multidisciplinary collaboration. This collaboration has evolved from multi-, cross-, inter-, to transdisciplinarity (Rousseau et al. 2018) with the chosen approach depending on the challenge's complexity. The most intricate and significant issues, like poverty and climate change, demand transdisciplinarity and systems engineering's systemic approach. Systems engineering's role in these scenarios, employing advanced methods and expert practitioners, is termed transdisciplinary systems engineering.

Transdisciplinarity is driven by three core motivations:

- Sustainability: Seeking lasting solutions to real-world problems.
- Transcendence: Overcoming barriers to cooperation and collaboration.
- Transgression: Challenging traditional disciplinary boundaries and conventional attitudes through critique, re-imagining, reframing, and re-contextualizing to discover innovative solutions.

While any discipline can adopt these values, systems engineering has inherently embodied them since its inception in the 1940s, predating the formalization of "transdisciplinarity" in the 1970s. That said, systems engineering's focus on transdisciplinarity has evolved. Initially strong, it later shifted towards process and formal methods. Recently, however, there has been a resurgence in its transdisciplinary emphasis. Not all systems engineering projects are transdisciplinary, but those addressing global challenges are increasing in significance and urgency, amplifying its further need, indicating a natural progression for systems engineers towards transdisciplinary competencies.

Transdisciplinary systems engineering is garnering attention in recent literature. Azad Madni (2018) in his book "Transdisciplinary Systems Engineering," defines it as an integrative discipline extending beyond engineering to harness concepts and relationships across various fields, aiming to resolve complex system problems with cross-disciplinary solutions. Madni envisions it as a transformative force in the discipline, expanding its scope to address significant scientific and societal issues.

This concept aligns with INCOSE's goal to create "a better world through a systems approach" (Lind 2022) and supports the assertion that systems engineering's purpose is to achieve elegant solutions to complex problems. The increasing focus on transdisciplinarity underscores systems engineering's evolving role in tackling global challenges through this lens.

CONCLUDING REMARKS

This article provides an historical overview of systems engineering's response to increasingly complex challenges. Initially, systems engineering focused on technical objectives, then shifted towards process and methodology. Currently, there is a movement to return to its original ethos of "pursuing elegant solutions to complex problems." The paper highlights systems engineering's inherent transdisciplinarity, a characteristic that has not always been widely recognized but is now gaining acknowledgment and appreciation within the field.

We argue that the future of systems engineering as a pivotal and relevant engineering discipline hinges on reinforcing its transdisciplinary nature and concentrating on solving complex problems elegantly. The paper introduces a framework to understand systems engineering's nature and evolution in terms of its principles, methods, and purposes. It illustrates how systems engineering is both influenced by and contributes to various disciplines and social institutions, creating a dynamic ecology of discovery, achievement, and vision.

The value of this framework is discussed, demonstrating its utility in fostering a shared understanding of systems engineering's potential and significance. This understanding supports institutions like INCOSE in their broader social mission to build a more sustainable and improved world.

In a subsequent article in this issue, we delve deeper into how systems engineering can maintain its relevance by taking practical steps to tackle intricate eco-socio-technical problems (Brook, Pennotti and Rousseau, nd). This involves collaborative efforts with other disciplines while continuously reinforcing and expanding systems engineering's foundational aspects. We believe that through these efforts, systems engineering can fully realize its longstanding transdisciplinary potential. ■

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Advancing System Engineering's Relevance in a Changing World

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ABSTRACT
The future value of systems engineering may well be measured by its contribution to INCOSE's vision of "a better world through a systems approach." To stay relevant, systems engineering must expand its scope beyond the technical realm by addressing today's most pressing and complex problems, which span technical, social, and ecological domains. This paper builds on our previous work on the evolving architecture of the systems engineering discipline, detailing how it can maintain its value by effectively engaging in eco-socio-technical challenges. We propose collaborative strategies with other disciplines to enhance and broaden its foundational base, which will be crucial for realizing its potential as a transdisciplinary field in an increasingly complex world.

KEYWORDS: evolution of systems engineering; complex problems; transdisciplinarity, systems engineering foundations, systems approach

INTRODUCTION

Since its inception, advances in systems engineering have come from facing increasingly complex and significant challenges. These challenges, primarily in the technical realm, have led to both successes and failures. Yet, the discipline has repeatedly demonstrated its societal value through iterative learning, effective solutions, and creative ingenuity.

Today, we face a rapidly changing world with problems of unprecedented complexity and global importance. These new challenges epitomize the need for INCOSE's vision of 'A better world through a systems approach' and stand to direct the future of systems engineering. How SE responds will determine its continued relevance and value.

In this article, we discuss how the systems engineering discipline can actively evolve and realize INCOSE's vision by addressing key contemporary issues. These include:

- leveraging and supporting the digitally driven industrial revolutions,
- addressing the looming climate crisis, and
- moving society towards long-term sustainability, in a sustainable world.

At a minimum, INCOSE's vision necessitates a broader consideration of SE's impact, even when restricting focus to technical solutions. For example, consider a systems engineering approach to sustainability, such as minimizing material and energy use during production and operation, promoting recycling and reuse of components and materials across many lifecycles. These systemic goals compel work on sustainability at all levels, involving many types of technical systems. This is significant because the activities to engineer a sustainable system are wide ranging, yet not all practitioners need to be at the forefront of the field to contribute to the broader vision.

Widening the scope of consideration parallels the scale of challenges we outline, challenges that demand greater ambition. This involves recognizing the social and ecological as key parts to 'systems of interest' since they dominate many of the problem and solution spaces which matter most. The social dimension is crucial, as many problems are rooted in humanity's actions, and only collective social efforts can work towards a future that benefits the global good.

Multidimensional problems of the sort we now face are more uncertain, complex, open-ended, and interconnected than those that have been usual for systems engineering. In this less familiar world, requirements are seldom stated explicitly, solutions are likely to be incomplete and temporary, and unknowable events will force continuous adaptation. For systems engineering to make a significant impact in this space, it needs to reflect on its professional values and readiness to learn, and adapt to help others recognize credible opportunities for collaboration.

We believe progress depends on shifting focus from a primarily technical discipline – one based on objective formal processes, methods and the manipulation of artifacts – to a discipline focused on achieving elegant solutions to complex problems that demand creativity and imagination. This shift aligns with the founding vision for the discipline: understanding the origins and nature of complex problems and work with specialized disciplines to appropriately address them through design.

There is no conflict of interest here. By

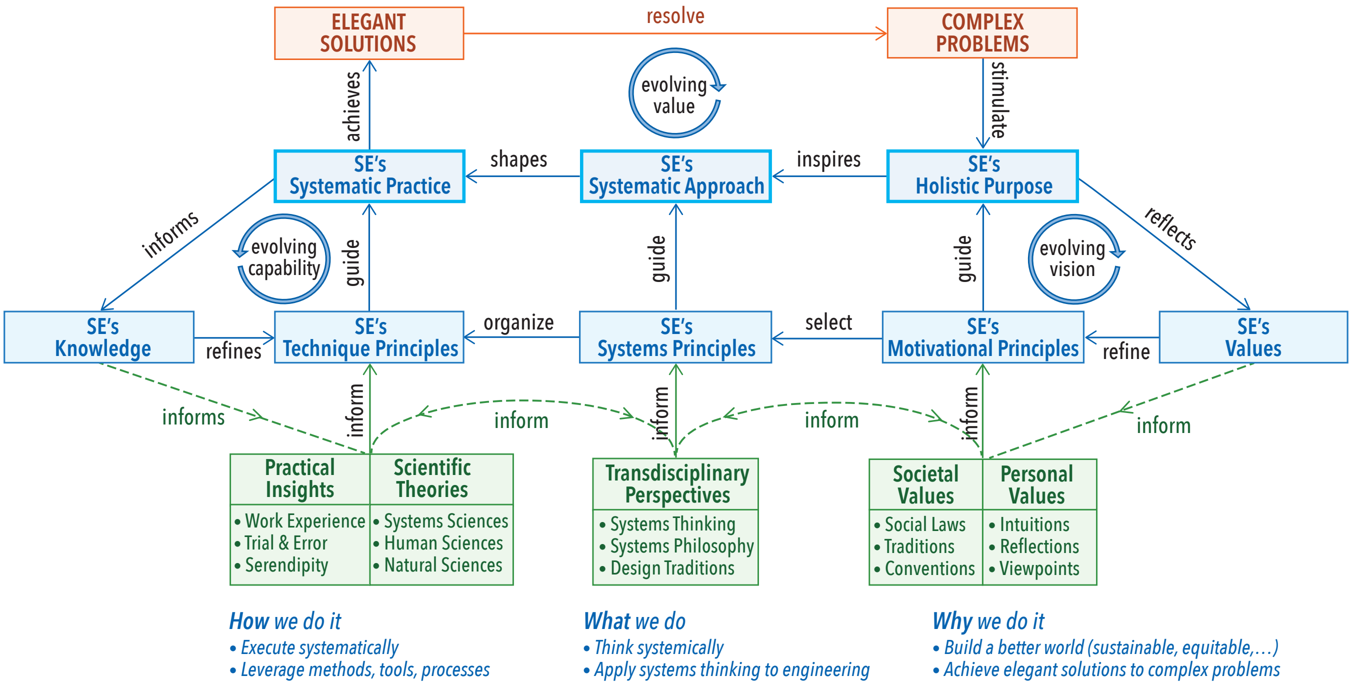

Figure 1. The Bridge: an architectural framework for the evolving systems engineering discipline

broadening its problem-solving capacity, systems engineering can better address the interconnected technical domain and increase its value to traditional areas. The model we outline below allows for this.

Yet, disciplines which are backward-looking often resist change. Although learning from the past to establish "best practices" is usually beneficial, such an approach may become a liability when faced with rapid technological shifts that render traditional heuristics less effective. Innovation, rather than adherence to established routines and standards, is key in such contexts.

Through innovation and adaptation systems engineering can continue to contribute to the "better world" of INCOSE's vision, thus sustaining and enhancing its value. This is mapped out in the architectural framework of systems engineering, which we call "the Bridge" (Pennotti, Brook, and Rousseau n.d.), shown again here in Figure 1. The Bridge can guide us to make the necessary changes, for example from a process-oriented to a solution-oriented discipline.

The basis of our position comes from understanding the systemic nature of the world's challenges. When we intervene, we set off interactions that are often remote and separated in time (Senge 1990). This systemicity means that systems engineering is the best hope for addressing the problems of our times, but only if it brings its systems approach to the fore and delivers interventions more systemically.

The coupling of the systems approach and systemic intervention is imperative for the discipline, but taking a systems approach is not exclusive to systems engineering. There is now systems biology, systems planetary science, systems economics, systems medicine, etc., all of which have vital contributions to make in their own spheres. Systems engineering's value is found in providing the practical means that guide other specialized systems disciplines in collaborating, communicating and leveraging their more specialized insights into joint efforts that address problems, multi-dimensionally. However, achieving this future will only come through the concerted efforts of the profession.

INSIGHTS THAT INFORMED OUR LEARNING JOURNEY

Before giving any recommendations for future action, we need to summarize some key insights we learned while developing the Bridge (Pennotti, Brook, and Rousseau n.d.).

1. Although systems engineering is a developed discipline, its current activities are largely concerned with the left-hand side of the Bridge, which deals with technique. Advancing its techniques allows the discipline to become more creative, agile and adaptive to new circumstances, especially given the opportunities offered by artificial intelligence (AI) and other rapid advances in digital technologies. That said, investing in the middle and right-hand side of the Bridge allows the field to evolve though unified values, approaches, and sense of purpose. Unfortunately, these topics have received rather less reflection and attention across the community.
2. The discipline and its practitioners need a clear, shared notion of "good" systems engineering to provide a basis for assessing the value of what they achieve. We are convinced that the concept of elegance can establish such a notion. Rousseau and Billingham (n.d.(b)) explores how elegance is used in other fields, justifies why designs should be elegant to have enduring value, and summarizes elegance as the purpose of systems engineering from several authoritative sources. In brief, good systems engineering delivers elegant solutions to complex problems.
3. Systems engineering is a transdiscipline because it spans and interfaces between the specialized engineering disciplines. This transdisciplinary approach manifests itself in its practice by championing overarching values like sustainability and diversity, breaking down barriers to cooperation and collaboration, and challenging the constraints of traditional disciplines.
4. Systems engineering is both systematic and systemic but needs to become more holonistic. Being 'holonistic' is to recognize, accommodate and leverage the myriad interconnections between phenomena. This views every system not merely as one system but as a system that is part of higher order systems and whose parts are also

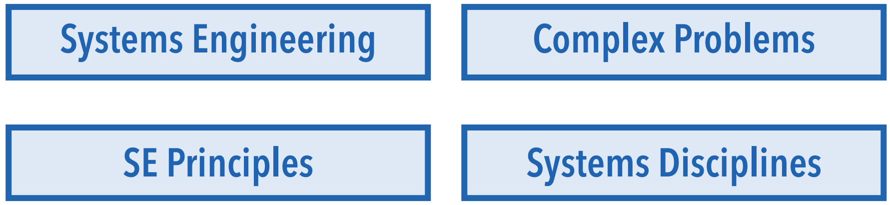

Figure 2. Key elements contributing to systems engineering's value

systems. Therefore, the world's systems are dynamic, interacting and evolving rather than forming fixed hierarchies (Rousseau and Billingham n.d.(a), Friedenthal et al. 2014, and Friedenthal et al. 2021). Holonism has wide implications which still need to be fully worked through in systems engineering.

5. Our architectural model is tailored for the systems engineering discipline, but its structure is generic and can be used to model other disciplines. It may prove a useful tool for a discipline wishing to model itself, explain itself to others, and find connections for collaboration.

These insights shed light on a future path for becoming a more effective discipline that helps participate and guide transformative change in the wider technical, academic and social context, while simultaneously strengthening its own foundations.

A TRANSDISCIPLINARY VISION FOR SYSTEMS ENGINEERING

The co-evolution of SE and its context

In this section, we present our vision for what systems engineering should become and the steps to take to get there. The following section, "Suggested Early Steps", provides some specific near-term actions that can initiate the process.

We organize this vision by four fundamental elements, presented in Figure 2, as a frame for our vision:

1. the nature of systems engineering as a discipline;
2. the kinds of complex problems systems engineering addresses;
3. the disciplines that form the theoretical foundations of systems engineering; and
4. the systems engineering principles that encode actionable knowledge.

Each of these elements has contributed to the evolution and value of systems engineering, but their characteristics change, and we need to better understand how change occurs and how they influence each other over time. Part of this is being done through constant review within and beyond the systems engineering community such as the outputs of INCOSE's FuSE Program, the INCOSE SE Handbook (Walden et al. 2023), the SEBoK (SEBoK Editorial Board 2023), and INCOSE's strategy documents (INCOSE 2014 and 2021, SEBoK Editorial Board 2023, and Walden et al. 2023).

In Figure 3, we outline desired future states for each element, aiming for feasible, attainable, and vital outcomes that demonstrate the value of systems engineering. Starting in the top-left, a transformed future for systems engineering, we target a discipline characterized by self-awareness, confidence, an outward-looking perspective, purposefulness, transdisciplinarity, adaptability to change, and a proactive stance on major challenges, earning recognition as a crucial contributor to solutions. Achieving such a state implies that systems engineering be principled, with practices founded on relevant, evolving principles that respond to our deepening understanding of the world and achieve successful outcomes.

Tackling complex problems necessitates advanced developments in research-based systems disciplines, encompassing systems engineering research, systems sciences, and the broad spectrum of systems science specialisms and applications. Insights from these disciplines should guide the principles that underpin the competency of a more transdisciplinary systems engineering.

By understanding the interconnections presented in Figure 3, we can actively steer and expedite this co-evolution. Figure 4, using blue arrows, illustrates how leveraging each element can sequentially enhance the next in a clockwise cycle, thereby refining systems engineering's approach to complex issues.

Starting top right, we suggest that confronting complex systemic challenges compels us to adopt more systemic and holonistic methods for analysis and explanation, expanding the research scope of systems-oriented disciplines. Such research can yield new scientific insights into the nature of complex systemic phenomena, which, in turn, can inform validated principles to enrich the actionable foundations of systems engineering. These essential principles can then guide systems engineering's effectiveness, enabling it to achieve elegant solutions to complex issues and thus improve the state of the multifaceted problems we confront.

We propose that, although mutual reinforcement could naturally occur through informal interactions, the pressing nature of many challenges demands a quicker pace, achievable through purposeful, directed actions, which we highlight here in the orange boxes in Figure 4. Through these actions, we believe, systems engineering can realize the envisioned state.

Acting jointly

Systems engineering alone cannot solve the most complex problems; it must collaborate with other disciplines to be effective. Other fields already possess deep insight into their systems of interest, offering crucial perspectives on where interventions could be beneficial. Collaborative efforts are vital for expanding boundaries and effectively addressing a broader range of problems. The interdisciplinary relationships fostered through such collaboration can and should deepen over time.

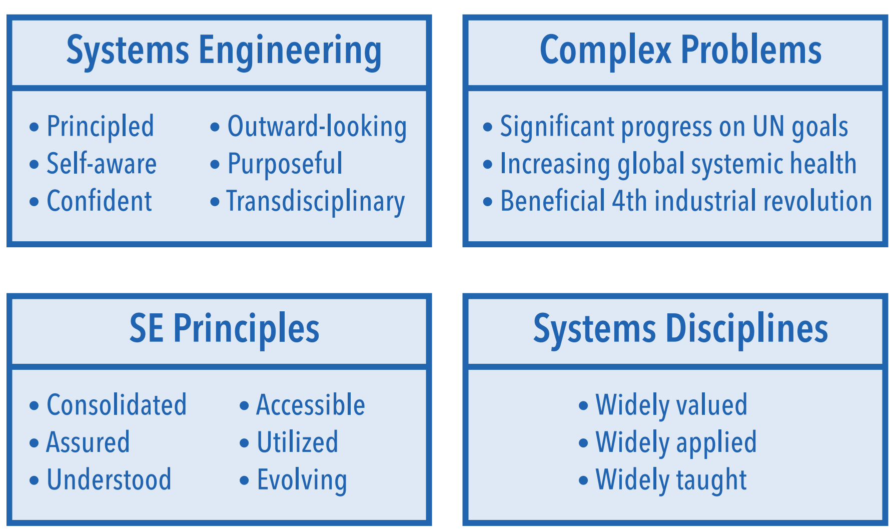

Figure 3. Vision for the future state and its context

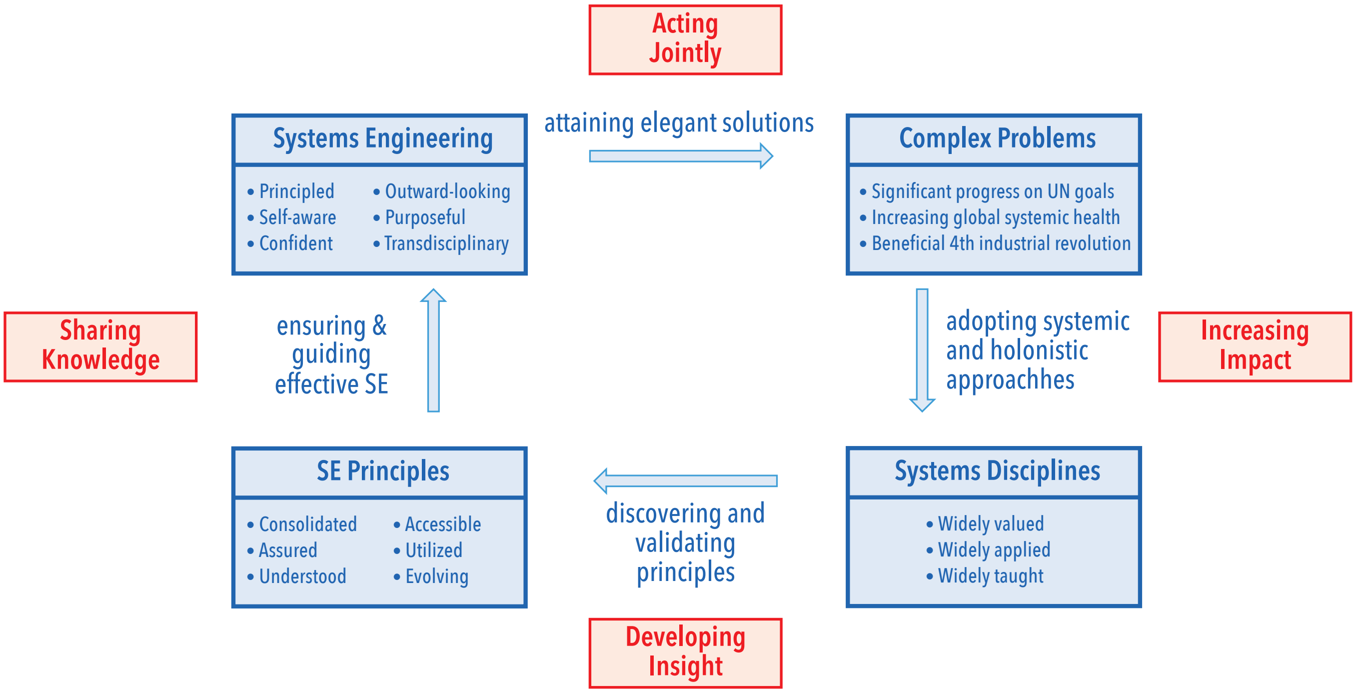

Figure 4. The dynamics of the co-evolution of the states of SE and its context

For successful collaboration, systems engineers must embrace:

- An openness and readiness to listen and learn from others;
- Humility in acknowledging the unprecedented nature of challenges and realism about the discipline's capabilities to address them;
- An ongoing curiosity about how the world works, its history, and potential futures;
- A commitment to perseverance, recognizing that the impacts of our efforts may unfold over time; and
- A dedication to serving others and enhancing humanity's condition.

Adopting an open and altruistic mindset necessitates a cultural shift, a change in focus, and the education of a new generation of engineers tasked with this vision. Expanding collaborative efforts and adjusting our attitudes only requires the determination to do so. As we will demonstrate, these principles apply equally to guiding other evolutionary steps.

3.3 Increasing impact

Engaging with and learning from other systems disciplines will enhance systems engineering's capabilities and foster mutually beneficial relationships. Systems engineering contributes via its established transdisciplinarity, systems and holonistic approaches, and extends experience in managing complexity within the technical domain. Through INCOSE, such relationships can deliver a global membership network, providing valuable international contacts and developmental opportunities.

In turn, other disciplines contribute insights into non-technical system behaviors, expertise in managing complex interventions, and methods for tracking long-term intervention effects, as exemplified by medical science.

These collaborations could expand existing disciplines, including systems engineering, and spawn new specialisms like systems biology and systems medicine. The resulting cross-disciplinary integration suggests a practical approach to achieving broader transdisciplinarity.

Through collaboration, system engineering's interventions become more robust, expansive, and impactful, enhancing its influence. This, coupled with systems engineering's proven ability to transform ideas into engineered solutions, could bolster its leadership role among the systems disciplines.

Developing Insight

Through expanding our scope, we will derive insights from a wide range of experiences. Both successes and failures will reveal new patterns and relationships, in line with the collaborative nature of science and engineering.

These insights will help us discover new guiding principles with varying levels of authority—from intuitive insights and agreed-upon heuristics to broad propositions. The development and application of these principles, and their evolution into universal principles that summarize knowledge efficiently, is discussed in another article in this issue. While universal principles are ideal, those which are effective only in specific areas are also valuable. Science progresses by transferring insights from one area to another. Successes broaden the applicability of our knowledge, and failures drive further research, leading to new or refined principles. The key to applying our knowledge practically is linking principles to their relevant contexts, a challenge that requires a systemic approach. Actively managing and refining our guiding principles, and the contexts in which they are effective, demands determination and a systems perspective.

Sharing Knowledge

As a principled organization, systems engineering should clearly demonstrate its values and commitment to upholding them. By articulating and owning our principles, we enhance our self-awareness, maturity, and confidence. Establishing a coherent set of principles not only grounds us but also streamlines education and training, facilitating the transfer of knowledge to new generations.

We advocate for a structured compilation of systems engineering principles to serve as a model for interdisciplinary sharing, prompting others to articulate their guiding principles similarly. This approach is crucial for fostering dialogue with related disciplines, particularly in areas of shared interest, as outlined in the Bridge model. Such dialogue strengthens our common ground, clarifies each discipline's commitment to its

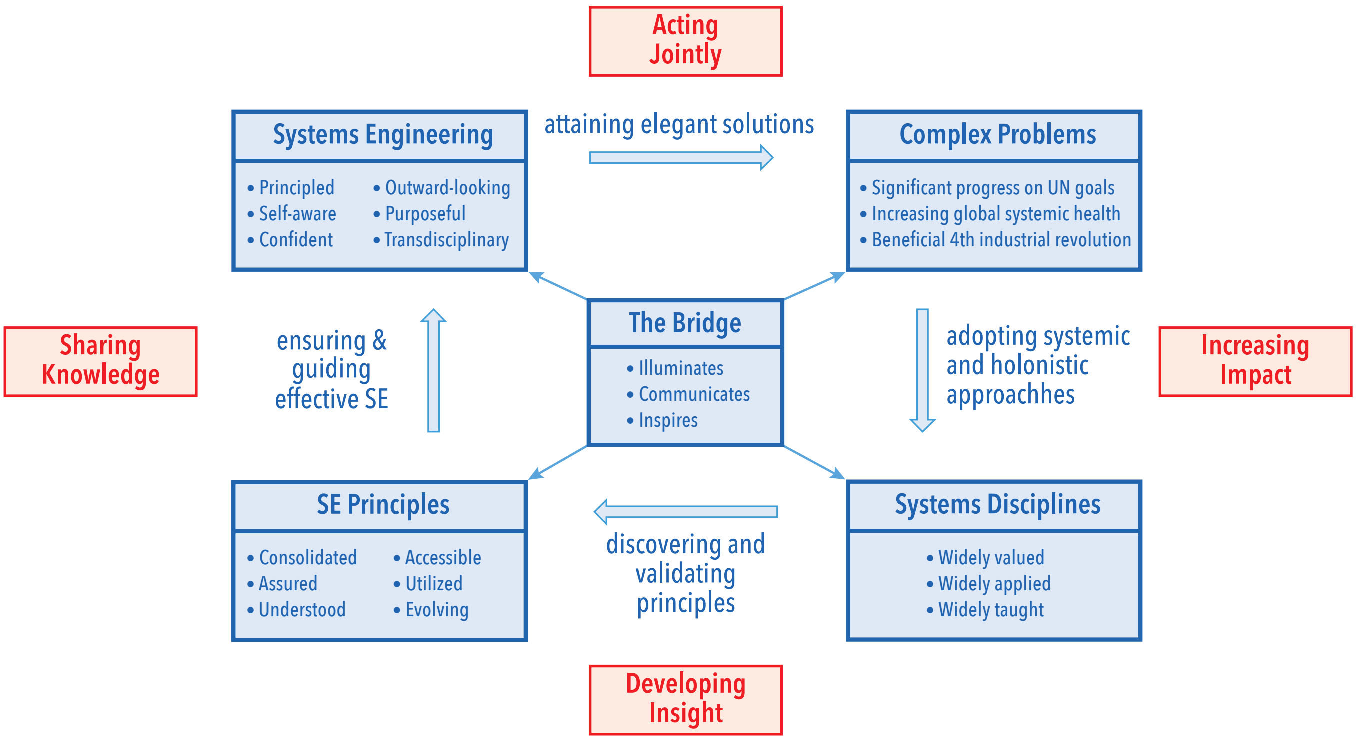

Figure 5. The Bridge as a facilitator of the co-evolution of systems engineering and its context

systems approach, and shares insights from diverse applications.

Encouraging this exchange promotes a dynamic, evolving base of knowledge that transcends disciplinary boundaries. This moves towards transdisciplinarity, envisioned by systems science pioneers, aligns with our expanding global perspective, opening the way to a new era of integrated understanding and collaboration.

The Bridge as a key to the future

Our vision for systems engineering and its future role emerged from studying the discipline's nature and its relationship with academia and society, leading to the Bridge model. This model helps us understand how systems engineering interacts with its surroundings, communicates our discipline's goals, and inspires us to fulfill its potential to help make a better world, as envisioned by INCOSE. We've concluded that the Bridge can guide us in creating a focused and ethical discipline that not only achieves INCOSE's goal of improving the world through a systems approach but also extends its influence and realizes its potential across multiple disciplines.

SUGGESTED EARLY STEPS

There are several practical steps to reach the future we have set out. The following are offered as suggested starting points, that others can build on.

1. **Joint initiatives with others:** Systems engineering serves as a crucial link and coordinator among diverse specialties, each contributing different competencies for effective action. We suggest INCOSE forge partnerships with related professional groups and start pilot projects targeting broader socio-technical issues, including those aligned with the UN Sustainable Development Goals. These initiatives might highlight systems engineering's limitations and thus inform its evolutionary strategy, potentially fostering improved collaboration and outcomes.
2. **Future-oriented research:** INCOSE should pursue a future with its specialist partners under a unified vision to enhance collaboration. By establishing a forum to address the challenges of increasing transdisciplinarity, INCOSE and its partners can set a research agenda that identifies key challenges and prioritizes research efforts.
3. **Active curation of systems engineering's principles:** Systems engineering's numerous guiding propositions need organizing and refining for effective use and future enhancement. Despite ongoing efforts, the integration of systems engineering's principles has not been thoroughly addressed. We propose INCOSE create an expert group to continuously curate and promote these propositions as they evolve, ensuring they are integrated effectively.
4. **Embed transdisciplinarity into systems engineering education and training curricula:** Future generations of systems engineers must be trained to have an natural grasp of transdisciplinarity, and to apply its values and principles in their engineering careers. INCOSE can do more to promote the uptake of transdisciplinary approaches in education, and to stimulate its further development. We recommend convening a group of academics and other interested parties to exchange best practice on transdisciplinary education, and how it might be better promoted in the future.

CONCLUSION

In this paper, we presented a model with actionable steps to evolve systems engineering from a technical discipline to a key player in solving complex, global challenges. This shift is crucial for systems engineering's future relevance, reputation, and contribution. By adopting our proposed agenda, systems engineering can unlock its full transdisciplinary potential and gain a renewed sense of purpose. Continuously integrating our experiences into systems engineering's core will guide current practitioners and inspire future ones. The Bridge framework offers a strategic tool to help in navigating this transformation. ■

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Five Perspectives on Transdisciplinary Systems Engineering

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ABSTRACT
This article offers insights from five INCOSE Fellows on the evolution and significance of transdisciplinarity in systems engineering. Michael Pennotti reviews the origins of systems engineering, emphasizing its inherent transdisciplinary nature and the need for continuous evolution. Azad Madni considers transdisciplinarity as systems engineering's true calling, crucial for the 21st century, and highlights his TRASEE™ education paradigm that underpins the Systems Architecting and Engineering program that he directs at the University of Southern California as pivotal for systems engineering's advancement. Hillary Sillito sees the climate crisis as systems engineering's most critical and complex challenge, asserting transdisciplinarity's crucial role in addressing it. David Rousseau examines the cultural and scientific underpinnings of transdisciplinarity, presenting systems engineering as a prime example. Peter Brook envisions the joint evolution of systems sciences and systems engineering to confront future challenges, advocating for transdisciplinarity as an essential role in systems engineering leadership for addressing global challenges.

INTRODUCTION

Transdisciplinarity is crucial for systems engineering as it tackles increasing complexity, broadens its scope for social and sustainability issues, and incorporates diverse knowledge from various fields. However, the concept, its advantages for systems engineering, its principles, and the pathway to full transdisciplinarity remain unclear to many.

In 2020, the International Council of Systems Engineering (INCOSE) initiated a program on the future of systems engineering (FuSE) to ensure its relevance amid Industry 4.0 and Society 5.0 challenges, highlighting the role of transdisciplinary systems engineering. At the INCOSE International Symposium in 2023, a panel by five INCOSE Fellows discussed "Transdisciplinary Systems Engineering: Its essence, necessity, and implementation pathway." These fellows, authors of this paper, outline their insights in five sections:

- Transdisciplinary systems engineering: a history and its implications (by Michael Pennotti);
- Transdisciplinary systems engineering: implications for research and education (by Azad Madni);
- Transdisciplinary engineering in the climate emergency (by Hillary Sillitto);
- The cultural and scientific foundations of transdisciplinarity (by David Rousseau); and
- Systems engineering's transdisciplinary future (by Peter Brook).

Their goal is to accelerate the vital transformation in systems engineering capability.

TRANSDISCIPLINARY SYSTEMS ENGINEERING: A HISTORY AND ITS IMPLICATIONS

Systems engineering emerged as a distinct discipline in the 1940s, first coined by Bell Telephone Laboratories. Bell Labs executive Mervin Kelly (1950) identified as one of the Lab's key elements a dedicated systems engineering organization, at the same level of importance as that of the research and development departments, citing the complexity of communication technology as the catalyst for its evolution. He outlined its roles in technical planning, association with research, project evaluation, and setting technical standards for quality and reliability.

Though the term originated in telecommunications, the approach was evident during World War II, notably in the RAF Fighter Command C2 System's design during the 1940 Battle of Britain, hailed as exemplary systems engineering by Derek Hitchins (2005).

Initially informal, systems engineering essentially applied systems thinking to tackle engineering problems. The first textbook by Goode and Machol (1957) presented experiences and insights without a general theory, covering early applications in communications, transportation, industry, commerce, and military systems.

Elmer Engstrom (1957) outlined two essential requirements for successful systems engineering: **defining clear objectives and thoroughly considering all the factors that bear upon the**

Table 1. Synergistic disciplines and associate relevant concepts in the USC SAE program

Synergistic Discipline	Relevant Concepts
Digital Engineering	Digital twin technology (Madni et al., 2020a and Madni et al. 2020b)
Cognitive Psychology	Cognitive bias, cognitive limitations (Madni 2014)
Decision Analysis	Preference, utility, and value (Madni 2020c)
Social Sciences	Social networks, crowdsourcing (Madni 2018 and 2019)
AI and Machine Learning	augmented intelligence (Madni 2020d), reinforcement learning (Madni 2018)
Entertainment and Cinematic Arts	Storytelling (Madni 2015), elegant design (Madni 2012)

Table 2. Examples of how TDSE can enhance systems engineering capabilities

Systems Engineering Capability	Key Concepts	Resultant Benefit
Complex systems modeling	Reinforcement Learning from AI/Machine Learning	Closed loop modeling; fill gaps, improve accuracy
Verification and Validation	Digital Twin Technology from Digital Engineering	DT-enabled V&V; Condition-based Maintenance
MBSE	Preference, utility, value from Decision Analysis	Quantification of value delivered by MBSE
Concept Engineering	Storytelling from entertainment and cinematic arts	Collaboration around stories; increased participation
Distributed Collaboration	Social Networks and Crowdsourcing from Social Sciences	Expertise gap filled; informed consensus

possibility of achieving those and their interrelations. This approach was exemplified in RCA's development of the compatible color television system.

Despite its initial lack of formal structure, systems engineering was crucial in achieving significant milestones, such as the 1969 moon landing. Early case studies reveal key themes: systems engineers' deep domain knowledge, reliance on domain-specific science and math, and a transdisciplinary approach that bridged technical and non-technical fields, embodying the essence of systems engineering long before the term "transdisciplinary" was coined.

Coincidentally, the same month as the Apollo moon landing, July 1969, saw the debut of the first formal systems engineering process, "MIL-STD-499 Engineering Management," by the US Air Force. This standard defined systems engineering as a closed-loop, iterative process with four interrelated activities, aimed at guiding contractors in preparing Systems Engineering Management plans and government personnel in evaluating and integrating those plans into contracts.

The introduction of MIL-STD-499 marked a significant shift, focusing on specific activities and artifacts over the primary objective of achieving system goals. This change led to the fragmentation of the systems engineering discipline into specialized roles such as requirements engineers, system architects, integrators, and testers, contradicting the original intent to transcend disciplinary silos. This fragmentation continues, with formal processes becoming increasingly detailed, exemplified by the ISO Standard 42020 (2019), which outlines six processes, 45 required activities, and 416 recommended tasks, showing the complex evolution of systems engineering standards.

Of course, processes alone don't guarantee success, as shown by Boeing's 737 MAX crisis in April 2019. Despite adhering to their design and certification processes, two fatal crashes resulted in 346 deaths, leading Boeing's CEO to make the controversial claim the aircraft was still safe because, "We followed exactly the steps in our design and certification processes that consistently produce safe airplanes." This incident highlights the pitfalls of focusing solely on procedural compliance.

Recently, Mike Griffin (2010) advocated for shifting systems engineering back to prioritizing elegant solutions over mere process adherence, reminiscent of Frosch's (1969) decades-old critique emphasizing the importance of elegance and the real-world applicability of solutions. This renewed emphasis on innovative, transdisciplinary approaches, supported by thinkers like Madni, aims to revitalize systems engineering, steering it towards its original goal of resolving complex problems through integrated, elegant solutions.

TRANSDISCIPLINARY SYSTEMS ENGINEERING: IMPLICATIONS FOR RESEARCH AND EDUCATION

In "Transdisciplinary Systems Engineering: Exploiting Convergence in a Hyperconnected World," Azad Madni (2018) introduces transdisciplinary systems engineering as a meta-discipline that merges systems engineering with other fields to tackle complex problems. This approach arises from the need to address 21st-century engineering challenges through the integration of systems engineering with digital engineering, artificial intelligence (AI), machine learning, and virtual world technologies. Madni's work led to the development of TRASEE™, an educational paradigm, implemented in the University of Southern California's systems architecting and engineering program. This shift aims to prepare engineers with a broader, more integrated skill set, reflecting the convergence of systems engineering with other cutting-edge disciplines.

Madni's work in transdisciplinary systems engineering focuses on integrating concepts from complementary disciplines. Examples are given in Table 2.

TRASEE, developed by Madni, introduces a transdisciplinary approach to engineering education, designed to prepare students for the complexities of 21st-century engineering challenges. It rests on the following foundational pillars:

1. **Transdisciplinary mindset:** Encourages leveraging concepts from various disciplines, fostering visionary thinking and self-reflection, while cautioning against becoming too attached to one's own ideas. This mindset is crucial for expanding systems thinking and balancing leadership traits like opportunism and pragmatism.
2. **Principles from the learning sciences:** Focuses on student-centric learning that builds on prior knowledge and enables application to new contexts. This approach facilitates the development of systems thinking and critical thinking by ensuring knowledge is interconnected and easily accessible.
3. **Storytelling as a pedagogical strategy:** Uses storytelling to inspire and engage students, enhancing knowledge retention and recall. Stories serve as a means for sharing tacit knowledge, exploring new practices, and accelerating experience through simulations. They effectively convey complex concepts like ethics and culture, thus supporting critical and systems thinking.
4. **Diversity in role assignment:** Promotes diverse thought, backgrounds, and cultures in project-based learning, enhancing team performance and leadership skills. This diversity is key to fostering an inclusive learning environment that mirrors real-world engineering challenges.
5. **Dynamic assessment of innovative thinking and leadership skills:** Evaluates students' ability to think creatively and lead effectively, especially in novel or complex situations. This includes assessing skills like critical thinking, systems thinking, and problem reformulation, ensuring students can apply innovative solutions to unprecedented problems.

TRASEE aims to mold engineers who are not only technically proficient but also capable of transdisciplinary thinking and leadership, equipped to navigate and solve the multifaceted problems of today's interconnected world.

Future plans call for formalizing methods to account for human behavior variability when engineering sociotechnical systems. Madni will use digital twin technology to simulate human responses in crises based on their education and track learners' progress. Additionally, we can integrate cross-disciplinary concepts into systems architecting and engineering courses, expand TRASEE to evaluate its adaptability across engineering programs, pursue collaborations between National Academy of Engineering and Royal Academy of Engineering to enhance transdisciplinary systems engineering, and publish a TRASEE guide for global communities. The aim is to transition systems engineering to a transdisciplinary approach, eventually rendering the term unnecessary.

TRANSDISCIPLINARY ENGINEERING AND THE CLIMATE EMERGENCY

In 2016-2018 INCOSE ran a project to update its definition of systems engineering. The new definition, with explanatory note, is as follows:

> "**Systems Engineering** is a **transdisciplinary** and **integrative** approach to enable the successful realization, use, and retirement of **engineered systems**, using **systems principles and concepts**, and scientific, technological, and management methods.
>
> We use the terms "engineering" and "engineered" in their **widest sense**: "the action of working artfully to bring something about". "**Engineered systems**" may be composed of any or all of people, products, services, information, processes, and natural elements."

This shift marks a return to systems engineering's roots as a meta-discipline that transcends traditional disciplinary boundaries, aiming for agility and enhanced collaboration across complex problems.

This approach is crucial for addressing multifaceted challenges like the climate crisis, which intersects various fields such as science, engineering, and sociology, underscoring systems engineering's role as outlined in INCOSE's Systems Engineering Vision 2035 (INCOSE 2021).

At COP26 (United Nations 2021), nations proposed plans to decarbonize energy systems, addressing just one aspect of the global challenge within societal and environmental constraints defined by the nine "Planetary Boundaries." This situation underscores the urgent need to view Earth as a limited resource, emphasizing the doughnut model's call for balancing human activity within ecological limits. The climate crisis, representing a race against tipping points like climate destabilization and mass extinction, demands a systems engineering approach to achieve sustainable development goals, including carbon reduction, equality, and a circular economy.

This multifaceted challenge requires a transdisciplinary strategy that views the climate crisis through a systemic lens, considering the interconnectedness of societal, environmental, and technological factors. Systems engineering emerges as a critical framework for navigating these complexities, advocating for collaboration, humility, and an expansive view beyond traditional domains to address existential threats to humanity. Engaging across disciplines, systems engineering aims to forge pathways towards a sustainable, equitable future, highlighting its pivotal role in addressing the century's paramount challenges.

THE CULTURAL AND SCIENTIFIC FOUNDATIONS OF TRANSDISCIPLINARITY

Transdisciplinarity has deep roots across various fields, pre-dating its formal naming and extending beyond systems engineering, which has inherently embodied its principles. Coined 52 years ago at the OECD's inaugural conference on interdisciplinary research, the term emphasizes a unified approach to addressing complex societal issues like climate change and poverty through shared values for effective interdisciplinary collaboration.

Transdisciplinary efforts aim to create sustainable solutions, overcome collaboration barriers, and challenge traditional disciplinary limits to address real-world problems. Systems engineering, having embraced these goals since the 1940s, exemplifies transdisciplinarity in action, even before the term was officially introduced. This approach combines cultural norms with a technical dimension, reflecting a broad and growing interest across sectors.

At the 1970 OECD conference, Jean Piaget highlighted that transdisciplinarity would foster convergence and maturation among fields through shared structures and thought patterns, potentially leading to a general systems theory. This idea traces back to the 1930s with von Bertalanffy's proposal of "General Systems Theory," emphasizing the interdependence of objects and their environments, marking a shift towards recognizing the limitations of single-disciplinary approaches for complex problems.

Systems science was identified as crucial for all disciplines involved in transdisciplinarity, offering general insights that could serve as both additional and unifying principles. This foundation enables disciplines to collaborate more effectively, potentially leading to new, integrated disciplinary systems with enhanced capabilities. Systems engineering, with its focus on orchestrating multi-disciplinary collaboration, emerges as inherently transdisciplinary and a discipline that bridges other fields to achieve systemic solutions. This positions systems engineering not just as a participant in transdisciplinary efforts but as a distinct transdiscipline that is integral to building a better world through a systems approach.

SYSTEM ENGINEERING'S TRANSDISCIPLINARY FUTURE

The world is made of systems and our biggest problems are systems problems. As we face the pressing challenge of maintaining a sustainable lifestyle on a finite planet, systems engineering offers a bridge from constructing complex technical systems to tackling global sustainability issues. Engineering's impact on society and the environment, from the creation of microchips to the development of smart cities, has been profound, both positively and negatively. Recognizing the Earth as a system with limited resources demands a shift in how we approach growth.

The discipline's contribution lies in its systems approach, which simultaneously addresses the systemic nature of problems and their solutions, ensuring that solution elements work together as intended. Having evolved in the 20th century to solve intricate technical challenges, systems engineering is now poised to apply its methodologies to broader, global concerns, where the complexity and 'systemness' of issues are intertwined. This transition highlights systems engineer's pivotal role in engineering solutions that are sustainable, systematic, and capable of addressing the interconnected problems our planet faces.

Our complex issues demand active engagement with existing systems to achieve specific goals, taking their complexity into account. These challenges can range, for example, from developing policies for future pandemics, creating new systems to enhance existing ones, enhancing agricultural yields through genetic modification, carrying out organ transplants across species, to bringing about beneficial changes in environmental or climate systems by carbon reduction.

As we aim for Net Zero, we face the necessity of reforming agricultural and manufacturing practices, ensuring raw material supply, altering lifestyle and work habits, while fostering global collaboration. Unexpected events like pandemics, financial crises, or wars could disrupt these efforts, highlighting the need for interconnected solutions, which are resilient to the unexpected. Science and engineering must collaborate broadly if we are to address challenges such as these.

Addressing these challenges on a larger scale necessitates a deeper understanding of complexity within new domains. The rise of hybrid sciences like Systems Biology, informed by genomics and ecosystem functionality, supports such interventions. This interdisciplinary approach, extending to ecology, oncology, epidemiology, and earth sciences, emphasizes a systems perspective, broadening the community of practitioners.

In essence, a web of problems demands a web of solutions, involving a web of collaborators.

Understanding and applying science improves our interventions, making us bolder and more confident. Science and engineering mutually enhance, but without scientific insight, interventions must be cautious, evolving through feedback.

Systems science plays a unique role, offering insights not as precise as in physical sciences but valuable for bridging gaps. Investing in a unified systems theory could be crucial for future successes.

Engineering and systems science should partner, embracing transdisciplinarity to solve complex problems and pioneer new sciences. This partnership echoes the collaboration that shaped the modern world.

We must invest in education and research to prepare engineers for future challenges. They should be versatile, curious, and skilled to navigate and innovate in an evolving world.

The views expressed in this final section are further developed in another article in this issue (Brook et. al, n.d.).

CONCLUSION

The five authors of this paper, as independent voices on the nature and importance of transdisciplinarity in systems engineering, agree that it is imperative for meeting the systemic challenges of humanity's near-term future, from climate change to Industry 4.0 and Society 5.0. In this paper they explain the origins and nature of transdisciplinary systems engineering and argue that we can meet the challenge of preparing for the future by embracing Griffin's 'elegance paradigm' and Madni's TRASEE™ education paradigm for systems engineering graduate programs worldwide. ■

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The Spectrum and Evolution of Systems Engineering's Guiding Propositions

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ABSTRACT
Systems engineering has numerous guiding propositions scattered across various publications and classified under different schema, leading to confusion and inconsistency. This paper presents a framework for understanding the origin and evolution of any guiding proposition and developing such a guiding proposition into a principle to meet the challenges of Industry 4.0 and Society 5.0. We argue that following this process will enhance the elegance and transdisciplinary value of systems engineering principles and aid in solving complex problems.

INTRODUCTION

Systems engineering emerged in the 1940s as a response to the challenges of designing complex systems involving multiple disciplines and technologies. Its theoretical foundations in systems science, first formalized in the 1960s, are still evolving. Efforts to define systems engineering's "systems approach" involve formulating "guiding propositions" that encapsulate systems thinking and the experience of veteran engineers for use by all systems engineers. However, these propositions are scattered across numerous collections with varying quality and terminology, making them difficult to learn, compare and reconcile.

The International Council on Systems Engineering (INCOSE) is addressing this issue through the future of systems engineering (FuSE) initiative (https://www.incose.org/communities/working-groups-initiatives/fuse), recognizing the need for reliable guiding propositions in the face of rising complexity and the fourth industrial revolution. In 2020, INCOSE formed a workgroup to bridge the gap between two FuSE projects focused on establishing systems engineering principles and heuristics (Watson 2022 and Dori et al. 2023).

The workgroup, known as the "Bridge Team," aimed to understand and connect the outputs of these projects. They introduced the neutral term "guiding propositions" to avoid terminological disputes and focused on the content, evaluation, and refinement of these propositions.

In this article, we present a framework developed by the Bridge Team to help systems engineers consolidate and refine their guiding propositions into established principles, emphasizing the importance of understanding the value and purpose of systems engineering and the origins and evolution of guiding propositions.

SIMILARITIES AND DIFFERENCES ACROSS COLLECTIONS OF GUIDING PROPOSITIONS

Our initial investigation focused on the nature and differences across collections of guiding propositions. We observed that guiding propositions:

- offer guidance for making decisions or taking actions in specific situations;
- begin as initial ideas based on past experiences or known patterns;
- can differ in their scope (how widely they can be applied), authority (how persuasive they are), and capability (how reliably they produce expected outcomes);, and
- can develop over time to have broader scope, greater authority, and higher capability.

The similarities suggested the possibility of a unified conceptual framework, while the differences indicated the need to preserve important distinctions within this framework. We evaluated the scope (generality) and authority (trustworthiness) of propositions separately and considered their capability as a combination of scope and authority. This approach provided a useful framework for discussing the nature and evolution of guiding propositions, as represented in Figure 1.

We will explore this framework further

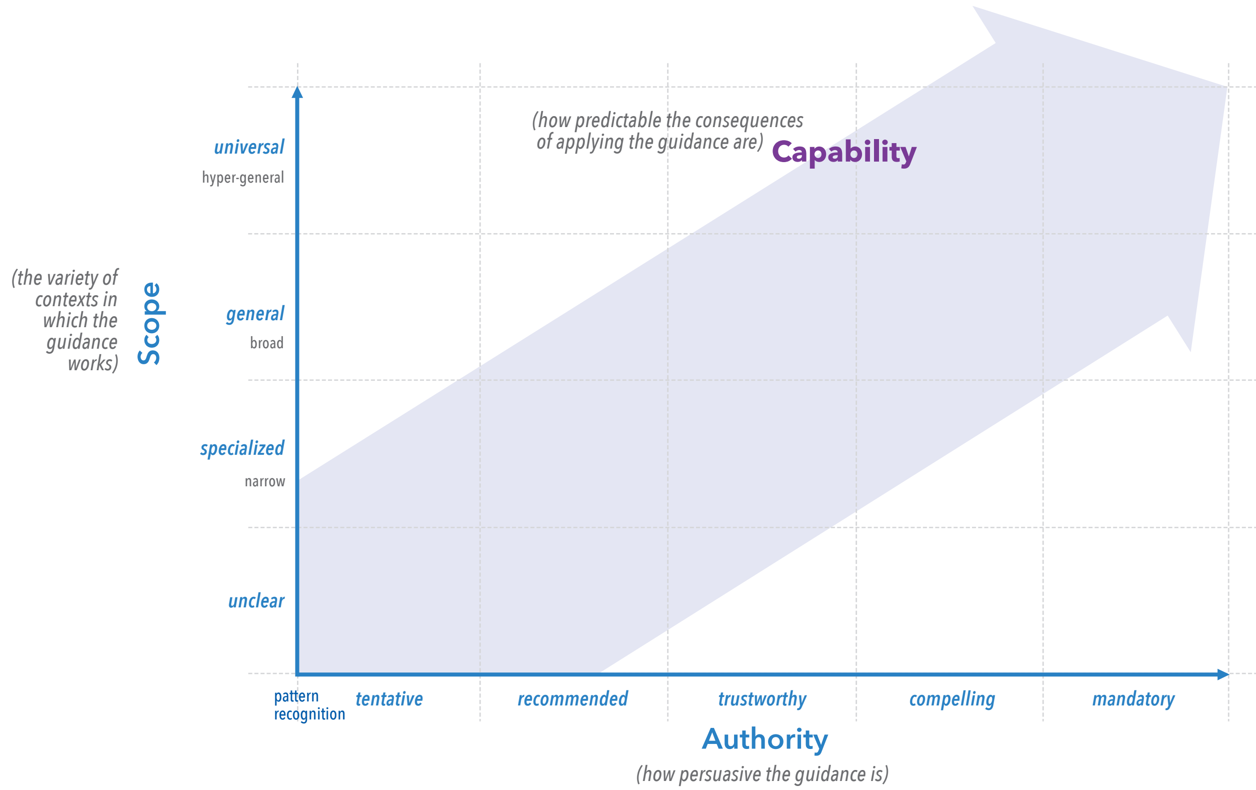

Figure 1. A canvas for tracking the development of system engineering guiding propositions

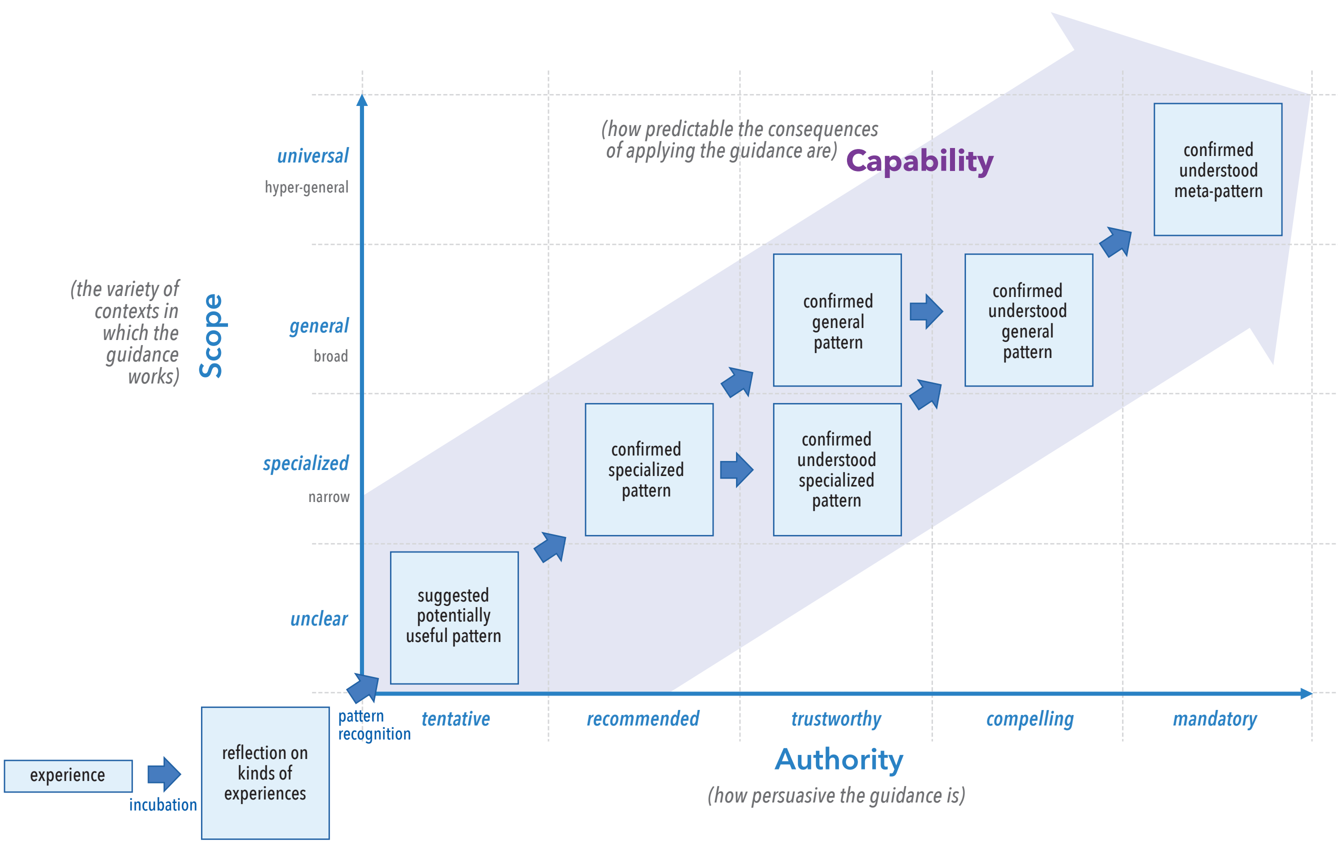

Figure 2. A model of evolution in the status of guiding propositions

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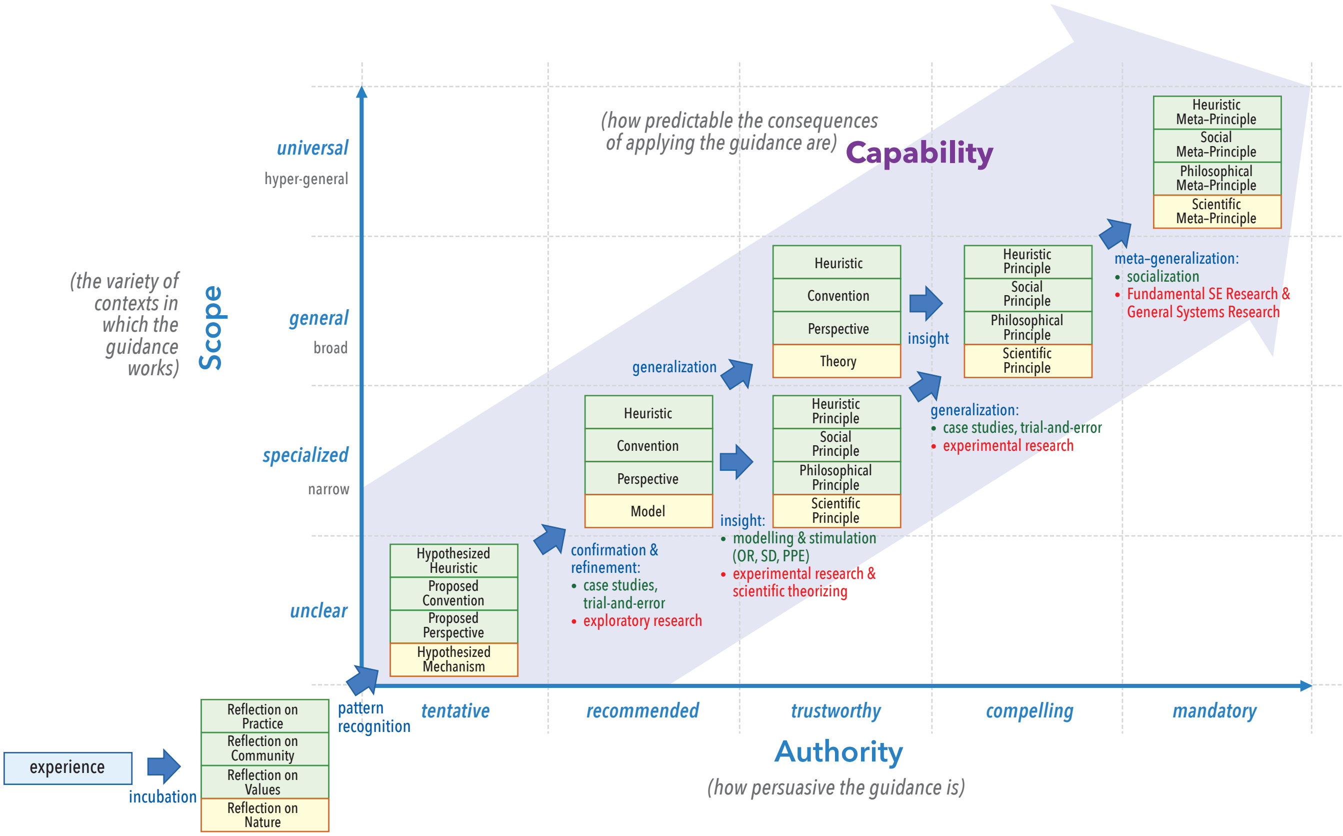

Figure 3. A model of methods used to generate, refine and generalize guiding propositions

by examining how the nature of guiding propositions changes as they evolve, how each evolutionary stage is achieved for different types of propositions, and the nature of the capabilities gained at each stage.

ORIGIN AND EVOLVING STATUS OF GUIDING PROPOSITIONS

Guiding propositions primarily originate from reflecting on experiences or information, where patterns are discovered that could be useful for anticipating outcomes in complex or uncertain future scenarios. Initially, these tentative patterns have low capability due to high specificity and low authority. Researchers' first objective is to confirm the pattern's robust presence across multiple instances of the specialized context, promoting it to a confirmed specialized pattern recommended for guidance in those instances.

Research aims to expand the pattern's generality across different contexts and to understand why the pattern exists. These steps increase both the pattern's practicality and insight into its effectiveness under various conditions.

The ultimate goal is to find hyper-general patterns, relevant always and everywhere, which become required for successful systems engineering and attain the status of being laws. As guiding propositions evolve, they are distilled from many tentative patterns into a smaller set of higher generality and greater trustworthiness, acquiring new attributes that increase their value. In the next section, we will discuss the evolutionary advances at each step.

METHODS FOR EVOLVING GUIDING PROPOSITIONS

To understand how guiding propositions evolve, we recognize different kinds of guiding propositions based on the types of experiences they reflect. We can categorize these experiences into reflections on practice, community, values, and nature, which roughly correspond to engineering, social science, philosophy, and natural science. These fields are all relevant to systems engineering, and although our categorization is not definitive it serves to illustrate our argument.

Guiding propositions can be grouped into two families: more qualitative, subjective, or culturally constructed (practice, community, and values) and more scientific, objective, and quantitative (nature). This division simplifies the modeling of how guiding propositions evolve.

To identify potential guiding propositions, we leverage reflection to recognize patterns in experiences or information. While there may not be formal methods for this, conscious beings have a natural talent for pattern recognition, making it possible to initiate this process.

When reflecting on different kinds of experiences or information, we derive various guiding propositions, such as heuristics, conventions, perspectives, and mechanisms from practice, community, values, and nature.

The first task is to confirm the value of the proposed guidance. For heuristics, conventions, and perspectives, this involves reviewing case studies and active testing in specific operational environments. For mechanisms, scientific exploratory research confirms their objective presence. Successful items become recommendable specialized heuristics, conventions, perspectives, and descriptive scientific models.

The next steps aim to gain insight into why the guidance is valuable and, if possible, generalize it for wider application. For specialized heuristics, conventions, and perspectives, insight can be gained through modeling and simulation using tools like operations research and systems dynamics. For specialized scientific models, insight comes from experimental research and theorizing, yielding explanatory scientific models. When we understand why a heuristic, convention, perspective, or model works, it can be considered a "principle."

Principles can be categorized based on their origins, such as heuristic, social, philosophical, or scientific principles. However, any guiding proposition with rational support can be a principle, with scientific principles being science-explained and others being science-informed.

Trustworthy specialized principles become more valuable and practical as they are refined and tested for wider contexts. This process involves case studies and trial-and-error for heuristics, conventions, and perspectives, and scientific research for scientific principles.

Success in these efforts yields systems engineering principles that are broad in scope and compellingly persuasive, essential for successful systems engineering projects. The goal is to develop "meta-principles" that are hyper-general, applicable always and everywhere in systems engineering, and mandatory for all systems engineers. These meta-principles reflect the systemic foundation of the real world and could greatly enhance systems engineering's capability.

To achieve this, we employ scientific research in general systems and fundamental systems engineering research. However, formulating a hyper-general principle is only half the battle; it must also be socialized so that everyone in the discipline is aware, convinced, and committed to employing it.

There are two classes of meta-principles based on their authority sources. Scientific meta-principles are determined by nature and represent systems laws. In contrast, meta-principles reflecting heuristics, conventions, and perspectives are more conditional and contingent, determined by culture, and include considerations like health, safety, and ethics. Once established, these cultural meta-principles are, for the given culture, as generally valid and mandatory as those derived from physics.

Principles representing cultural agreements are not arbitrary but grounded in insight into why it is in our favor to uphold them, often involving systemic intuitions or arguments. As systems sciences advance, we can expect these principles to be increasingly supported by scientific explanatory arguments.

In summary, the evolution of guiding propositions in systems engineering involves refining and testing specialized principles for broader contexts and ultimately developing meta-principles that are universally applicable and mandatory. This process is supported by both scientific research and the socialization of these principles within the discipline.

THE EVOLUTION OF SETS OF GUIDING PROPOSITIONS

Although we have discussed the forward evolution of individual guiding propositions, becoming more general and authoritative, the reality is that at any particular moment systems engineering's many guiding propositions exist at different levels of refinement. This creates a complex dynamic as propositions are tested, compared, confirmed, improved, generalized, socialized, and so on. There are also feedback loops in this dynamic, which are significant.

At any time, someone reflecting on a guiding proposition or a combination of them could be triggered to identify a new pattern and propose a new guiding proposition. This could be a new scientific hypothesis, a proposal to put an existing non-scientific guideline onto the scientific development track, or one that combines several guiding propositions into a more compact or general one. This process not only generates new guiding propositions but can also reduce the number of propositions in the set and make the set more scientific.

The ideal is to minimize the number and complexity of guiding propositions to simplify teaching, learning, and selecting the appropriate ones for judgment or action. At the same time, the goal is to maximize the capability that a set of guiding propositions brings to systems engineering, which is partly linked to the degree to which it is grounded in science. Understanding degrees of capability and how they are attained through evolutionary steps and methods is the subject of the next section.

THE EVOLUTION OF SYSTEM ENGINEERING'S CAPABILITY

As guiding propositions evolve, the benefit of their application becomes more predictable. The more general they are, the less likely they are to conflict with the context of use, and the better we understand the mechanisms behind why they work, the more likely they are to be applied appropriately. Consequently, the capability conferred on systems engineering by these guiding propositions increases as they grow in generality and authority. However, this capability is not just about predictability but also about the power of the propositions to guide systems engineering's judgments and actions effectively, ensuring systems engineering's value.

This power evolves alongside generality and authority, proceeding in stages where different kinds of power are gained at each evolutionary step. The nature of these gains allows us to assign a scale to the "capability" axis, representing the conjunction of increased scope and authority.

Starting at the bottom left-hand corner of the canvas and working up the diagonal:

- Initially, guiding propositions are proposed or hypothesized based on their potential usefulness. If the first validation step confirms their usefulness, we can say they work (are effective) and are worth refining further.
- The next validation step might focus on gaining insight into why they work when they work. Achieving this enables us to optimize the guidance, making it more exact, removing extraneous elements, identifying enabling or limiting conditions, making the proposition efficient in practice.
- The next step is to generalize, making the proposition more robust, useful, effective, and efficient in a wider range of contexts, and not failing or degrading when the context of use changes.
- The final step aims at meta-generalization, seeking principles equivalent to laws that apply always and everywhere. Achieving this means we can extrapolate its impact to all contexts and times, minimizing unintended negative consequences.

These qualities of effectiveness, efficiency, robustness, and minimum unintended consequences are associated with solution elegance. Therefore, we can say that the more elegant systems engineering's principles are, the more they assure the capability of SEs to make appropriate judgments and take appropriate actions.

THE FURTHER EVOLUTION OF SYSTEMS ENGINEERING'S TRANSDISCIPLINARITY

Systems engineering principles are not just maxims but are supported by descriptive and explanatory models and theories increasingly grounded in scientific insights. These provide theoretical foundations for systems engineering and are based on systems thinking, systems science, and general systems theory, contributing to the evolution of systems engineering's theoretical foundations in the study of systems.

As these principles become more general, their utility extends beyond systems engineering, becoming transdisciplinary. Since all specialized disciplines study or intervene in some kind of system, general insights into the nature of systems gained by systems engineering can be useful to these disciplines, helping them develop a systems specialization to complement their historical orientation. These insights and principles can provide a common ground of terms and concepts that enable specialized disciplines and systems engineering to collaborate on addressing complex problems, embodying the spirit of transdisciplinarity. In this sense, systems engineering is not only a transdisciplinary enterprise but could also become a leader in the evolution of transdisciplinarity.

SUMMARY AND CONCLUSIONS

The project aimed to understand the relationships between different collections of guiding propositions for systems engineering, such as principles and heuristics. We found these propositions guide systems engineers in making judgments and actions but vary in scope and authority. We developed a framework to assess a guiding proposition's maturity and identified methods for their development. We explored four classes of guiding propositions: heuristics, conventions, perspectives, and mechanisms. We proposed that propositions with a reasonable understanding of why they work should be called "principles," with qualifiers like "heuristic principle" or "scientific principle" as needed.

Developing guiding propositions into principles expands systems engineering's theoretical foundations and strengthens its grounding in the study of systems. As principles evolve, they become more "elegant" as proposed by Griffin (2010). We emphasized the need for guiding propositions to be more scientific to address the challenges of Industry 4.0 and Society 5.0. The future requires greater transdisciplinarity, and we argued that as systems engineering principles become more transdisciplinary, systems engineering could lead in advancing transdisciplinarity in practice. Achieving this would ensure SE's systems approach remains relevant in building a better world into the distant future. ■

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Transitioning Science to Practice

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ABSTRACT
National security challenges require a new approach to collaborative problem solving to address emergent challenges or opportunities. To effectively address these challenges, development of artificial intelligence (AI) technologies including machine learning (ML) and deep learning (DL), is underway. Advancing AI/ML capabilities requires transdisciplinary research encompassing the fusion of technology and emergent scientific discovery. Achieving this requires a departure from traditional research and development (R&D) methods. New development processes need to support the understanding that research progresses iteratively, technology insertion is incremental, and the final capability is evolutionary. We propose a novel systems engineering/research model called the vortical model. The vortical model introduces an iterative framework through which emerging advances in research outcomes are effectively demonstrated and validated for integration, as new capabilities, at varying technology insertion points. Our goal is to facilitate the transfer of knowledge from emerging research for swift, effective integration into the organization's mission capabilities.

INTRODUCTION

Many of the significant US national security challenges of our near future will require a new approach to collaborative problem solving across many specialized disciplines whether the topic is a new intelligence algorithm, a new weapon system, or a focused response to a global threat such as weapons proliferation, climate change, drug trafficking, cyber security, or another yet unforeseen challenge or opportunity. For these or other unforeseen challenges the solution set will likely require a level of cross-disciplinary research involving the intersection- or fusion- of technology and emerging scientific discovery.
This relationship between science and technology has been described by Michael Polanyi (1958), Figure 1 Polanyi's Relationship Between Science and Technology. Polanyi postures that science informs the building of new technologies; as these technologies are implemented, they in turn open up new questions and challenges for scientific research.

This reciprocity between technology and science is particularly applicable for artificial intelligence (AI) and machine learning (ML)- enabled capabilities. By its nature AI/ML is emergent and exploratory; AI/ML enabled systems properties arise as a product not only of the individual components of the system, but also from the relationships and interactions of those relationships. This presents development challenges that require a combination of

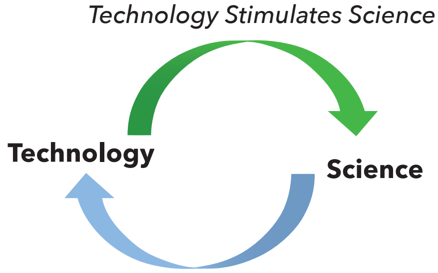

Figure 1. Polanyi's relationship between science and technology

skilled engineering design in coordination with the advancement of scientific insight from research activities, enveloped within the context of a specialized domain.

Traditionally, realization of advances from data science research, as with other applications of emerging science, generally happens along one of two paths. The research progression path, which is focused on enabling science and development execution, focused on engineering of a capability or system. Research progression involves a set of investigative activities, hypothesis-based, building on recent scientific discoveries or projected research outcomes, intended to mature conceptual applications into demonstrable, proof-of-principle results through deliberate experimentation. While research is, by definition, somewhat unpredictable, and speculative in nature and may often require new insights drawn from multiple scientific or technical disciplines to eventually realize the desired outcome, we postulate that adherence to good scientific methodology, or research best practices, may improve the likelihood of a successful outcome.

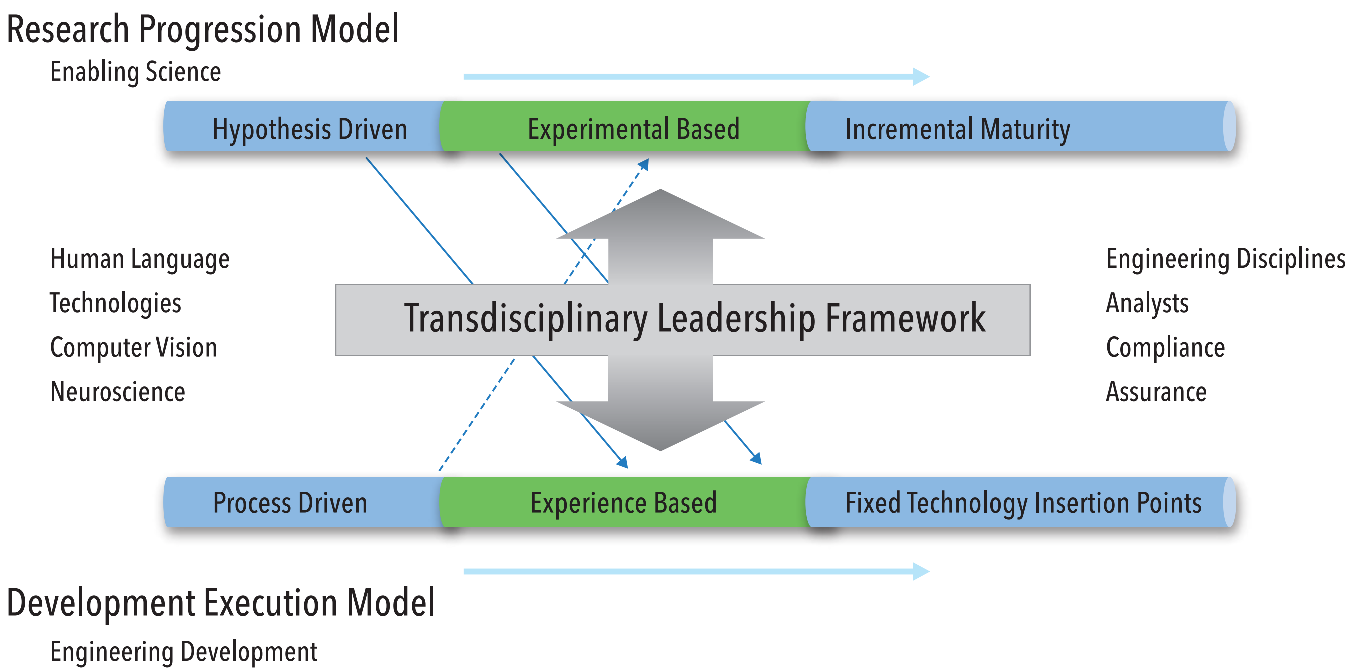

Figure 2. Research enabled development model

Development execution, on the other hand, is much more process oriented and engineering driven. It includes a set of disciplined methodologies for translating the most promising and best performing research outcomes into repeatable and reliable applications over a somewhat more predictable timeframe through roughly projected human and technological resources. These pathways are depicted as parallel access in Figure 2, with the interdependent linkage between emergent scientific research and engineering development and integration, akin to Polanyi's relationship between science and technology, provided through the transdisciplinary (more often cross-disciplinary) leadership framework introduced herein.

A key constraint to note here is that the development execution pathway can only accept new research outcomes at certain windows of opportunity, or technology insertion points, within the development lifecycle. This constraint thus requires close coordination and regular communication between the research and development project teams such that both teams are aware of timing for upcoming insertion points and are equally prepared to support the transition of new enabling technologies into the development process when ready. In addition, AI/ML innovation cannot be done solely along one axis or, in some cases, multiple parallel research axes. There needs to be a concerted effort for facilitating bridging of the respective research and development trajectories such that the corresponding advances may be applied in concert to achieve a desired outcome. In addition, effective AI/ML capabilities are context driven and the science/technology relationship needs to be fortified for a successful transition and ultimate adoption of the technology to occur. This characteristic requires a strategic transdisciplinary approach to development. Transdisciplinarity is a strategy for bridging insights from multiple discrete disciplines in an attempt to create a holistic view with the goal of creating new conceptual, theoretical, methodological, and translational innovations that integrate and move beyond each respective discipline (Colwell and Eisenstein 2001, Committee on Facilitating Interdisciplinary Research 2005, and Madni 2017). Rather than simply having multiple disciplines represented or working on the same project team, the transdisciplinary framework described herein attempts to foster a deeper level of collaboration and insight. The AI/ML ecosystem forces transdisciplinarity because of its emergent behavior as it often contains one or more trajectories that evolve, integrate, and co-adapt to each other to evolve as the problem itself changes and the system and its environment co-adapt to each other (Colwell and Eisenstein 2001, Committee on Facilitating Interdisciplinary Research 2005, and Madni 2017). While transdisciplinary collaboration, when properly orchestrated, can yield outcomes with far greater efficiency than the sum of independent efforts, effective transdisciplinarity does not come easily or naturally.

This paper proposes a new systems engineering/research vortical model concept as a more effective approach for research and development (R&D) of complex AI/ML-enabled capabilities. The vortical model has a conceptual process template for hybrid R&D programs, expands on the spiral nature of underlying systems engineering practices. The model, which applies systems engineering practices in concert with a set of research best practices to incorporate a degree of systems engineering perspective and rigor, is intended to support and enhance transdisciplinarity. The goal of transdisciplinarity is that researchers from various disciplines, cultures, and experiences, contemplate problems from a perspective beyond personal experience; using new insights gained from imagining the problem through a transdisciplinary lens to consider aspects of the problem from the perspective of their corresponding peers and not just from their own point of view.

Several key aspects of this approach are currently being applied to ML based computer vision research to improve optical character recognition capabilities. The work involves a cross disciplinary team of mathematics researchers, software engineers, analysts, and systems architects. We will use their work as a case study to illustrate how using this model accelerates the path toward successfully transitioning research results to operational practices.

CHALLENGES WITH SYSTEMS ENGINEERING PRACTICES IN RESEARCH

Formal methods have long been utilized in engineering projects to ensure the suitability of the resulting product or system for its intended purpose. Systems engineering provides the necessary methods and

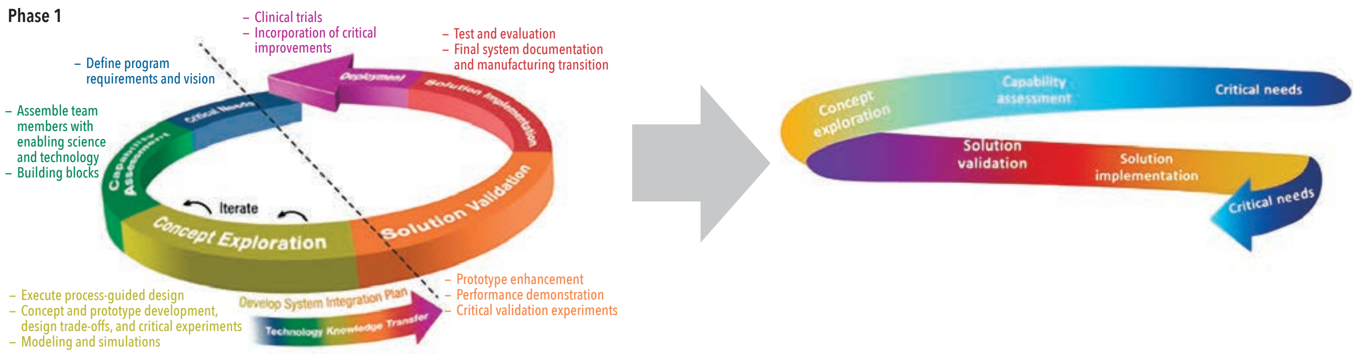

Figure 3. Spiral development model uncoiled

tools to effectively manage relationships, interdependencies, and interactions across all system components. By incorporating systems engineering rigor, risks can be reduced, uncertainty can be controlled, and the transition from research to operations can be facilitated. While systems engineering is commonly applied in development activities to enhance the design and development process, it is often overlooked in the realm of research, as it is perceived to limit exploration and creativity. However, to accelerate innovation, it is essential to harmonize research and development processes, enabling the smooth transition of new technologies into operational use. This requires improved communication and coordination between those involved in emerging research outcomes and those responsible for resource planning and prioritization for enterprise system integration.

Currently, there is a lack of documented processes or models outlining the structure of research and discovery advancement. Moreover, there is no "silver bullet" that guarantees successful innovation and effective technology transition into operations. Existing literature acknowledges the challenges associated with technology transitions (Ellwood et al. 2022. Dean et al. 2022, and Stefan 2022). Ellwood et al. note that the complexity of the process, along with competing stakeholder goals and multiple potential pathways, makes technology transitions difficult to achieve. Managing uncertainties, risks, and the diverse needs of each stakeholder along these pathways is crucial. Contrary to the notion of linear progression, technology development is an iterative, parallel, and integrative process involving various stakeholders. Successful technology transition proposals emerge from purposeful integration of stakeholders' needs, risks, and values. In the work by Lefevbre et al. (2022), they emphasize the importance of trust, effective communication, and information flows as contributing factors to successful technology transitions.

EXPLORING AGILE SYSTEMS ENGINEERING FOR RESEARCH

Research is cyclical and iterative. It starts with a vision, a hypothesis, or an understanding; but as work progresses and is evaluated, research often transforms and can diverge from its initial intent. Agile systems engineering, based on iterative and incremental development – where solutions evolve through collaboration between self-organizing, crossed functional teams – can be a good fit for this environment. The agile systems engineering methods can provide an appropriate balance between the discipline needed to achieve results while maintaining flexibility for research exploration and agility to accelerate innovation. The process also promotes a more collaborative environment, provides an opportunity for rapid feedback, and more readily allows adjustments to the research direction if needed at earlier stages.

However, while research is an interactive process that focuses on one specific capability, each of these capabilities are refined, matured, and then integrated (through development) into a larger complex workflow/system. In these systems it is very important to pay particular attention to the larger broader system/workflow that the capability will be a part of, to ensure that full system intricacies and interactions, and unexpected emergent consequences of AI/ML output are considered (Krishnan 2015). To effectively provide for bridging and interlacing R&D from a holistic system perspective, the systems engineering model must allow for evolutionary/emergent dynamics and distributed collaborative design, while also maintaining the broader system view (Dahmann and Baldwin 2008).

INTRODUCING THE VORTICAL DEVELOPMENT MODEL CONCEPT

The development execution model depicted in Figure 2, is traditionally modeled as a cyclical process of piecewise linear activities that can be represented as the spiral process depicted in Figure 3.

This spiral development process has been successfully applied to address changes in user needs, obsolescence, or significant improvements in technology over the span of a product's (or system's) lifecycle (Bhuvaneswari and Prabaharan 2013).

However, the development of AI/ML systems requires a shift in how R&D is traditionally pursued, and new development processes need to support the understanding that research is iterative, technology insertion is incremental, and the final capability is evolutionary. To address the unique challenges in developing AI/ML enabled systems, and to facilitate R&D progress, the concept of a vortical systems development model is introduced. The vortical model extends the foundational and well-characterized spiral systems engineering and development model, Figure 3, to incorporate the agility and flexibility of agile systems engineering methods. Additionally, the vortical model introduces an iterative framework through which emerging advances in research outcomes are effectively demonstrated and validated for integration as new capabilities at the next technology insertion point or window of opportunity. This iterative process of accelerating, evaluating, and preparing emerging research outcomes for potential incorporation into the development cycle adds a third, vortical, dimension of increasing maturity to the traditional spiral development approach.

We have demonstrated and documented an agile research methodology intended to provide improved focus on research activities and awareness of progress in advance of upcoming technology insertion windows, with the additional goal of more quickly validating or rejecting emerging research outcomes for increasing the velocity of transitions from research to development. As a particular research project matures, the component of underlying research risk is gradually retired and any

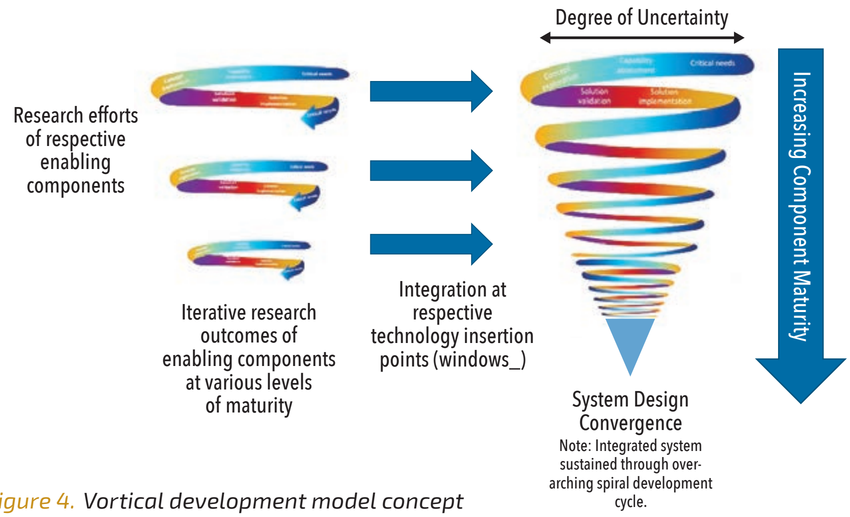

Figure 4. Vortical development model concept

required training and evaluation datasets are curated and iteratively expanded, policy and resource constraints are inevitably addressed, and validation, performance characterizations become more efficient. Accordingly, the tightening of corresponding spirals representing research progression activities, or maturity, along the third dimension, informs a new graphical visualization model that evolves the morphing of traditional spiral development into the vortical research and development model shown in Figure 4.

The model also provides a mechanism for facilitation of transdisciplinary research progression. The model is based on the premise that an AI/ML-enabled system is usually a large effort comprised of several components or discrete building blocks, each with its own unique and concise research questions or more manageable design tasks. While each of these components are viewed as independent, they are related to each other through the contextual framework and management structure of the larger system, or what is termed a system-of-systems. System-of-systems engineering principles delineate the need to understand and optimize subsystems, then optimize subsystem-to-subsystem to system interactions (Dahmann and Baldwin 2008). The same system-of-systems optimization approach, with incremental integration, must be followed to fully realize the potential of AI systems, hence the feedback path indicated in Figure 2. As a complex project is distilled into concise research questions or more manageable design tasks, these components begin to look more like independent projects–related to each other only through the contextual framework and management structure of the larger system. Figure 5 illustrates this framework.

Unfolding Figure 5, the R&D baseline begins with various system components that can be viewed as discrete building blocks. Distillation of the system components into smaller pieces allows parallel research tracks or development efforts, for higher risk subsystems/technologies. This enables the option to prioritize critical items that may pose development risks for schedule or performance objectives. It also breaks the overall system into smaller projects; and on this smaller scale, we can more readily explore new research management models to facilitate and potentially accelerate research progress (Harshbarger 2014a and 2014b, and Burck et al. 2011). Because these baseline components are often at various levels of maturity, the vortical model uses several synchronous agile development sprints that allow for a coordinated spiral development of these enabling components/building blocks. These components are then incrementally introduced into the workflow. Incremental integration of each building block/slash enabling technology helps to reduce risk and allow an evaluation of the system design as each component is integrated. This also allows the emergent behaviors of the integrated capabilities to be evaluated before continuing. Allowing redesign and rethinking to occur at an earlier point in the total system design process reduces risks and allows for redirection sooner rather than later in the development timeline if needed. In addition, these iterative designs allow the team to incorporate lessons learned while managing impact to linked components.

CASE STUDY

As an example, we provide a case study where the vortical model concept was applied to machine learning based computer vision research to improve optical character recognition (OCR)

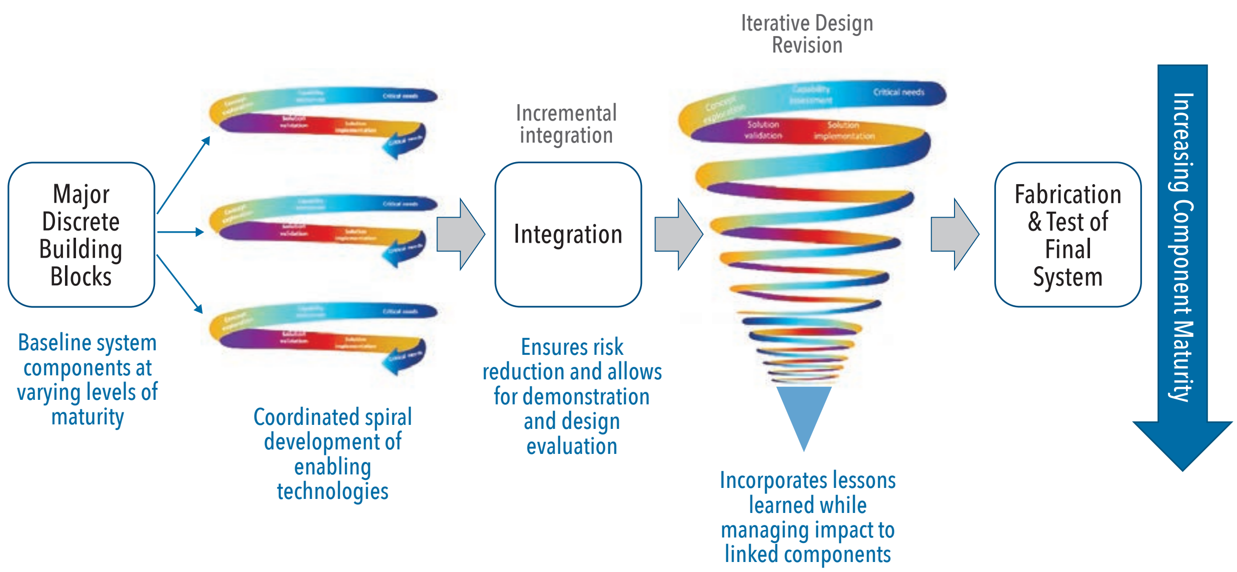

Figure 5. Adapted from A Conceptual Process Template for Hybrid R&D Programs (Harshbarger 2014)

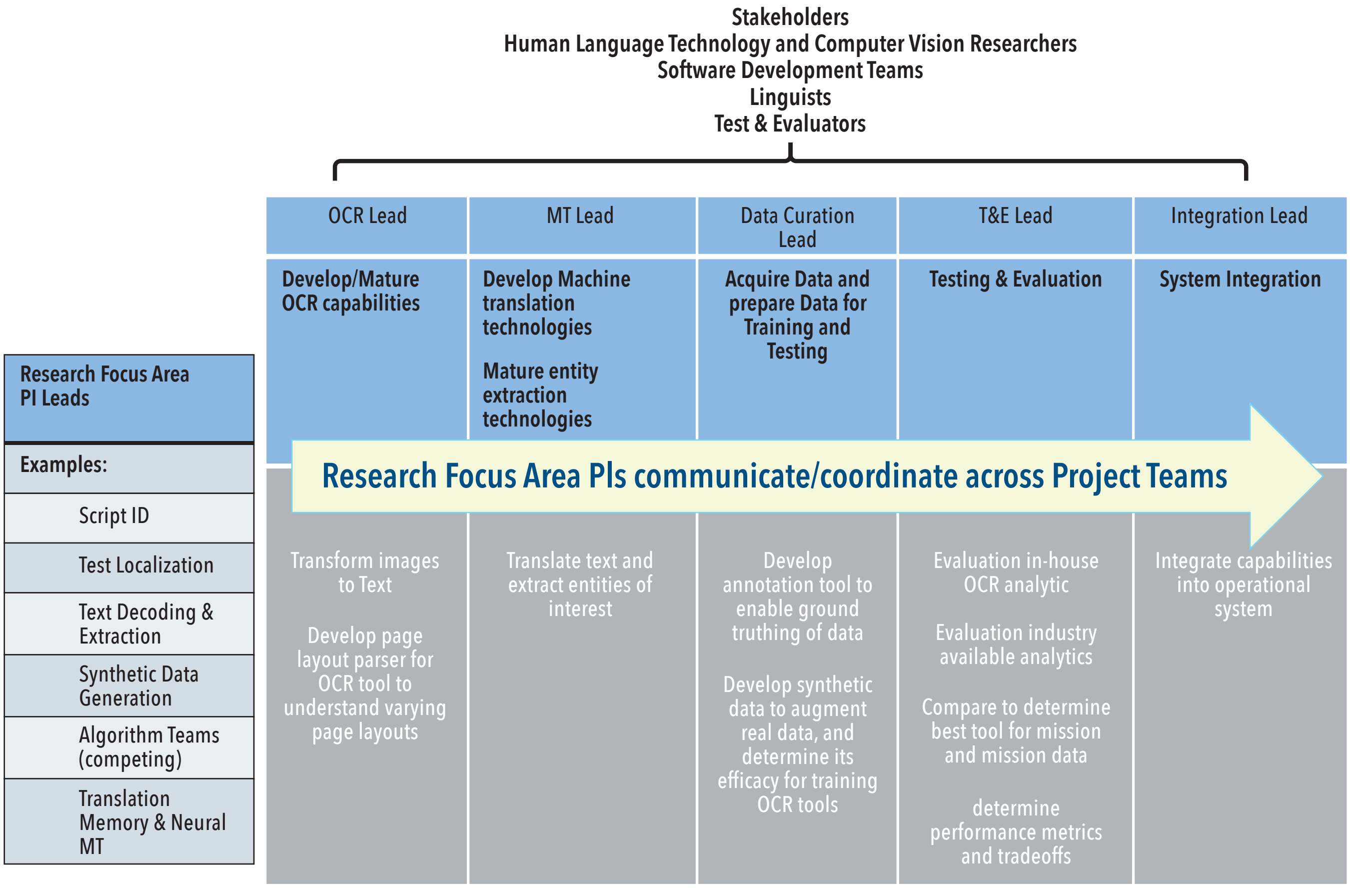

Figure 6. Collaborative team structure

capabilities. We will use this work to illustrate how the model is used.

Background—Developing OCR Capabilities.

A group of human language technology (HLT) research teams and a team of computer vision (CV) researchers began to look into building a new, and improving existing, capabilities that would allow them to generate information from document images over diverse languages and scripts (writing systems), and over widely varying layout complexity. This led to the creation of a system workflow that would allow them to accomplish the required fusion of HLT with CV technologies under the direction of specialists in the various languages and application domains. While at a high level it seems that there are only three areas of convergence, OCR, machine translation, and entity extraction; the fact is the complexity of the problem required the exploration of several new capabilities. For example, document images can have varied amounts of page layouts; 3-columns, 2-columns, or 1-column layouts, with images interspersed throughout the page. Computer vision capabilities were needed to identify the page layout, extract the actual text from the image, and then group the text accordingly for the machine translation capabilities to then translate the extracted text. Ground truth or labeled data needed to be generated, which was a project onto itself, as there were no tools that were effective in developing the ground truth, and sufficient data to use for training was not readily available. In addition, machine translation and entity extraction technologies needed to be modified for the various language scripts.

Team Structure

To bridge the respective scientific challenges with the domain understanding and technologies necessary that would lead to a fully integrated and demonstrable system required a transdisciplinary team of mathematics researchers, software engineers, analysts, and system architects. The goal was to have a development process that would lead to a fully integrated and demonstrable end-to-end system and facilitate research progression while initiating development/engineering design for data preparation and end-to-end system workflow. The research teams collaborated to identify what the technology high-level workflow should look like at completion, and then the system was broken down into manageable research or development pieces. The details of each workflow before convergence were left to the research leads. Distillation of the system components into smaller pieces allowed the research leaders to insert diverse teams within the innovation process.

Figure 6 illustrates a team structure where research principal investigators work in conjunction with designated subsystem development team leads to ensure research outcomes converged at design decision points. This structure is facilitated by other team engagement strategies and visioned to bridge the respective scientific research and development domains, and to create a transdisciplinary effort to bridge insights from across the various disciplines.

As Figure 6 depicts, the CV team worked on developing algorithms/capabilities to parse image documents and extract text from the images. This work depended heavily on annotated data of image documents: to enable that portion of the work, a specific annotation tool was developed and adopted. The testing and evaluation (T&E) team worked on evaluating industry and academically available tools, as well as developing a baseline on which to measure.

The linguists were used to do language translation, and domain experts worked with the human language technology teams to provide domain knowledge needed for developing effective translations and to identify entities of interests.

The key here is that each component leader understood their respective functional role, corresponding system requirements, and interfaces with their subsystem and within the context of the entire system so that the components could easily interoperate. They set specific goals for their team, as well as prescribed the system inputs, outputs, and what evaluation metrics must be met. Additionally, they had to work in concert with the corresponding principal investigators (PIs) to enable scientific research to ensure a clear understanding of the state of emerging science for incorporation of best available results. Similarly, each PI shares the responsibility for thinking beyond their research focus area to consider aspects of how their research outcomes would be incorporated together with other supporting technologies and ultimately integrated into the resulting system.

Using the Proposed Vortical Development Model

Bridging the respective scientific challenges requires a process that would develop a fully integrated and demonstrable system. The full system development process needed to be iterative, as information gleaned from one step was incorporated into the next. Distillation of the system components into smaller pieces allowed for parallel development for higher-risk subsystems/technologies and enabled the option to complete critical items that may pose development risks for schedule or performance objectives. It also delineated the overall program into smaller projects that more closely approximate the size and scope for self-contained explorations or tasks that may be assigned to a smaller research team, intern, student project, time-bound event, or leveraging an industry available technology. On this smaller scale, we could readily explore new research management models to facilitate and potentially accelerate research progress. Figure 7 illustrates the iterative, incremental, and evolutionary process for the OCR project.

The project was broken down into small base components: text layout tools, annotation tools, evaluation of commercial OCR tools, entity extraction tools, etc. While the HLT teams, working hand in hand with domain experts and linguists, focused on improving their machine translation for several languages and

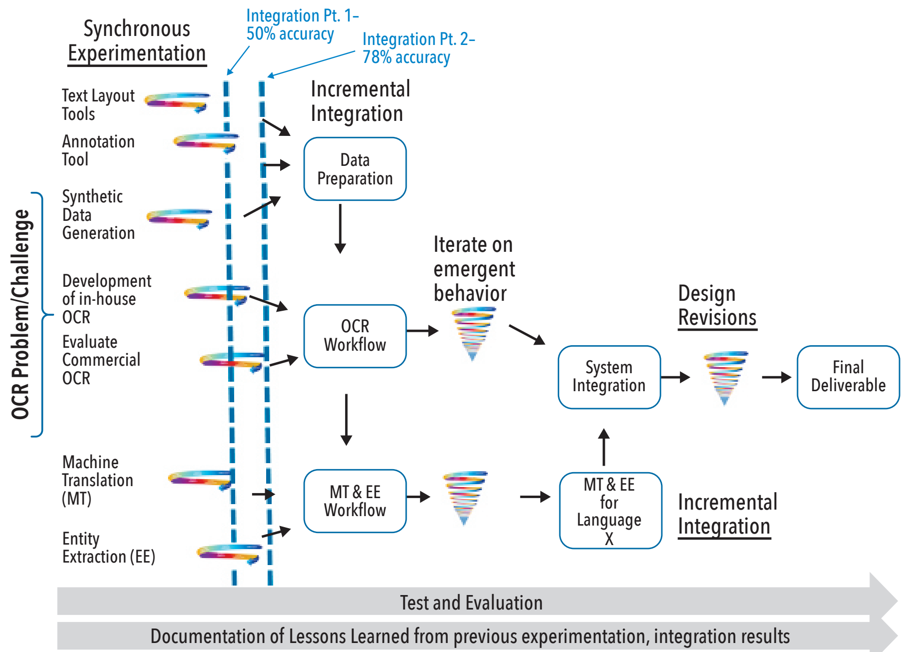

Figure 7. Example of iterative, incremental, and evolutionary development for OCR

their entity extraction analytics, the CV team focused on exploring methods and available industry/academic analytics to improve their baseline OCR capabilities. In addition, several spinoff experiments were conducted to develop and prepare ground truth data. This included the exploration of the efficacy of synthetic data generation. These teams worked within a modified agile development process using pseudo sprint cycles of approximately 3-weeks induration. This modified agile approach incorporated lessons from the individual execution models and allowed AI/ML properties to emerge through incremental integration into the overall system workflow. While research is clearly not software development, we adopted these agile (sprint-like) cycles to encourage best practices that promise to positively affect research progression.

While research maintained their cadence of new exploration, the T&E team maintained their own cadence in evaluating commercially and academically available tools. The cyclical process generated valuable lessons learned from the engineering development processes, and research experimentation results achieved during one stage were captured and incorporated into the subsequent phase efforts. Establishing an agile cadence allowed the team to synchronize communication and perceptions as it provided checks and balances from various perspectives. Issues were regularly discussed, tips and lessons learned readily shared, and solutions to problems were creatively solved collaboratively. For example, a synthetic data generation system was developed to see if the OCR engine could benefit from additional training. The two teams worked together to develop training data in a specific language and further train the OCR engine. The resulting model was then evaluated where it was found that the additional training not only improved error rates in the target language but in other languages as well. These findings led the team to generate and train the OCR on an expanded language set of synthetic data that eventually led to the universal language OCR engine.

As depicted in Figure 7, the research teams worked alongside the production designers to ensure the effective transfer of knowledge into an operational capability, using incremental integration practices, continually incorporating mature capabilities up to the last insertion point opportunity, and then optimizing as an integrated whole until the next insertion point.

CONCLUSION

The challenge remains to accelerate the implementation and adoption of AI/ML capabilities for mission because research and development is associated with high risks, great uncertainty, and unpredictability. As scientists explore the "known unknowns", as well as the "unknown unknowns," introducing some needed system engineering discipline – while maintaining agility – is key in accelerating the operationalization of new capabilities; yet very difficult.

In addition, AI/ML environments are emergent systems, requiring a transdisciplinary approach for effective adoption, and traditional systems development methodologies do not fully support the needs of this environment. We proposed a new vortical development model concept that balances flexibility for research discovery, introduction of engineering rigor for easier transition to operations, as well as support for incremental and optimization requirements to address systems-of-systems complexity.

The model begins by using the systems engineering foundational practices that provide a degree of engineering rigor and incorporates agile systems engineering methods to support and accelerate transitions. The model also supports transdisciplinarity in the hope that researchers from various disciplines, cultures, and experience may begin to contemplate problems from a perspective beyond personal experience, using new insights gained from imagining the problem through a transdisciplinary lens.

As this process is further developed the goal will be to incorporate additional aspects of the vortical development model, and to potentially encompass a full set of emerging best practices for effective facilitation of transdisciplinary research progression for artificial intelligence systems. ■

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