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## Engineering Praxis Ethos: Designing Experiences to Support Curricular and Instructional Improvement in STEM Education

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### Abstract

This paper discusses engineering praxis ethos (EPE), a proposed framework for constructing a STEM learning environment embedding interrelated components of learner experience and design activity, which can support curriculum and instructional design and evaluation in STEM education. The authors propose that STEM is a meta-discipline that relies on the design life cycle, the intellectual root of engineering disciplinary knowledge. The nature of design and design activity calls attention to domain-specific needs of STEM teachers and focuses discussions and critiques about the epistemological adequacy of integrated STEM content knowledge. Given the urgent need for learners to develop 21<sup>st</sup> century skills in STEM, the authors argue for the feasibility of incorporating both mathematical and simulation models using new technologies when designing experiences for learners. An example of teaching and learning systems thinking in undergraduate engineering education highlights how EPE can be a viable theory of action for STEM educators.

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### Introduction

A review of STEM education research in the United States reveals significant interest and investment at all levels and across many domains over the past two decades (Li, et al., 2020a; Li, et al., 2020b). Recent scholarly efforts reflect varied instructional, theoretical, programmatic, and technology-based approaches to STEM education (Akerson & Buck, 2020; Duschl & Bismarck, 2016; Johnson et al., 2020; National Research Council, 2011). However, whether any of these efforts have truly had a lasting impact on student success in STEM is unclear (Gao, Li, Shen, & Shun, 2020). This phenomenon has triggered substantial funding for research in several areas of STEM education, including learning, program evaluation, technology use, and assessment (Johnson et al., 2020). The STEM education enterprise has grown more complex as viewpoints and ideologies compete for inclusion in the formation of STEM education theory along with its pragmatic applications (Akerson & Buck, 2020; Duschl & Bismack, 2016; English, 2016; Leung, 2020). In general, many philosophies, perceptions, and paradigms about STEM education have focused on how to implement policies and teaching practices, rather than specific content and its epistemological aspects that forms the basis for curriculum and instructional design. Many researchers agree that discerning what exactly is meant by "STEM" is a formidable challenge. Many educational

initiatives even remotely associated with science, technology, engineering, or mathematics could be considered innovations in STEM education. Unfortunately, this lack of a solidifying philosophy or definition of the nature of STEM education threatens to diminish support for education reform efforts over the long-term. Within STEM education, teachers, researchers, instructional designers, and leaders know that procedural mastery alone is insufficient for student success. Demands of 21st century higher education and the 21st century workplace require “21st century skills” (National Research Council, 2012). The ability to memorize facts and procedures – areas most commonly tested in state accountability systems – will be useless without the ability to apply knowledge and skills within and across stem disciplines. The term “21st century skills” has been defined in many ways. However, the National Research Council sheds important light on this discussion by outlining 21st century competencies that are crucial for success in education, work, and life: critical thinking, problem solving, communication, collaboration, and learning to learn. As a result, we need to understand how foundational STEM concepts (e.g., computational thinking, mathematical modeling, systems-thinking) are best learned (National Science Foundation, 2018; 2020).

## **Theoretical Background**

We propose that STEM is a *meta-discipline* with its own epistemic underpinnings (Kennedy & O’Dell, 2014) and not merely a curricular approach used to teach the individual disciplines while making some effort to highlight their interdependence (Akerson & Buck, 2020). STEM is also a domain of theoretical knowledge that engages each discipline as they exist in the world, part and parcel of each other (Morrison & Raymond Bartlett, 2009). Our proposed view of STEM influences our approach to STEM integration, making it more trans-disciplinary rather than multi- or inter-disciplinary. That is, our aim is to propose how STEM education can develop knowledge and skills from all four disciplines by teaching in a STEM learning environment (SLE) that focuses on real-world problems and projects through learning experiences (Leung, 2020). Many SLEs are based on principles to foster *productive disciplinary engagement*, which “combines moment-by-moment, interactional aspects of student engagement with ideas of what constitutes productive discourse in a content domain” (Engle & Conant, 2002, p.84). These principles include 1) identifying operating contexts and needs, 2) problematizing subject matter; 3) giving students authority to address such problems, 4) holding students accountable to others as well as shared disciplinary norms, and 5) providing students with relevant resources. Productive disciplinary engagement occurs when learners use the discourses and practices of the discipline in authentic tasks in order to “get somewhere” (develop a product, improve a process, gain better understanding of a phenomenon, etc.) over time. Productive engagement in meaningful, authentic activity is essential for motivation and progress toward flexible, adaptive expertise in STEM. We propose that developing philosophical, conceptual, and epistemological underpinnings within an SLE may be a way to conceptualize *what* we teach in STEM and *how* students learn STEM content.

Learning in an SLE occurs in the context of modal engagements (MEs). Hall and Nemirovsky (2011) describe MEs as “a way of participating in activity, with others, tools, and symbols” (p. 5). Design activity in SLEs can be viewed as a series of interconnected ME’s that occur as students encounter and interact with different material and representational forms, social configurations, and physical settings. MEs bring to the forefront the multi-modal, embodied nature of learning that is central to participation in SLEs where students and teachers use gesture, speech, and action to engage with a variety of media (Walkington, et al. 2014). MEs may be seen as the drivers that define

what knowledge is needed (and in what sequence) to address a given problem. In this way, MEs can function as a correlating center (CC) for learning proposed by Wicklein (2006) and by Sanders (2008). Engineering design activity can potentially bring key concepts from multiple disciplines and provide a structure for their application through design and modeling processes. It can provide the framework that guides integrated activities and understanding in a way which enhances relevance and therefore, engagement by the learner (Nathan, Srisurichan, Walkington, et al., 2013). In general, the SLE nurtures in students a general feeling of competence through the features of engaging activities where students can come up with innovative ideas (Borge, 2016). According to Guthrie (2010), the engineering education community should foster holistic engineering curricula that broaden students' understanding of, and ability to work within, the social context. There should be flexibility in building an SLE which is guided by the level of student engagement, student interactions, and student feedback about working in an SLE.

## Engineering Praxis Ethos

Robinson (1998) highlights what he calls the *intellectual root of engineering*. He states that, intellectually, engineering is the development of an explanatory and argumentative framework that, given real-world constraints, identifies and validates the best solution to a problem. If engineering is applied scientific, mathematical, and technical knowledge to develop solutions to practical problems, then it is possible that engineering *design activity* and the *design life cycle* conceptually covers the STEM fields. Engineering selectively makes use of formal knowledge from science, mathematics, and technology in its design process. As a result, we propose the term *engineering praxis ethos* (EPE) to refer to the kinds of experiences and activities necessary to support a more robust and complete view of STEM content than what currently forms the basis of curriculum, instruction, and education research. EPE's components — experiences, activity, and teaching by design — are proposed as parts of integrated STEM content and what comprises a STEM learning environment (SLE). A summary of EPE and a framework for visualizing EPE is shown in Figure 1.

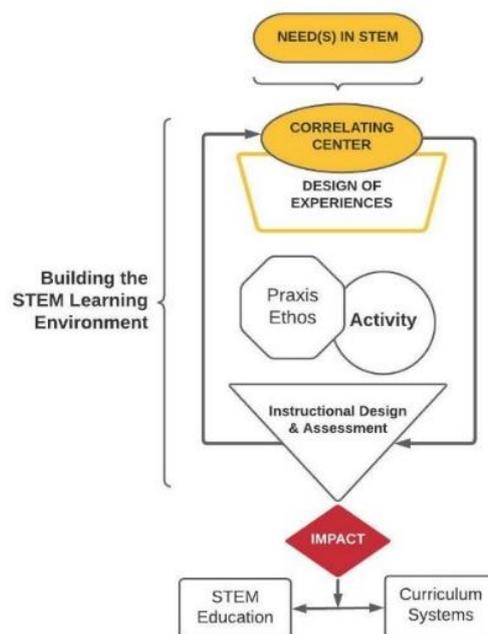


Figure 1. The Engineering Praxis Ethos (EPE) Framework

Because of its iterative nature, EPE allows continuous improvement to support student learning outcomes. Productive disciplinary engagement captures the kind of interactions with people and objects likely to result in deep learning of STEM concepts and practices. Engagement is productive to the extent that conceptual or practical progress on a problem is made over time. Engagement is disciplinary when students use the discourse and practices of a specific STEM discipline while working collaboratively.

### **The Correlating Center and Design of Experiences**

For the practicing holistic engineer, the “problem/need” is a critical life cycle phase that aims at investigating the end goal by exploring the context through a series of questions such as: Who is in need? What is needed? Why is it a problem? On the other hand, “the design/activity” describes the “how and where” objectives and tasks will be executed at the CC to address the end need. Curricular emphasis shifts from organizing instruction around formal structures of fields of study to a sequence of meaningful and purposeful activities that guide students through the integrated use of knowledge (National Academy of Engineering and National Research Council, 2014). We argue that the design of experiences for learners should include five key characteristics of SLEs identified by Koretsky et al. (2014, pp. 10-11) that are also integral parts of design engineering:

- (1) *A challenging problem.* Each activity presents a problem challenging enough to require multiple students to be engaged in order to solve it. Students must develop the vision and mindset to understand connections to previous, similar experiences and to contextualize the problem.
- (2) *Real world constraints.* All authentic learning environments include some form of real-world constraints. These are the boundaries of the solution space, i.e., time, the limits of available technologies, the laws of physics, resources, materials, legal and regulatory frameworks, and their potential impact on the solution.
- (3) *Realistic data.* Access to realistic and manageable data is a key component of SLEs.
- (4) *Iteration.* The activity requires some form of looping or iteration. Feedback is an essential element as it steers design activity to local progress.
- (5) *Roles.* The role students as well as teachers play while engaged within the SLE reflect productive disciplinary engagement.

One attribute ascribed to design activity is the ability to tolerate and navigate ambiguity and uncertainty. This appears most often in the view of design as an iterative loop of convergent and divergent thinking. Convergent thinking is knowledge-based and tends toward a verifiable “truth” at some level. In design parlance, convergent thinking leads to a point solution. Conversely, divergent thinking is concept-based and diverges over a “solution space” and does not necessarily lead to “truth.” Practitioners imagine the solution space as a field of possibilities which can contain nearly unlimited classes of solutions. The dynamic between convergent and divergent thinking leads to trade-offs and a subsequent collapse to a reasonable solution based on predetermined technical, economic, aesthetic, regulatory, and political criteria along with constraints embodied in the requirements (Bucciarelli, 1994).

### **Ethos and Activity**

According to Grasso and Martinelli (2010), the future engineer must be one who can think broadly across disciplines and consider the human dimensions that are at the heart of every design challenge. As seen in emergent

projects related to Human-System Integration or Socio-Technical systems, systems engineers must be adept at thinking as a social process (Bucciarelli, 1994), i.e., social thinking or how humans try to make sense of others' thoughts, feelings, and intentions in context, whether we are actively interacting, or figuring out what is happening from a distance through various forms of communication. Researchers in the design sciences emphasize that the early stages of the design process are "inherently argumentative," requiring the designer to continually raise questions and argue with others over the advantages and disadvantages of alternative proposals (Rittel and Webber, 1973).

Designers value the ability to use several languages or representations used in design, including verbal or textual statements. In discourse, the role of language is expressive, and the goal is to effect communication among a group. Placing language in the context of a community of experts provides one the opportunity to consider how meaning and argument evolve in a communal setting. This socio-cultural context provides a rich theoretical framework for considering how engineering design involves development of a sign system. Graphical representations (e.g., context diagrams) are used to provide pictorial descriptions of designed artifacts, along with shape grammars, which provide formal rules of syntax for combining simpler shapes into more complex shapes. Design attributes of convergent-divergent thinking, working in teams and fluency in two or more design "languages" culminate in the construction of models (Robinson, Sparrowe, Clegg, & Birdi, 2005). In today's systems, analytical, digital, graphical, and mathematical models are used to express aspects of an artifact's structure or behavior.

Data analytics offers a powerful means to make sense of a range of events or phenomena and is typically in response to a need. Analytics informs the problem, the field of potential solutions, the collapse to a defensible solution, and vectors for implementation and execution. In practice, designers must control unwanted variation and rely on the accuracy of sampling and representativeness of models. If all relevant factors necessary to confirm the data are included in the mathematical model, then the model is tested to determine if it has achieved external confirmation and validation. If the model is not assumed to contain the data specifications, thus preserving the independence of the data, then an alternative solution may include a proposal that data are collected via some other system — a theory of measurement or an application of statistical technique. Since statistics and measurement systems are themselves models, we claim that any act of mathematical analysis, to avoid epistemological irregularity, must involve the human activity of comparing models. Successful mathematical modeling thus depends on enough familiarity of the phenomenon to be "measured," knowledge of constraints in "measuring" the phenomenon, and the reliability and validity of the constructed model.

Data analytics is an exciting process critical to engineering design in that a mathematical model possesses its own structure. This structure may not be limited to logical organization but may also include functional organization. The system can be dynamic and allow one to explore its structure by varying parameters to describe the invariance and emerging patterns in the system. For instance, in simulations, a form of modeling, the mathematician undertakes multiple realizations, and adjusts its structure to produce desirable outcomes. This process is usually identified as a "what if..." iteration. It is an environment that supports the development of reasoning and argument, as one seeks to explain a range of outcomes and the underlying invariants. An appreciation of such structure,

consequently, allows a designer to also see some connectedness between formal, syntactical signs or symbols and their referents.

### Instructional Design and Assessment: A Systems Perspective

Curriculum development and instructional design are often synonymous terms. Some clarify each by saying that curriculum development is *what* students will learn, while instructional design is *how* students will learn it. Yet, neither can be resolved without changing the other. Curriculum and instructional design involve the forming of educational content and the contents of educational forms. Therefore, teachers can neglect neither theory nor design. In this respect, we also adopt a systems perspective for building coherent instruction in STEM education (Cobb, et al., 2018; Roschelle, Knudsen, & Hegedus 2010; Rowland & Adams, 1999). Focus on student learning goals and an explicit vision of high-quality instruction mapped to development of instructional improvement plans lie at the heart of our curricular activity system. It is curricular because we take seriously the learning progression that addresses important concepts and constructs in STEM.

Productive disciplinary engagement occurs during design activities that both teachers and students can enact and participate in. We can consider our approach to curriculum and instruction as a system itself because our design aims to engineer an aligned set of related components that coherently support the desired curricular activities. As a result, we propose that our curricular activity system rely on a “backward mapping” or "backward design" framework that focuses both curriculum and instruction on deepening student understanding and effectively using content knowledge and skills (Wiggins & McTighe, 2005). This is necessarily a reflective process for instructors. Curriculum is planned backward from long-term, desired results through a cyclic design process of identifying desired results, analyzing assessment evidence, and designing learning experiences and instruction (see Figure 2).

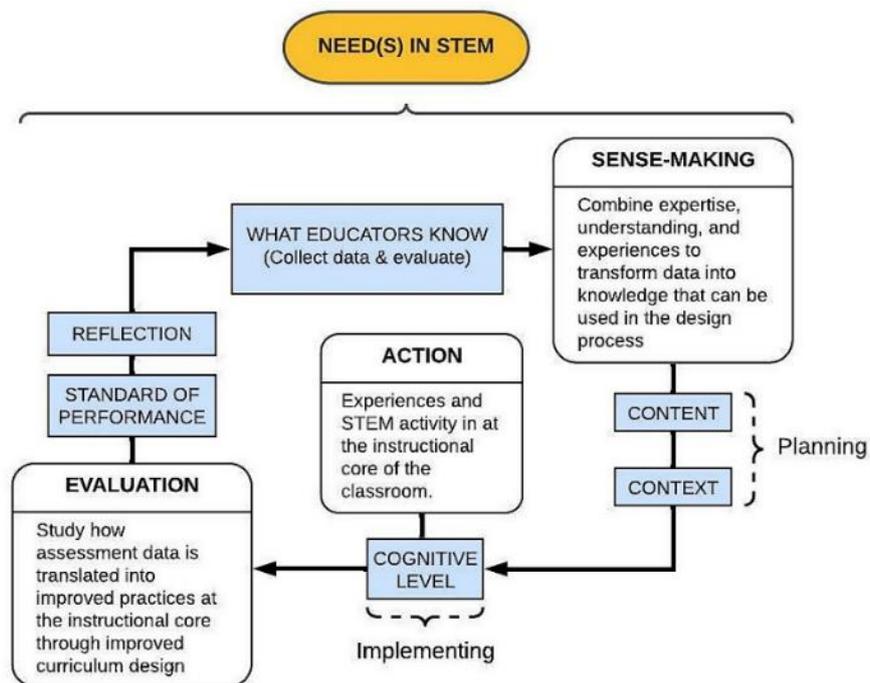


Figure 2. A Reflective Instructional Design Framework

Backward curriculum design helps avoid the common problems of treating the textbook as the curriculum, rather than as a resource, and implementing activity-oriented teaching in which no clear priorities or purposes are apparent. Furthermore, in backward design, teachers are coaches of understanding, not mere purveyors of content knowledge, skill, or activity. They check for successful meaning-making and application by the learner. Backward design reflects a continual improvement approach to student achievement and teacher practice. The framework components in Figure 3 are identified along with their respective reflective questions in Table 1.

Table 1. Reflective Instructional Design Framework Components and Questions

<i>Component</i>	<i>Questions</i>
Content	What conceptual and procedural knowledge do my students need?
Context	What skills do my students need to approach solutions to problems?
Cognitive Level	What observable behaviors should my students exhibit to demonstrate learning?
Standard of Performance	How will I bridge conceptual and procedural knowledge?
	What are the learning activities that make that bridge?
	How should my students demonstrate their mastery of knowledge?
Reflection	What did I learn in this cycle? Which students did I reach? What do I need to change?

By having design activity as the CC, the instructor is no longer primarily responsible for providing information. Instead, the teacher becomes a teacher of higher thinking and a facilitator of information sourcing and knowledge construction. This, we believe, will encourage activities which highlight problem analysis and evaluation, relationship building and management, negotiating real-world constraints, creation of solutions, knowledge and concept construction & reconstruction, planning, and anticipating roadblocks and failure modes. We provide below an example of our framework in action focusing on the development of a core form of reasoning necessary for future engineers, namely, systems thinking (ST) and discuss the implications for both engineering and instruction in STEM education (see Figure 3).

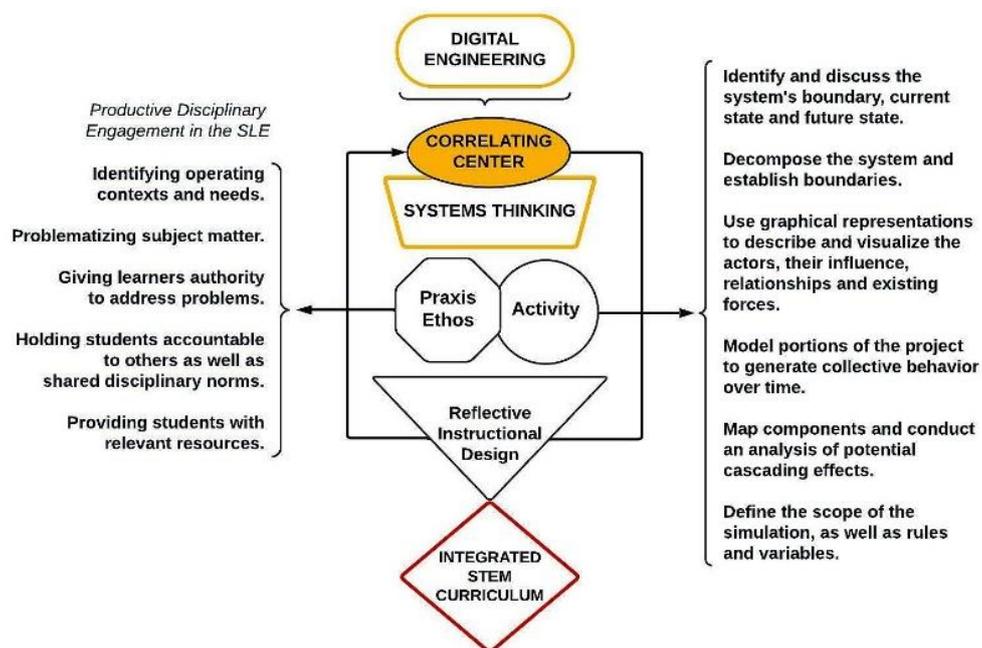


Figure 3. The EPE Framework in Action

We argue that within an SLE, a *system* is essential to discuss within any STEM activity. It defines the differential contributions of the parts and makes the necessary coordination of actions possible. Without a discussion of system, one could never move from purpose to elaboration to argument. Furthermore, structure is an essential element of any tool. An adequate account of structure and of human development of understanding systems would provide many of the essential elements of the teacher’s criteria for identifying critical content that must be learned.

## **A Current Need of Engineering**

The future of systems engineering (SE) currently faces a digital transformation, transitioning from a document-centric process to a holistic model-based (or model-centric) approach where system designers, developers, managers, contractors, and other stakeholders are involved throughout the lifecycle of a system. As a result, decision makers will have access to more and higher-quality information and options from which to draw conclusions, as they will have access to an authoritative source of truth, a key goal for model-based systems engineering (MBSE). Integrated analytics models will increase the amount of information available to decision makers and will help them make sense of it. Table 2 shows Lockheed Martin’s understanding of this critical transition (Hart, 2015).

Table 2. Lockheed Martin’s Transition from a Document-centric to a Model-centric Process

<i>Topic</i>	<i>Document-centric</i>	<i>Model-centric</i>
Information	<ul style="list-style-type: none"> <li>● Predominantly text</li> <li>● Ad-hoc diagrams</li> <li>● Repeated in multiple documents</li> </ul>	<ul style="list-style-type: none"> <li>● Both textual AND visual</li> <li>● Constructs defined once and reused</li> <li>● Shared across all domains</li> <li>● Consistent negotiation in diagrams</li> <li>● Well-defined relationships</li> </ul>
Information Views	<ul style="list-style-type: none"> <li>● Documents</li> </ul>	<ul style="list-style-type: none"> <li>● Provides multiple viewpoints</li> <li>● Filtered by domain, problem space</li> </ul>
Measuring Impact of Change	<ul style="list-style-type: none"> <li>● Spanning multiple documents</li> <li>● Requirements isolated from system</li> </ul>	<ul style="list-style-type: none"> <li>● Relationships define traceability paths</li> <li>● Is a natural part of the modeling process</li> <li>● Programmatically automated</li> </ul>
Measuring Integrity	<ul style="list-style-type: none"> <li>● Manual inspection</li> </ul>	<ul style="list-style-type: none"> <li>● Programmatically automated</li> <li>● Animations</li> </ul>

Rapidly developing technology will explore, visualize, and understand a complex trade-space, rooted in MBSE, and will provide early insight into the impact of decisions ranging from technical solutions to complex public policies. As a result, digital engineering (DE) demands a different breed of engineer that has a broader range of engineering skills and the ability to undertake analysis on a systems-wide basis by understanding a system’s performance and behavior (Stupples, 2006). The 21<sup>st</sup> century engineer needs to integrate systems-thinking (ST)

fully and seamlessly into their work (Litzinger, 2016). More than ever before, engineers need to have a level of engineering science knowledge that includes technical planning, system integration, verification and validation of models, cost and risk (economics), supportability and efficiency analyses for total systems, cognitive and behavioral psychology, and social theory (Stupples, 2006). The transformation to DE reveals two critical challenges (Bone, Blackburn, Rhodes, et al., 2019) that we will examine in our study and are reflected within proposed learning taxonomies for ST (Froyd, Pchenitchnaia, Fowler, & Simpson, 2007; Stave & Hopper, 2007; Zhang & Vanasupa, 2011) as well as the *Framework for K-12 Science Education* (National Research Council, 2012):

- (1) *Models and modeling.* Modeling methodologies must embed demonstrated best practices and provide computational technologies for real-time learning within DE environments. Model integrity is a key focus for model development in order to trust the model's predictions through understanding and quantifying margins of uncertainty. Engineers must understand the possibilities, constraints, and rulesets for compositions of models in order to achieve cross-discipline integration of models.
- (2) *Data analytics.* The current state of big data and data analysis is expanding. Recent research (Bone et al., 2019) focuses on the critical question of how visual analytics can be used in systems decisions involving complexity and large volumes of data. This has implications for Artificial Intelligence, machine learning, and constructing high performance computers. Systems engineers must gain deeper understanding of data, which can lead to improved decision-making and approaches to visualizing complex datasets.

The current workforce must understand what is needed to educate model developers, users and decision makers to work in a DE environment. It must be transformed into a culture that adopts and supports DE across the life cycle.

Transforming the workforce culture for DE begins with understanding the current state as well as identifying enablers and barriers to successful transformation. Research conducted by Bone and her colleagues (2019) concluded that current technology can support the development of state-of-the-art MBSE and enable the Department of Defense's (DoD) transformation to a DE ecosystem across the full SE life cycle. As a result of this research, the DoD is beginning to realize the immense benefits of this framework for transition (p. 340): 1) improved acquisition; 2) Improved efficiency and effectiveness; 3) Improved communication (better trade-space exploration and reduced risk); and 4) Improved designs and resulting systems and solutions. Currently, MBSE is a widely adopted approach for critical research and development centers. For example, the NASA Jet Propulsion Laboratory's mission to drive robotic space exploration relies heavily on MBSE for a number of critical reasons: 1) to manage multiple architectural alternatives; 2) to determine model reliably; 3) to ensure correctness and consistency of multiple, disconnected engineering reports; and 4) to manage design changes before a full design exists.

## **Systems Thinking**

We may define a system as a functionally related assemblage of interacting, interrelated, or interdependent elements forming a complex whole (INCOSE, 2015). Specifically, an engineering system can be defined as "an interconnected set of technical elements characterized by a high degree of complexity, elaborate processes, and

social intricacy aimed at fulfilling an important function in society” (Litzinger, 2016, p. 37). However, defining ST in SE has been a formidable task for members of the SE community. Arnold and Wade (2015) present a definition of ST for use in a wide variety of disciplines, with particular emphasis on the development of ST educational efforts. Of particular importance, the authors emphasize that “systems thinking is, literally, a system of thinking about systems” (p. 670). Based on their review of existing definitions and descriptions of ST, they posit the following definition: “Systems thinking is a set of synergistic analytic skills used to improve the capability of identifying and understanding systems, predicting their behaviors, and devising modifications to them in order to produce desired effects (p. 675).” According to Oliveira and Crepaldi (2017) epistemology of ST emerged strongly in science beginning in the 1920s and may now be considered a new paradigm of science (or, at the very least, a post-modern view of science) (Vasconcellos, 2020). This new paradigm focuses on complexity, instability, and intersubjectivity, thereby overcoming the assumptions of traditional science. As research in epistemology of ST has evolved (e.g., Couso & Simarro, 2020; Erduran, 2020; Peschl, 2006; Verhoeff, et al., 2018), so too has research in the field of holistic engineering education (Grasso & Burkins, 2010).

While ST approaches were originally employed in professional fields such as business, biology, physics, and engineering, more recently these approaches have been applied in educational contexts (Koral-Kordova, Frank, & Miller, 2018; Yoon, 2008). There is some practical research available in the literature that describes how one can learn and apply ST in STEM education, namely, science education (Gilissen, Knippels, & Joolingen, 2020; Verhoeff, et al., 2018; Yoon, 2008; York, et al., 2019) and engineering education (Koral-Kordova & Frank, 2012; Koral-Kordova, et al., 2018; Lavi & Dori, 2019). Because of the emergence of ST education and the complexity of defining learning objectives for ST, Froyd and his colleagues (2007) developed a framework in order to make an attempt at addressing this challenge. Based on this framework and prior work (Stave & Hopper, 2007; Zhang & Vanasupa, 2011), Litzinger (2016, pp. 45-46) proposed a detailed set of cognitive learning objectives that are categorized by five competencies and mapped to systems and system modeling statements within the *Framework for K-12 Science Education* (NRC, 2012). Table 3 shows this alignment.

Table 3. Cognitive Learning Objectives related to ST

<i>Competency</i>	<i>Relational Framework Statements</i>	<i>Possible Learning Objectives</i>
Apply basic terminology and concepts	Define relevant terms/concepts including system, component, boundary, resources, flow, feedback, and properties.	<ul style="list-style-type: none"> <li>● Define and apply key terms and concepts.</li> </ul>
Define the system	Specify the boundary of the system.	<ul style="list-style-type: none"> <li>● Define and justify a system boundary in both verbal and graphical representations.</li> </ul>
Identify and characterize interactions	Identify interactions and recognize that they involve transfers of energy, matter, and information among system parts.	<ul style="list-style-type: none"> <li>● Identify processes that involve feedback.</li> <li>● Identify long- and short - term system behavior.</li> <li>● Create verbal, graphical, and mathematical representations of system</li> </ul>

<i>Competency</i>	<i>Relational Framework Statements</i>	<i>Possible Learning Objectives</i>
		interactions.
Create models of the system	Create models of systems at different levels from lists and simple sketches to detailed simulations and prototypes.	<ul style="list-style-type: none"> <li>• Create graphical system representations</li> <li>• Create and solve a math model of a system</li> </ul>
Solution processes	Define metrics and alternatives and select one that meets the specifications.	<ul style="list-style-type: none"> <li>• Develop a goal statement for the problem.</li> <li>• Define the appropriate systems.</li> <li>• Generate and evaluate approaches.</li> <li>• Repeat solution process to refine, as needed.</li> </ul>

Whatever methods are chosen to teach ST, a fundamental skill to be developed is the ability to comprehend the scope and scale of a complex technological system intertwined with natural and socio-political systems (Litzinger, 2016). In addition, Davidz & Nightingale (2008) identified creative thinking and strong communication skills as central to ST, since complex systems problems are addressed by teams. An emphasis on models is also necessary if complex systems are to become tractable to any form of analysis.

### **MBSE and Systems Thinking**

Systems Engineering (SE) is a mature and widely used discipline in engineering to address complex technical challenges. In addition, SE shares many principles and tenets of design and systems thinking. Since SE may be considered a highly structured design process, developing ST can be seen as a design problem (Borge, 2016). Litzinger (2016) states that “In many ways, Systems Engineering is an example of a highly structured design process” (p. 40). SE has both a ‘systematic’ and ‘systemic’ nature (Chestnut 1967). The systematic nature of systems engineering focuses on both management processes and MBSE methods. The National Defense Industrial Association (NDIA) defines MBSE as “an approach to engineering that uses models as an integral part of the technical baseline that includes the requirements, analysis, design, implementation, and verification of a capability, system, and/or product throughout the acquisition life cycle” (NDIA, 2011, p. 9) Models are graphical, mathematical, or physical representations of a concept, phenomenon, relationship, structure or system. The objectives of a model include 1) to facilitate understanding; 2) to aid in decision making (examining 'what if' scenarios); and 3) to explain, control, and predict events. The key to a successful model-based approach is scoping the problem: 1) What do you want to get out of your models? 2) What fidelity do you need to accomplish those goals? and 3) What are the success criteria for the effort?

Scoping and managing a modeling effort is both an art and a science. A fundamental challenge for system engineers is to capture a problem with an effective model and then facilitate transferring the information of that problem to practical systems engineering tools and methods. The early problem definition phase, stakeholder analysis, requires an application of ST (Cloutier, Sauser, Bone, & Taylor, 2015). Systems engineers then use ST

principles when exploring and designing system behavior architecture and using MBSE tools and languages. Strategies, such as those suggested by Boardman and Sauser (2008) in *Systems Thinking: Coping with 21st Century Problems*, include conceptagon, systemigrams, system dynamics, and agent-based modeling (see Table 4).

Table 4. Strategies, Objectives, and Relationships to ST in MBSE

<i>Strategy</i>	<i>Objective</i>	<i>Description</i>	<i>Systems Thinking</i>
CATWOE	To define the root cause for system of interest.	Identifies end customers; actors in the system; transformation or system purpose; world or customer perspectives; an authorities to change the system.	A high-level of abstraction for the system of interest – defining the context and boundaries while describing objectives, roles, and relationships.
Conceptagon	To provide a holistic view that facilitates communication and collaboration.	Provides an abstract definition of the system’s structure, boundaries, conforming entities, processes, and emergence.	A high-level systemic description that aims to promote a coordinated and effective collaboration among individuals.
Systemigrams	To support system description and design through iterative conversations with stakeholders.	Representations that define functions and relationships among entities. Iteration facilitates updates to the system model as stakeholders analyze relationships.	A language description of the system of interest through models that describe system status, end goal, actors, and functionality.
System Dynamics	To identify causal relationships on the system and their impact on the system behavior.	Reinforces and balances feedback loops that help understand the relationship among system variables, their evolution, and their impact.	Feedback loops support the characterization of relationships among entities to understand system behavior and identify leverage points.
Complex Systems	To recognize the characteristics of complex systems.	Geographically distributed systems that when integrated lead to emergent behavior.	Description of system entities, their structure and relationship, and the resulting behavior.
Agent-Based Modeling	To represent the system via hypothesized scenarios to capture emergent behavior.	The system is modelled through a collection of autonomous decision-making entities. Policies are explored via what-if scenarios.	Hypotheses in terms of variables, relationships, influence, and parameters facilitate the exploration and identification of leverage points.

Shifting to MBSE using digital models (i.e., DE) enables engineering teams to readily understand design change impacts, communicate design intent, and analyze a system design before it is constructed. *Data-centric specifications* enable automation and optimization, allowing SEs to focus on value added tasks and ensure a balanced approach is taken.

Unprecedented levels of ST can be achieved through integrated analytics, tied to a model-centric technical baseline. Typical systems engineering problem definitions have many degrees of freedom in the initial state. The requirements given at the start are never complete or clear nor are they sufficient to define achievable and measurable goals, so a progressive definition of new requirements is necessary (Shafaat & Kenley, 2015, citing D tienne, 2006). SEs develop heuristics to tackle complex problems systematically and holistically over time as they learn more about the problem, and this often requires collaboration among participants with multiple competencies. ST critically aids an engineer in understanding the cultures of stakeholders, the importance of collaboration, the current system state AND future system state and system dynamics (i.e., how the impact on one component influences the overall performance). Once an engineer understands the system (i.e. applies ST), then SE provides the structured methodology to conduct the transition to DE because of the development of both holistic and systematic perspectives.

### **Systems Thinking as the Correlating Center**

For the practicing engineer, the “problem/need” and “the design/activity” act as the correlating center (CC). The CC dictates and informs what knowledge will be needed and in what sequence when approaching the problem. Specifically, the CC dictates what knowledge and skills will be needed through the life cycle of the project. This can lead to better scheduling and cost performance. Similarly, engineering design in our model acts as the CC and pre-empts issues of timing and sequence within STEM curricula. We would no longer need to attempt “fitting” topics and classes from science, technology, engineering, and mathematics into a traditional curriculum. The CC would now assist in determining what knowledge to acquire or reconstruct, what topics are taught and in what sequence. By having design activity as the CC, the SLE will include activities which highlight problem analysis and evaluation, negotiating real-world constraints, creation of solutions, knowledge and concept construction & reconstruction, planning, and anticipating roadblocks and failure modes.

### **Designing Experiences for Systems Thinking**

We propose using design principles for constructing the SLE (Koretsky et al., 2014) for students in order to expose students to a holistic perspective when managing complex systems. The curriculum and its dynamic component (a SLE) will build upon a solid conceptual foundation of “system” to ensure that it is defined, conceived, and realized in a utilitarian way. Students should be able to show how it is possible to use systems in order to think more deeply and to act more decisively. This approach is made possible by emphasizing the simultaneity of perspectives, the role of paradox, and the centrality of soft issues in resolving complexity. To capture how the integration of independent components provide emergent behavior over time, the curriculum introduces students to fundamental concepts such as complexity vs complicated systems, chaos theory, non-linear non-equilibrium

systems, multi-agent systems, emergent behaviors, among others. To develop models and perspectives on the system of interest, students rely on cross-collaboration exercises, a paradoxical mindset, and Systems Modeling Language (SysML) and MBSE methodology to develop multiple perspectives and model representations on the system to be studied.

Students will be using computational tools to visualize system thinking concepts such as emergence, complexity, leverage points, networks, and feedback loops, among others. Tools to be utilized during the course include Cameo Systems Modeler, which is a leading platform in MBSE developed by Dassault Systems, Vensim, and Python programming language. The reasoning behind using Cameo relies on exposing students to the leading industry cross-collaboration platform for the development of virtual models. Students will develop SysML diagrams including Requirements, Use Case, Activity, Block Definition, and Internal Block Definition, to capture and represents multiple perspectives of the system. In addition, Vensim, system dynamics tool, will be utilized to illustrate the concept of non-equilibrium systems. Students will be able to apply and visualize the output of stochastic processes during simulations. Lastly, Python programming language with particular focus on agent-based modeling will be used to represent socio-technical systems and the effects of interactions leading to emergent behaviors. Table 5 below shows the activities in which students could engage and the ST concepts they would develop as a result of their immersion in the SLE. It also highlights the importance of these activities for the future of DE.

Table 5. SLE Activities (Purposes, Strategies, and Tools) and Targeted ST Concepts

<i>Activity</i>	<i>Strategy &amp; Tools</i>	<i>Targeted ST concepts for DE</i>
Select a complex system of interest and be able to identify and discuss pertinent stakeholders, their roles and influences, as well as the system’s boundary, current state, and future state.	Soft Systems  Cameo System Modeler: Block Definition Diagrams	<ul style="list-style-type: none"> <li>• <i>Targeted ST concepts:</i> Parts-Wholes &amp; Isolation-Relationships</li> <li>• <i>Digital engineering needs:</i> <ul style="list-style-type: none"> <li>○ Define model structure.</li> <li>○ Define modelers’ roles.</li> <li>○ Think of the big picture.</li> </ul> </li> </ul>
Decompose-the system and establish boundaries which results in defining the system (including constraints). Discuss the relationships between needs, objectives and goals, the scope of the project, its functions, and behaviors.	Conceptagon  Cameo System Modeler: Requirements, Block Diagrams	<ul style="list-style-type: none"> <li>• <i>Targeted ST concepts:</i> Parts-Wholes &amp; Analysis-Synthesis</li> <li>• <i>Digital engineering need:</i> Define the purpose and scope of the model to be developed.</li> </ul>
Design the problem from a multi-stakeholder’s perspective. Through graphical representation, describe and visualize the actors, their influence, relationships, and existing forces.	Systemigrams  Cameo System Modeler: Requirements, Block Diagrams	<ul style="list-style-type: none"> <li>• <i>Targeted ST concepts:</i> System Mapping &amp; Disconnection-Interconnectedness</li> <li>• <i>Digital engineering need:</i> Identify logical and physical structures in model-based concepts.</li> </ul>

<i>Activity</i>	<i>Strategy &amp; Tools</i>	<i>Targeted ST concepts for DE</i>
Model portions of the project to generate collective behavior over time. Assign influence to particular feedback loops. Illustrate the impact of one solution on the overall system.	System Dynamics Vensim	<ul style="list-style-type: none"> <li>• <i>Targeted ST concepts:</i> Feedback Loops &amp; Silos-Emergence</li> <li>• <i>Digital engineering need:</i> Define parametric models and develop trade off studies</li> </ul>
Map components and conduct an analysis of potential cascading effects. Provide a visual and analytic representation of connectedness among components, subsystems, and systems. Describe network concepts (nodes, ties, hubs) and network structures.	Complex Networked Systems Cameo System Modeler: Requirements, Block Diagrams, Internal Block Diagrams.	<ul style="list-style-type: none"> <li>• <i>Targeted ST concepts:</i> Feedback Loops: Emergence: Causality; Linear -Circular</li> <li>• <i>Digital engineering needs:</i> <ul style="list-style-type: none"> <li>○ Model interconnection and variable dependency among components.</li> <li>○ Elicit and map stakeholders' and system requirements that address problems.</li> </ul> </li> </ul>
Define the scope of the simulation, as well as rules and variables. Visualize how patterns emerge from a set of rules among agents.	Agent Based Modeling  Python	<ul style="list-style-type: none"> <li>• <i>Targeted ST concepts:</i> <ul style="list-style-type: none"> <li>○ Feedback Loops, Emergence &amp; Causality</li> <li>○ Disconnection - Interconnectedness &amp; Silos</li> </ul> </li> <li>• <i>Digital engineering needs:</i> <ul style="list-style-type: none"> <li>○ Integrate models to derive emergent behavior that cannot be seen through independent diagrams.</li> <li>○ Understand agent-based simulations that assist strategic-decision making.</li> </ul> </li> </ul>

## Concluding Remarks

Given the rapid advancement of research in STEM, within STEM education, there appears to be reconsideration of how knowledge is constructed and applied. Some of the most striking advancements in STEM are made through the combined use of knowledge spanning across traditionally different professional fields. Long-standing traditional subject domains are being enriched and expanded through the integration of knowledge from other formerly stand-alone subjects to form new combinations of intellectually integrated knowledge that feeds investigation, discovery and understanding. Biology, for example, is crossed with physics and engineering. Solar heating research is melded with building material research and new construction technology. More so than ever before, there is a greater understanding that new forms of cognitive knowledge are highly productive and perhaps the key to addressing what are some of the most crucial problems facing humankind. However, a yet unrealized goal of STEM education is how to conceive of, organize, and teach integrated STEM content in schools in order

to prepare students for evolving STEM professions.

To more fully realize the major goal of STEM education means to move away from the conventional separate STEM subjects curriculum. To make this shift, however, is a daunting challenge. It will demand new ways to think about schooling, its purpose, and the organization and presentation of instruction. However, like engineering systems, educational systems are shaped by and shapes a variety of technical, environmental, social, societal, and political processes (Lemke & Sabelli, 2008). McNeil (1990) suggested that for integrated curricula to be most effective, there has to be a clear relationship between what students learn in one subject with what students learn in the other associated subjects possibly in a different place and time. This requires an ongoing, close working relationship among teachers based on reflective instructional design.

As a result, we propose EPE because it is an innovative approach to STEM education that has few precedents in educational systems. We are hopeful it can spur more extensive longitudinal research. Research and development in the SLE should utilize design-based perspectives and methods to address and study problems of development and implementation in the educational system. Like engineering design, design-based implementation research is iterative and longitudinal because it affords researchers the opportunity to uncover and make visible the workings of innovation so that, over time, it can be improved. Within education, such research seeks curriculum coherence and associated best pedagogical practices that helps build a coherent instructional system that can benefit students and teachers.

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