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Tinkering Towards Systems Thinking: Integrating Hands-On Design Activities in First-Year Engineering Education

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Abstract

The complexity of modern engineering challenges necessitates early exposure to systems engineering (SE) and systems thinking (ST) in undergraduate curricula. However, traditional engineering education often delays the introduction of SE/ST concepts, leaving students unprepared to manage interconnected systems and competing priorities. This paper explores a tinkering-based approach to hands-on learning as a method for embedding SE/ST principles in first-year mechanical engineering courses. By engaging students in activities that emphasize exploration, iteration, and reflection, the tinkering framework aligns with Kolb's Experiential Learning Theory, making abstract SE/ST concepts tangible and accessible.

The paper presents the deployment of three hands-on activities designed to foster SE/ST skills: product decomposition, the Titan Submersible case study, and a paper airplane design challenge at 3 university sites. In the product decomposition activity, students disassemble a wind-up toy to identify subsystems, internal and external interfaces, and the role of material and design choices in overall functionality. The Titan Submersible case study uses role-playing to simulate stakeholder dynamics, encouraging students to evaluate competing priorities and make decisions based on ethical, financial, and technical considerations. The paper airplane design challenge engages students in iterative prototyping to optimize performance, emphasizing trade-offs in system design and resource constraints.

Analysis of student feedback and reflections from 1 course section reveal that these activities enhanced engagement, creativity, and understanding of SE/ST concepts. Reflections from the paper airplane challenge, for instance, highlight the value of iterative tinkering, but also suggest improvements, such as introducing greater material diversity and complexity. Across all activities, students developed critical competencies in problem-solving, collaboration, and managing interdisciplinary trade-offs, skills essential for modern engineering practice.

This paper advocates for the integration of tinkering-based activities as foundational elements in engineering curricula. By prioritizing hands-on, systems-oriented learning experiences, educators can better prepare students to tackle real-world challenges with confidence and creativity. Future directions include scaling these activities for diverse learning environments and exploring their application in digital and interdisciplinary contexts.

Keywords: Design process, Systems thinking, Experiential learning, First-year engineering

1. Introduction

The rapid advancement of technology and the increasing complexity of engineering systems demand a fundamental shift in how future engineers are educated [1, 2]. Traditional engineering curricula often prioritize component-level design and theoretical problem-solving, leaving the integration of systems engineering (SE) and systems thinking (ST) concepts to upper-level courses. This delay can leave students unprepared to navigate the multifaceted challenges of modern engineering practice, where success depends on managing interconnected systems, addressing competing priorities, and balancing trade-offs across diverse constraints. To bridge this gap, it is essential to introduce SE and ST principles [3, 4] early in the academic journey.

Systems engineering provides a structured approach to designing and managing complex systems throughout their life cycles. It emphasizes stakeholder needs, system integration, and iterative validation, ensuring that designs meet technical, social, and economic objectives. Systems thinking complements this by encouraging a holistic perspective, fostering an understanding of interconnections, and addressing broader contextual implications. Together, these frameworks equip engineers with the tools to tackle challenges ranging from renewable energy optimization to autonomous vehicle design and infrastructure resilience. Despite their importance, SE and ST concepts are often underrepresented in early engineering education, missing an opportunity to build a foundational mindset that prioritizes creativity, adaptability, and complexity management [5, 6, 7].

A promising strategy to address this gap is the adoption of tinkering as a pedagogical approach [8, 9]. Tinkering, rooted in experiential learning theory, emphasizes hands-on exploration, iteration, and reflection. By engaging students in activities that require physical manipulation, iterative prototyping, and open-ended problem-solving, tinkering transforms abstract SE and ST principles into tangible experiences. This approach aligns with Kolb's Experiential Learning Theory [10], which underscores the importance of moving through concrete experiences, reflective observation, abstract conceptualization, and active experimentation. Tinkering allows students to actively engage with the material, fostering curiosity and a deeper understanding of how systems function and interact.

Unlike traditional laboratory exercises that follow predefined steps, tinkering provides the freedom to explore and iterate [11], mimicking the unpredictability and problem-solving demands of real-world engineering practice. This paper examines the implementation of three hands-on tinkering activities designed to introduce SE and ST concepts in first-year mechanical engineering courses. The first activity involves the decomposition of a wind-up toy, where students explore systems, subsystems, and the interfaces between components. The second activity is a case study on the Titan Submersible, a role-playing exercise that immerses students in stakeholder dynamics and highlights the influence of competing priorities on engineering decisions. The third activity is a paper airplane design challenge, where students engage in iterative prototyping, trade-offs, and resource constraints to optimize system performance.

These activities aim to engage students while fostering critical thinking and problem-solving skills, equipping them with a foundational understanding of SE and ST principles. Furthermore, they provide a scalable and adaptable model for integrating systems-oriented learning into introductory courses. This study evaluates the impact of these activities on student engagement, comprehension, and overall preparedness for the complexities of modern engineering practice. By reimagining how SE and ST concepts are introduced, educators can create a more effective and inspiring learning environment that prepares students to address real-world challenges with confidence and creativity.

2. Framework for Hands-On Systems Thinking Activities

The framework for integrating hands-on activities into first-year engineering courses is rooted in experiential learning principles and systems engineering (SE) and systems thinking (ST) methodologies. These approaches prioritize engaging students through iterative, exploratory, and reflective processes that transform abstract concepts into tangible experiences. This section outlines the development and application of a tinkering-based framework for teaching SE/ST, supported by research and best practices highlighted in prior studies.

Tinkering, as a pedagogical strategy, draws on Kolb's Experiential Learning Theory [10], which emphasizes four stages: concrete experience, reflective observation, abstract conceptualization, and active experimentation. Activities designed with this framework foster a holistic understanding of SE/ST concepts, engaging students in both the technical and non-technical aspects of engineering practice. By focusing on active exploration and iteration, students can build critical skills such as problem-solving, stakeholder analysis, and system optimization.

The framework also integrates key elements of making and design-based learning [12], which can improve student engagement and comprehension. Research indicates that tinkering activities provide a vital bridge between theoretical knowledge and practical application, particularly in first-year engineering courses. This connection helps students understand the relevance of SE/ST concepts while sparking excitement for their discipline. For example, early hands-on activities, like product decomposition and design challenges, can enhance creativity and give a deeper understanding of engineering principles.

This framework for hands-on systems thinking activities offers a replicable and impactful approach to teaching SE/ST principles in first-year engineering courses. By integrating tinkering and making into the curriculum, educators can engage students in meaningful, systems-oriented learning experiences. The activities not only foster critical skills but also prepare students to tackle complex engineering challenges with confidence and creativity. Future work will focus on refining these activities based on student feedback and expanding the framework to include interdisciplinary applications and digital tools.

Activity Design and Development

The development of these hands-on activities begins with identifying learning objectives aligned with SE/ST principles. These objectives are then embedded into structured activities that encourage exploration and iteration [13]. Each activity is designed to meet specific criteria: scalability to different classroom sizes, accessibility through low-cost materials, adaptability to diverse settings, and alignment with introductory engineering topics.

The first activity, Product Decomposition, exemplifies the use of tinkering to teach subsystem analysis and component interactions [14, 15]. By disassembling a wind-up toy, students visualize internal interfaces and interactions, gaining insights into the complexity of engineering systems. This activity's iterative nature, exploring, hypothesizing, and documenting observations, allows students to engage with SE/ST concepts actively. Students also create functional block diagrams to synthesize their understanding, connecting the physical breakdown of components to theoretical system design principles.

The second activity, Titan Submersible Case Study, introduces role-playing to highlight the importance of stakeholder perspectives in SE/ST. By assigning roles such as engineers, community members, and business leaders, students engage in debates about the readiness of a deep-sea submersible for operational use. This activity emphasizes how stakeholder priorities influence decision-making, a critical aspect of SE/ST. Reflection on stakeholder dynamics and system trade-offs further reinforces the complexity of real-world engineering challenges.

The third activity, Paper Airplane Design Challenge, immerses students in iterative prototyping, system optimization, and resource management. This open-ended design task encourages students to explore trade-offs in weight, aerodynamics, and stability, simulating the iterative nature of engineering design. Feedback from this activity underscores its effectiveness in engaging students, though it also highlights areas for refinement, such as incorporating greater material diversity and increased complexity.

Activities were implemented at three university sites, with approximately 300 students in total. Instructor feedback played a key role in refining the activities. Student reflections were collected from one section of 60 first-year mechanical engineering students at a single site in Fall 2024.

Iteration, Reflection, and Scalability

Critical to the success of this framework is its emphasis on iteration and reflection. These elements ensure that students move beyond passive learning to actively engage with the material. For example, in the paper airplane activity, students reflect on their design iterations to identify improvements, while in the Titan Submersible case study, they revise their stakeholder arguments based on peer feedback and initial outcomes. This process mirrors engineering practices, where iterative testing and stakeholder engagement are vital to project success.

The scalability of these activities is another crucial feature of the framework. Designed to be adaptable to various classroom sizes and setups, the activities use low-cost materials, making them accessible to institutions with varying resources. For example, the wind-up toy activity costs less than $1 per student while offering rich opportunities for systems-level exploration.

3. Activity Summaries

The three hands-on activities, product decomposition, the Titan Submersible case study, and the paper airplane design challenge, are designed to engage first-year mechanical engineering students in systems engineering (SE) and systems thinking (ST) concepts. These activities integrate technical and non-technical aspects of engineering to create a rich learning experience, fostering critical skills such as problem-solving, collaboration, and stakeholder analysis. By connecting each activity to specific SE/ST learning goals, students gain a foundational understanding of how to analyze, design, and optimize complex systems.

Product Decomposition (Wind-Up Toy Dissection)

The product decomposition activity introduces students to the concepts of systems, subsystems, and interfaces by tasking them with disassembling a small wind-up toy. An example is shown in Figure 1. This activity enables students to visualize the internal workings of a system and explore the functional interactions between components. Students examine how subsystems are designed to work together intentionally, as well as how incidental interactions might emerge during operation. By creating functional block diagrams, students map these interactions and connect their observations to SE principles, such as managing complexity and defining system boundaries. This activity emphasizes the importance of understanding how components contribute to overall system performance, aligning with ST goals of holistic analysis.

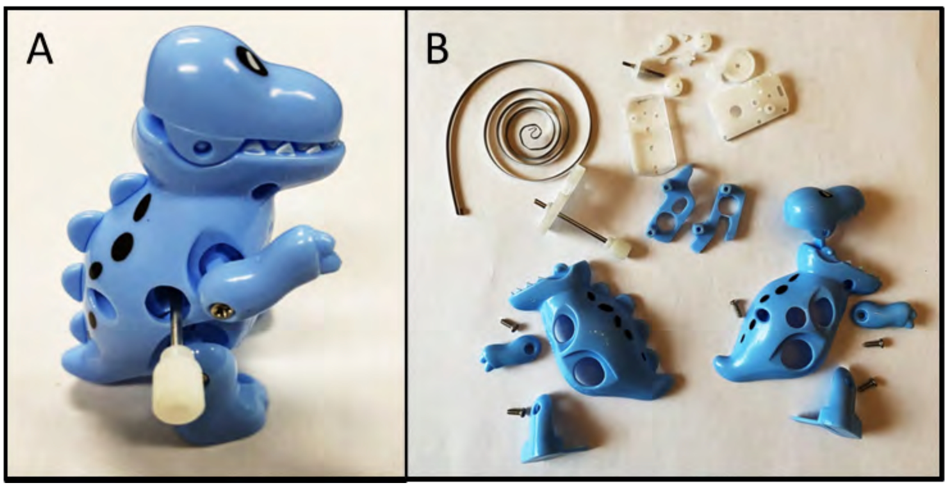

Figure 1. Wind-up toy disassembly example

<u>Setup:</u> Each student receives a wind-up toy and two small screwdrivers (Phillips and flathead). The instructor also prepares guiding discussion prompts and access to a digital submission platform for post-activity reflection.

<u>Classroom Implementation:</u> The activity begins with a short introduction and exploration, followed by an instructor-led disassembly in which students analyze external and internal subsystems. Students are encouraged to identify intentional and incidental interactions, interfaces, and the flow of inputs/outputs throughout the product. The session concludes with reassembly and synthesis of subsystem relationships.

<u>Learning Outcomes:</u>
- Identify systems, subsystems, and interfaces
- Analyze internal and external interactions
- Understand system boundaries and environmental context
- Practice abstraction by mapping components to functions

Assessment: Students submit a functional block diagram of the system and brief reflections on product complexity, surprises during disassembly, and potential for design scaling. Reflection prompts and optional quiz further support evaluation.

Titan Submersible Case Study (Stakeholder Role-Play)

The Titan Submersible case study focuses on the critical role of stakeholders in engineering decision-making. Through role-playing, students assume the perspectives of various stakeholders, such as engineers, community members, and business leaders, and debate the readiness of a deep-sea submersible for operational use. Example slides are shown in Figure 2. This activity encourages students to consider diverse priorities, such as safety, financial implications, and environmental impacts, while making engineering decisions. By navigating these competing concerns, students practice integrating technical and non-technical factors into their analyses, a cornerstone of SE. The iterative argumentation process reinforces ST principles by requiring students to evaluate system trade-offs, identify potential points of failure, and propose compromises that account for stakeholder needs.

Figure 2. Submersible case study role-playing

Setup: Students are assigned stakeholder roles (engineer, business leader, community member) prior to class or at the session's start. Materials include character cards and slides.

Classroom Implementation: After a brief overview of submersible tourism and OceanGate's Titan Submersible, students form stakeholder groups to prepare arguments. In two debate rounds, each group presents its stance to a panel of "Board Members," who vote after each round. Between rounds, students refine their positions based on peer feedback. A final debrief encourages cross-stakeholder reflection.

Learning Outcomes:
- Recognize the diversity and impact of stakeholders
- Integrate technical, ethical, and social considerations
- Understand trade-offs and decision complexity in real-world systems

Assessment: Students respond to reflection questions regarding stakeholder influence, potential alternative outcomes, and the importance of identifying stakeholder needs. Instructors may assess individual or group insights for depth of understanding.

Paper Airplane Design Challenge (Iterative Systems Optimization)

The paper airplane design challenge immerses students in a practical design task that involves iterative prototyping, optimization, and resource management. Students are challenged to design paper airplanes that achieve specific performance criteria, such as flight distance, stability, or payload capacity. This activity highlights trade-offs in system design, such as balancing weight and aerodynamics, which are fundamental concepts in both SE and ST. Students also grapple with real-world constraints, such as limited materials and time, mirroring the challenges engineers face in professional practice. By reflecting on their design iterations, students develop a deeper understanding of how to evaluate system performance and make data-driven improvements. This activity aligns with ST learning goals by encouraging students to think critically about system interdependencies and the broader context of their design decisions. Figure 3 shows students engaged in the activity.

Figure 3. Paper airplane design challenge

Setup: Each student team receives a fictional budget and a materials "store" with items such as paper, tape, and pipe cleaners. Teams documented a bill of materials form.

Classroom Implementation: Instructors introduce SE/ST concepts and facilitate material selection. Teams then design and iteratively test their planes, optimizing for chosen performance criteria (distance, payload, stability). A group debrief and evaluation follow. Modifications such as theme-based constraints or public flight tests can add engagement and complexity.

Learning Outcomes:
- Experience trade-offs and design constraints
- Apply systems thinking to design iteration
- Practice collaborative prototyping under real-world constraints

Assessment: Students submit reflections on design choices, iteration process, constraint impacts, and definitions of success. Instructors assess for understanding of systems-level decisions and creative problem-solving.

Each activity is carefully designed to provide a progressive learning experience that builds on SE/ST principles. The product decomposition activity introduces students to the foundational concepts of systems and subsystems, laying the groundwork for more complex analyses in the Titan Submersible case study. The role-playing in the case study builds on this foundation by integrating stakeholder perspectives, preparing students to address the multifaceted challenges of engineering practice. Finally, the paper airplane challenge consolidates these skills in a dynamic, hands-on design task that emphasizes iterative problem-solving and optimization. Together, these activities provide a cohesive framework for introducing SE/ST concepts in a manner that is engaging, accessible, and directly relevant to students' future careers as engineers.

4. Student Impressions and Reflections

Student reflections and feedback provide critical insights into the effectiveness of hands-on activities in fostering systems engineering (SE) and systems thinking (ST) skills. Across the three activities, product decomposition, the Titan Submersible case study, and the paper airplane design challenge, students consistently highlighted the engaging and practical nature of the tasks, as well as their value in bridging theoretical concepts with real-world applications.

In the product decomposition activity, students expressed enthusiasm for the opportunity to interact directly with physical systems, describing the task as a "fun and eye-opening way" to understand subsystems and their interactions. Many students noted that the process of disassembling the wind-up toy allowed them to visualize how components worked together to achieve the toy's functionality. One common reflection was that the activity helped clarify the often-abstract concept of system boundaries by showing where one subsystem ended, and another began. Students also appreciated the hands-on nature of the activity, which many felt was a refreshing departure from traditional lecture-based learning. However, some suggested that providing a wider variety of products to disassemble could further enhance the learning experience by exposing them to a broader range of subsystem configurations and interfaces.

The Titan Submersible case study elicited strong reactions from students, who found the role-playing exercise both challenging and rewarding. Many students reported that adopting the perspective of a specific stakeholder, such as an engineer, business leader, or community member, helped them understand the complexities of engineering decision-making. The debates and discussions underscored the importance of considering diverse viewpoints and balancing competing priorities. Students noted that the activity improved their ability to think critically about trade-offs and the broader implications of engineering solutions. Several reflections highlighted the value of the iterative argumentation process, as students revised their positions based on peer feedback and additional information. However, some students expressed difficulty fully embodying their assigned roles, suggesting that more detailed background materials or character descriptions could enhance their ability to engage with the activity.

The paper airplane design challenge was well-received for its creativity and interactive format. Students appreciated the opportunity to experiment with design variations and test their prototypes in real time. Many reflected on the value of iterative problem-solving, noting that the process of building, testing, and refining their airplanes mirrored the iterative nature of professional engineering practice. The activity also prompted discussions about resource management, as students worked within constraints of materials and time to optimize their designs. Feedback from students indicated a high level of engagement and enjoyment, with several describing the challenge as a "highlight" of the course. However, some suggested incorporating a greater variety of materials or introducing additional constraints to make the activity more complex and realistic.

Overall, student feedback across all three activities highlighted the effectiveness of hands-on tinkering in fostering engagement and understanding of SE/ST concepts. Students appreciated the tangible nature of the activities, which helped demystify complex ideas and provided a context for applying theoretical knowledge. The iterative and reflective elements of the activities were particularly impactful, as they encouraged students to think critically and adapt their approaches based on observations and feedback. Suggestions for improvement, such as diversifying materials or providing more detailed guidance, offer valuable insights for refining these activities in future iterations.

Through these reflections, it becomes clear that the integration of hands-on, systems-oriented activities not only enhances learning outcomes but also inspires a deeper interest in engineering. By connecting students to the challenges and complexities of real-world engineering practice, these activities lay a strong foundation for their continued development as systems thinkers and problem-solvers. Future work will continue to incorporate student feedback to ensure that these activities remain engaging, effective, and relevant to the evolving demands of engineering education.

5. Findings

The implementation of hands-on tinkering activities in first-year engineering courses offers significant benefits for fostering systems engineering (SE) and systems thinking (ST) skills. These activities address several key challenges in traditional engineering education, such as the delayed introduction of SE/ST concepts and the disconnection between theoretical knowledge and practical application. By emphasizing active learning, iterative design, and reflection, the approach described in this paper demonstrates a scalable and impactful framework for integrating SE/ST principles into the foundational curriculum.

One of the primary advantages of this approach is its ability to engage students in meaningful, real-world problem-solving. The activities, such as the product decomposition task and the paper airplane design challenge, provide concrete experiences that make abstract SE/ST concepts more accessible. Students consistently reported that these activities helped them visualize subsystem interactions, understand system boundaries, and explore trade-offs in system design. For example, the iterative prototyping involved in the paper airplane challenge closely mirrors the processes engineers use in professional practice, reinforcing the value of experiential learning.

The Titan Submersible case study highlights another critical dimension of SE/ST: the integration of technical and non-technical considerations. Through role-playing, students gained insights into how stakeholder priorities influence engineering decisions and learned to navigate the complexities of balancing competing interests. This activity underscored the importance of stakeholder engagement, a core aspect of SE, while also demonstrating the applicability of ST to ethical, financial, and social dimensions of engineering. Such activities bridge the gap between technical skills and the broader context of engineering practice, preparing students to approach complex challenges holistically.

However, the implementation of these activities is not without challenges. Some students struggled with the open-ended nature of the tasks, particularly in the Titan Submersible case study, where embodying stakeholder perspectives required a nuanced understanding of their roles. Feedback from students suggested that providing more detailed background materials or structured guidance could enhance their ability to engage with such activities. Additionally, while the activities are designed to be scalable and cost-effective, their success depends on careful facilitation and clear alignment with learning objectives. Instructors need to be prepared to guide discussions, provide feedback, and connect the activities to broader SE/ST principles.

Another key discussion point is the scalability and adaptability of the framework. The hands-on activities described in this paper were designed with accessibility in mind, using low-cost materials and modular formats that can be implemented in diverse educational settings. For example, the product decomposition activity utilizes wind-up toys costing less than $1 each, making it feasible for large classes or institutions with limited resources. Similarly, the iterative nature of the paper airplane design challenge allows for easy modification to suit different learning environments or time constraints. This flexibility ensures that the activities can be adopted and adapted by a wide range of educators, increasing their potential impact.

The iterative and reflective elements of these activities are also worth emphasizing. Encouraging students to iterate on their designs and reflect on their learning not only deepens their understanding of SE/ST concepts but also fosters critical thinking and adaptability. Reflection prompts used in the activities, such as analyzing system trade-offs or considering alternative stakeholder outcomes, help students connect their experiences to broader engineering principles. These reflective practices align closely with Kolb's Experiential Learning Theory, further reinforcing the value of hands-on tinkering as an educational approach.

6. Conclusions

The integration of hands-on tinkering activities into first-year engineering courses presents a transformative approach to teaching systems engineering (SE) and systems thinking (ST) principles. These activities address critical gaps in traditional engineering education, where SE/ST concepts are often introduced too late or remain disconnected from practical applications. By embedding SE/ST early in the curriculum through engaging, iterative, and reflective learning experiences, educators can better prepare students for the complexities of engineering practice.

The three activities detailed in this study, product decomposition, the Titan Submersible case study, and the paper airplane design challenge, demonstrate the potential of this approach to engage students, foster curiosity, and develop critical skills. The product decomposition activity allows students to explore subsystems, interfaces, and the intricacies of component interactions, making abstract SE concepts tangible and relatable. The Titan Submersible case study emphasizes the importance of stakeholder engagement and interdisciplinary decision-making, providing students with an appreciation for broader implications of engineering solutions. The paper airplane design challenge highlights the iterative nature of design, emphasizing trade-offs, optimization, and the management of real-world constraints. Student feedback and reflections consistently underscore the value of these activities in deepening their understanding of SE/ST concepts. Students appreciated the opportunity to apply theoretical knowledge to hands-on tasks and recognized the relevance of these activities to real-world engineering challenges. The iterative and reflective elements of the activities were impactful, helping students develop critical thinking and adaptability, essential for systems-oriented problem-solving.

The scalability and accessibility of these activities further enhance their value as a pedagogical tool. Designed with cost-effectiveness and modularity in mind, they can be implemented in diverse educational settings, from large lecture halls to smaller, resource-constrained institutions. This adaptability ensures that the framework can reach a broad audience and contribute to the widespread integration of SE/ST principles in engineering education.

However, the study also highlights areas for improvement and future exploration. Providing more detailed guidance for role-playing activities, diversifying materials, and introducing complexity to tasks could enhance student engagement and learning outcomes. Expanding the framework to include digital tools, interdisciplinary applications, and longitudinal assessments of learning impacts would provide a more comprehensive understanding of its effectiveness.

Future directions for this work include refining the activities based on student feedback, expanding the framework to incorporate digital tools and interdisciplinary applications, and investigating long-term impacts on student learning and career readiness. By continuing to evolve and adapt these activities, educators can ensure that they remain relevant and effective in preparing students for the complexities of modern engineering practice.

The integration of hands-on tinkering activities into first-year engineering courses represents a powerful strategy for enhancing SE/ST education. By combining active learning with real-world applications, these activities not only engage students but also equip them with the skills and mindset needed to succeed as engineers. As the challenges facing the engineering profession grow increasingly complex, educational innovations like these are essential for cultivating the next generation of systems thinkers and problem-solvers.

The adoption of tinkering-based activities represents a step forward in engineering education. By engaging students in hands-on, systems-oriented learning experiences, this approach not only fosters critical SE/ST skills but also inspires a deeper interest in the engineering profession. As educators continue to refine and expand this framework, it holds great promise for cultivating the next generation of engineers equipped to tackle the increasingly complex challenges of our world. This work advocates for a reimagining of first-year curricula, where hands-on, reflective, and systems-oriented activities take center stage, shaping confident, creative, and capable engineers ready to make a meaningful impact.

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