2026 ASEE ANNUAL CONFERENCE June 21–24, 2026 | Charlotte Convention Center, NC
Host Sponsor UNC Charlotte
Paper ID #50222

Festival of Errors: A Conceptual Multi-layered Active Learning Model for Strengthening Math Attitudes

Dr. Sheila Tabanli, Rutgers, The State University of New Jersey

Dr. Sheila Tabanli is an Associate Teaching Professor of Mathematics at Rutgers University–New Brunswick. With over 25 years of experience across K–16 classrooms, her work focuses on expanding access and opportunity by bridging the gap between research and practice through asset-based, evidence-driven approaches. Grounded in cognitive science and social-emotional learning, she developed an interdisciplinary course that has produced longitudinal evidence of reduced DFW rates in gateway math courses. Recognized by students as a "trendsetter" and "game changer," this work led to the development of the RR2PG (Reducing the Research-to-Practice Gap) instructional framework and the CONNECT-STEM Community of Practice, a cross-disciplinary faculty network advancing inclusive, evidence-based teaching. As a Rutgers fellow, she authored a guidebook and developed the 3C Pedagogical Model (Compassionate, Connected, and Community-centered learning through cognitive apprenticeship). A recipient of the Rutgers–New Brunswick Chancellor's Faculty Excellence in Broadening STEM Access Award and the 2026 NJ STEM Educator of the Year Award, Dr. Tabanli is deeply inspired by her students' resilience and committed to empowering the next generation of diverse STEM leaders. Her scholarship has been featured in Forbes, Inside Higher Ed, and The Chronicle of Higher Education.

Dr. Lydia Prendergast, Rutgers, The State University of New Jersey

Associate Dean Women in Science and Engineering: Transformative academic leader with 20+ years advancing STEM education through experiential learning, collaboration, and strategic program development. Proven record of building sustainable, high-impact initiatives that empower learners and educators. Passionate advocate for authentic, hands-on experiences that prepare future leaders to thrive.

Festival of Errors: A Conceptual Multi-layered Active Learning Model for Strengthening Math Attitudes

ABSTRACT

Mathematics serves as a foundational pillar for engineering and a gateway to numerous STEM disciplines. However, many first-year college students struggle in calculus due to insufficient preparation in algebra and pre-calculus, in addition to a lack of confidence in mathematical skills. To address these challenges, in this conceptual paper, we report on a collaborative intervention design at Rutgers, the State University of New Jersey, a flagship research university between the Douglass Women in Science and Engineering program director and faculty from the Mathematics Department. The constructed design integrates multiple evidence-based elements, including UDL-aligned problem solving, real-life contextualization, collaborative reasoning, and a structured opportunity to examine errors, to create a learning experience that strengthens mathematical attitudes across formal and informal settings. The design begins with offering a real-life scenario that a college student at any level of mathematics course can understand. The design continues with a gamified math-based challenge that is co-designed by GenAI tools to help contextualize the problems related to students' perceived math level. Using Universal Design for Learning principles, this model allows students to follow different solution paths that ultimately converge in a shared error-analysis activity designed to build self-efficacy, reduce math anxiety, and strengthen collaboration. This collective “Festival of Errors” brings their varied approaches back together, normalizing mistakes as part of authentic engineering practice and reinforcing iteration, refinement, and resilience. The framework highlights a contemporary STEM figure whose innovation and real-world impact serve as an inspiration for this activity and to help students shape their own STEM identities and build their strengths. Grounded in educational psychology and engineering education research, the overall design aims to deepen students’ sense of belonging, support resilience, and promote success in STEM contexts. A mixed-methods assessment has been developed for future implementation, integrating the Growth Mindset subscale of the MAPS instrument with qualitative reflections to capture both quantitative shifts and students’ interpretive insights. The appendix includes a replicable activity blueprint to support adaptation in varied institutional contexts. This conceptual paper contributes to the growing body of knowledge in engineering education research by offering a theoretically integrated and scalable model for embedding identity development, productive failure, and agency into multiple educational settings.

I. Introduction

Mathematics is a cornerstone for engineering education and a gateway to numerous STEM disciplines. Yet many students entering calculus face significant challenges due to gaps in algebra and pre-calculus content knowledge and readiness in these prerequisites. These academic gaps are often compounded by low confidence and math anxiety, which hinder persistence in STEM pathways. Research on gateway courses consistently identifies calculus as a high-risk point or a “weed out” course, leading to high failure. According to [1], the average DFWI rate for Introductory Calculus is 34.33%, which is higher than both the introductory chemistry and introductory accounting courses. These competitive weed-out courses are a source of considerable dissatisfaction among undergraduates [2]. Disparities in STEM education are well documented, with graduation data showing that Black and Hispanic students are more likely than White students to switch out of a STEM major [3, 4]. Furthermore, it is important to note that women are disproportionately affected by this phenomenon: the odds of a woman being dissuaded from continuing in calculus are 1.5 times greater than those for a man [5]. In [5], Ellis posits that a lack of mathematical confidence, rather than a lack of mathematical ability, may be responsible for the high STEM attrition rates for women. Math anxiety further worsens these challenges, as students with higher levels of anxiety tend to avoid math-related content and courses over time, resulting in poorer academic outcomes independent of the actual math ability [6, 7]. These affective barriers are critical because they reduce engagement, productive struggle, and persistence, which are crucial ingredients for success in quantitative disciplines. In other words, addressing only the mathematical gaps may not be sufficient to address students' persistence in STEM. On the other hand, addressing only the affective domain gaps may be an incomplete intervention as well. Therefore, developing a multi-phase educational intervention that emphasizes training in controlling negative emotional responses to math stimuli combined with math content training will be more effective in revealing a population of mathematically competent individuals, who might otherwise go undiscovered [7].

Engineering education research increasingly calls for theoretically grounded interventions that integrate cognitive development, identity formation, and affective engagement within authentic disciplinary contexts [19]. This paper responds to that call by proposing a conceptual framework that incorporates multiple design elements, including novice–expert orientation development [8, 16], problem-solving activities aligned with Universal Design for Learning (UDL) principles [9], and gamified "missions" that structure phases of the hands-on intervention [12]. Within this broader model, collaborative error analysis functions as a mechanism through which students examine reasoning. The framework provides a structured space for reconvening varied solution paths and normalizing mistakes as part of engineering practice grounded in iteration and refinement. This conceptual paper contributes to engineering education research by extending current applications of growth mindset and UDL beyond isolated interventions toward an integrated, identity-supportive model for mathematically intensive engineering pathways. The model is designed for implementation at Rutgers University in both a credit-bearing mathematics course and a co-curricular STEM living-learning community, which allows investigation of how theory-informed design operates across formal and informal learning environments [18, 19, 20].

This framework advances the following propositions for engineering education research, which will be examined empirically in a forthcoming companion paper:

Proposition#1: Embedding structured, collaborative error analysis across formal and informal STEM learning environments allows growth mindset to be experienced as a learning practice rather than only measured as a belief.

Proposition#2: Integrating UDL, gamification, and contextual personalization across formal and informal settings may support identity development and persistence in mathematically intensive STEM pathways.

II. Theoretical and Conceptual Frameworks

This study is grounded primarily in Bandura's Social Cognitive Theory (SCT) [10], particularly the role of self-efficacy in shaping engagement and persistence and is extended through research on productive struggle and UDL to examine how beliefs, learning processes, and instructional design jointly support STEM identity and success. SCT posits that self-efficacy, defined as the belief in one's ability to perform a task, directly affects persistence, motivation, and achievement [10,11]. In mathematics education, students with higher self-efficacy are more likely to engage in productive struggle, persist through challenging problems, and recover from errors [19]. In contrast, students with lower self-efficacy, including many women in STEM, face a greater risk of disengagement and attrition [5].

Building on SCT, growth mindset theory provides an evidence-based approach to reframing students' beliefs about ability and failure [8]. Intervention designs that encourage students to interpret mistakes as opportunities for learning have been shown to improve self-efficacy, reduce math anxiety, and increase persistence in STEM courses [5], [8]. Together, these theories support the design of interventions that address both affective and cognitive beliefs prior to engaging students in complex mathematical problem-solving tasks.

Our proposed conceptual framework design extends these theoretical principles into a practical, evidence-based intervention that integrates beliefs, learning processes, and instructional design to support students in STEM. These three interdependent layers are described as follows:

1. **Beliefs (Psychological Layer):** The psychological layer addresses how students interpret ability, error, and belonging in mathematically intensive environments. Drawing on growth mindset theory and STEM identity research, this layer positions error analysis as a structured and communal practice rather than an individual deficit. Activities such as the "Festival of Errors" [15, 28] normalize mistake-making as an essential feature of engineering reasoning, supporting self-efficacy, reducing impostor feelings, and strengthening students' identification with STEM fields. By foregrounding resilience and perseverance through both peer collaboration and representation of diverse STEM role models, this layer reframes mathematical struggle as evidence of engagement in authentic disciplinary practice.
2. **Learning Processes (Cognitive Layer):** The cognitive layer centers on productive struggle, metacognitive development, and the strategic management of cognitive load [21], [22], [23]. Students engage in carefully scaffolded algebra- and calculus-based problem solving designed to reduce unnecessary cognitive overload while preserving conceptual rigor [22]. Tasks are structured to guide learners through a disciplined problem-solving progression: first understanding the problem, then developing a plan, executing a solution, and reflecting deliberately on both results and errors, reflecting core principles of the engineering design process and reinforcing engineering habits of mind [24]. This sequencing supports metacognition and positions error analysis as an integral component of mathematical reasoning. Generative AI tools are incorporated as contextualization scaffolds that personalize problem scenarios to students' mathematical backgrounds. Rather than replacing analytical thinking, AI functions as a cognitive support that provides adaptive entry points, clarifies representations, and enables iterative

feedback. In doing so, it helps manage extraneous cognitive load while sustaining productive struggle and deliberate error analysis [22].

3. **Instructional Design (Structural and Equity Layer):** Grounded in Universal Design for Learning (UDL) principles [9] and equity-oriented pedagogy [25], this layer highlights how multiple means of engagement and mathematical pathways shape the learning experiences. Students may select tasks from a choice menu, participate in gamified challenges such as the Festival of Errors, and engage in team-based activities that highlight resilience and perseverance in STEM. AI-assisted task generation also supports scalability and instructor adaptability, aligning with emerging research on AI-supported instructional design [26]. By aligning formal coursework with co-curricular STEM programming, this layer establishes an integrated learning ecosystem rather than isolated experiences, consistent with research on high-impact educational practices and student persistence [27].

By integrating these layers, the framework conceptualizes how beliefs, cognition, and instructional design interact to foster STEM identity, resilience, and academic success. Design tools such as role playing, gamification, role model narratives, and generative AI supported contextualized co-design are used to support engagement. These tools operationalize SCT and growth mindset principles into scalable and inclusive learning experiences. The layers of the framework and how they connect with one another are depicted in Figure 1.

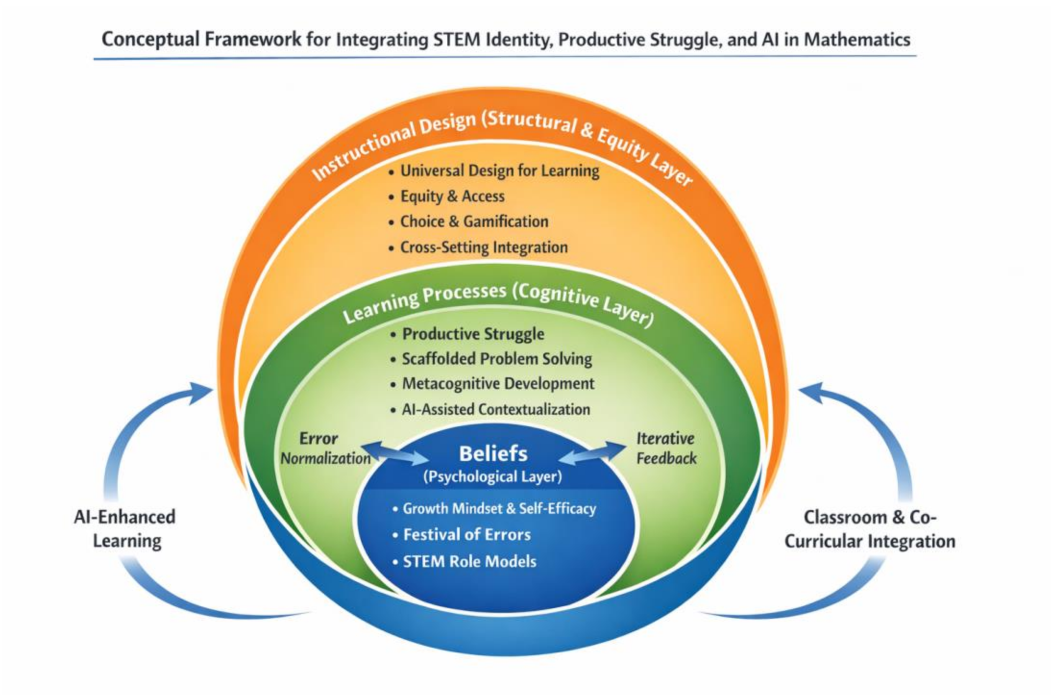

Figure 1. Conceptual Framework for Integrating STEM Identity, Productive Struggle, and AI in Mathematics (conceptualized by the authors; visual rendering assisted by ChatGPT, GPT-5.2).

III. Design Elements

The design elements operationalize the conceptual framework, translating the theoretical layers of beliefs, cognition, and instructional design into scalable, student-centered activities. This section highlights how these elements function across multiple learning environments, including a supplemental undergraduate math course and a STEM living-learning community event for women, demonstrating the framework's applicability in both formal and informal contexts.

Each design element exemplifies how theoretical principles inform practical activity design: beliefs shape how students interpret errors and setbacks, cognitive scaffolds guide problem-solving and reflection, and structural supports enable access, choice, and scalability. This approach provides a transferable model for embedding productive failure, metacognition, and identity development into diverse STEM learning environments. The figure below shows how the conceptual layers in the framework are translated into scalable STEM learning activities. The conceptual layers—psychological, cognitive, and structural—directly inform the design of student activities as depicted in Figure 2.

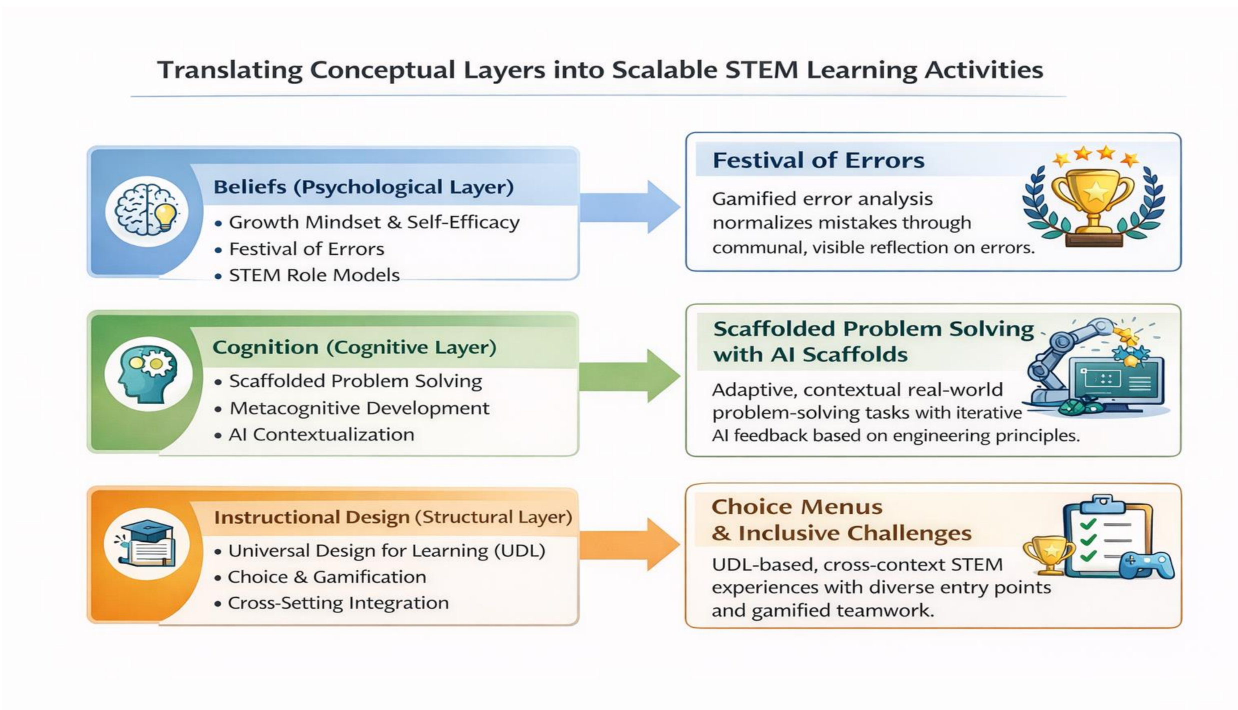

Figure 2. Conceptual Framework for Integrating STEM Identity, Productive Struggle, and AI in Mathematics (conceptualized by the authors; visual rendering assisted by ChatGPT, GPT-5.2).

With this foundation in place, the next sections illustrate how these conceptual layers were translated into the structure of the activity design, detailing each step's role in operationalizing the framework. The activity opens with a contextualized problem setting, and then moves through 5 steps, or missions. Figure 3 illustrates the progression of the missions.

Figure 3. Sequence of Missions in the STEM Learning Activity (conceptualized by the authors; visual rendering assisted by ChatGPT, GPT-5.2).

*Realistic Contextual Setting***:** The overall framing and lesson title were selected to resonate with young-adult learners and serve as an inviting entry point into the mathematical ideas that follow. A relatable, curiosity-sparking theme helps draw students in and sets a tone that lowers barriers to engagement. The activity then opens with a realistic scenario that gives purpose to the quantitative work, See Figure 4. Presenting students with a familiar problem context helps them see why mathematics matters and how the underlying relationships operate in real situations. This grounding allows abstract ideas to become more interpretable and transferable to new settings. Additionally, the setting includes a contemporary STEM figure whose real-world impact serves as an inspiration for this activity and for the learners. Including real contributors helps students connect mathematics to lived experiences, demystifies the discipline, and supports students in imagining themselves as part of the STEM community.

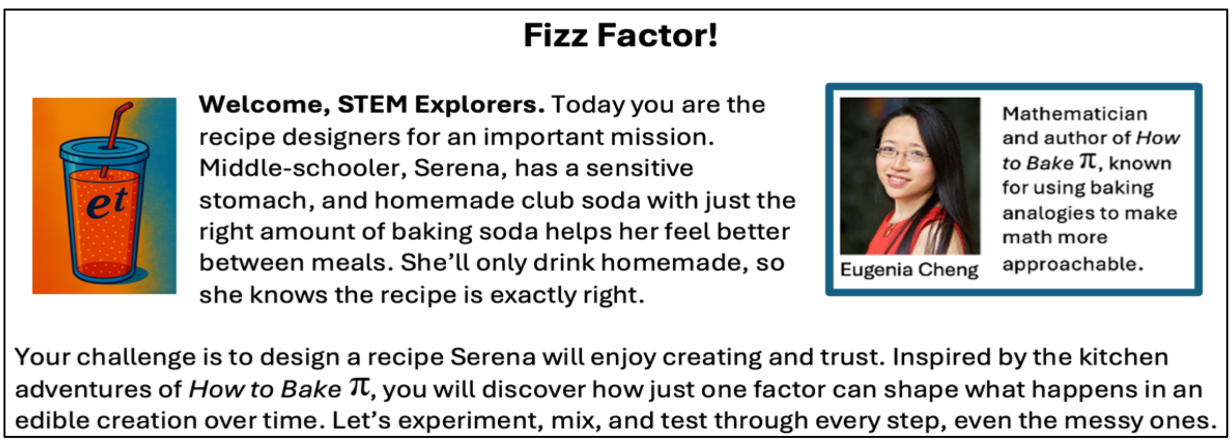

Figure 4: Gamified Activity Setting

Missions 1+2: The next step introduces a standard algebraic exercise for the activity (Figure 5). Here, they work with an exponential equation, manipulate the expression, and use algebraic reasoning to determine when the concentration stays effective. The problem-solving exercise continues with a structured UDL approach. To ensure flexible access points for a diverse range of learners, the mission employs a gamified "choose-your-path" structure that allows students to engage with the mathematical model at a level aligned with their comfort and prior knowledge (Figure 6). Students may approach the task through algebraic manipulation, calculus-based analysis, or conceptual reasoning, each offering a valid entry point for exploring the concentration model, while still working toward the shared goal of determining an effective solution.

Mission 1: Let's Concentrate

The concentration of ¼ tsp baking soda is expressed as: $\mathbf{C(t) = C_0\, e^{-0.2t}}$, where **t** is time in hours, and $\mathbf{C_0 = 100}$. The club soda is effective for Serena when the baking soda concentration stays above 50. Determine how long it remains effective for Serena and explain your reasoning.

Figure 5: Standard Algebraic Exercise

Mission 2: Choose Your Fizzy Path

Serena eats her meals every 4 hours, so the club soda must stay effective for that duration. The recipe is very simple: 1 liter water, 1/8 tsp salt, and ***1/4 to 1/2 teaspoon baking soda***. How much baking soda should be used? Choose Path A, B, or C and use the table below.

Baking Soda	C_0	C(4)	Effective?
¼ tsp	100		
⅓ tsp	133		
½ tsp	200		

Path A: Algebra / Precalculus Explorer
- Will all the baking soda measurements work after 4 hours?
- Use words, sketches, or simple calculations.
- How does the concentration change over time?

Path B: Calculus Navigator
- Find C'(t) and interpret how fast the concentration is changing at t = 4 hours
- What does the rate tell you about the club soda's effectiveness?

Path C: Conceptual Thinker
- Describe what happens to the concentration over time
- Why are remedies taken at regular intervals?

Figure 6: Personalized Pathways Grounded in UDL

Mission 3: Error normalization and iteration are utilized as epistemic reframing in engineering mathematics. Engineering practice fundamentally involves iterative refinement, debugging, and failure-informed design. However, students often experience mathematics in engineering pathways as performance-oriented and error-averse. The "Festival of Errors" component reconceptualizes mistakes as visible and communal learning artifacts rather than private indicators of deficiency. Shown in Figure 7, by gamifying error analysis and explicitly celebrating revision, the framework operationalizes productive failure as epistemic participation in engineering thinking. This work contributes to engineering education research by reframing error analysis from remediation to identity-positioning.

Mission3: Collaborate with other STEM Explorers - Detect the best solutions.

3a: Another explorer wrote: "After 4 hours the concentration will be 92 because 100 – 4×0.2 = 92."
1. Identify what was done correctly.
2. Find the mistake(s).
3. Explain the correct reasoning.

3b: Compare your Mission 1 and Mission 2 solutions.
1. Compare effectiveness results of the baking soda measurements.
2. Identify key similarities and differences in reasoning.
3. Agree on the clearest beginner-friendly explanation for Serena.

Figure 7: Error Detection and Solution Collaboration

The remaining components of the activity (Missions 4 + 5) include a student identified spotlight of an inspiring STEM professional, a hands-on club soda–making experience, and a concluding survey. The full activity appears in the Appendix. The hands-on component reinforces the mathematical ideas explored earlier by allowing students to test the model through direct experimentation, adding a tactile modality that supports sense-making and active engagement. The survey uses a validated instrument and is described in the following section.

Guiding Principles for the Survey: The psychological layer of the framework is informed by the *Mathematics Attitudes and Perceptions Survey* (MAPS) [16], a validated instrument developed to examine students' beliefs, attitudes, and orientations toward mathematics. MAPS has been used to compare novice learners with more expert-like populations (e.g., faculty and advanced graduate students) to better understand how mathematical beliefs align with disciplinary ways of thinking. Findings reported in the MAPS literature suggest that students' beliefs about mathematics can shift over time in ways that do not necessarily move toward expert-like orientations, highlighting the need for intentional instructional structures that support productive dispositions [16].

Within this conceptual model, MAPS functions as a construct-level guide. Due to time constraints and in the interest of our design study, only the growth mindset subscale of MAPS is included to gauge participant interest in the informal setting. Specifically, the Growth Mindset subscale that is focused on beliefs about the malleability of mathematical ability provides a theoretical lens for designing learning experiences that address fixed versus growth-oriented interpretations of competence. Representative items from the original MAPS are extracted from the growth mindset subscale and included below:

MAPS Growth Mindset subscale questions from the survey:

1) Math ability is something about a person that cannot be changed very much. (Likert Scale)
2) Nearly everyone is capable of understanding math if they work at it. (Likert Scale)
3) Being good at math requires natural (i.e. innate, inborn) intelligence in math. (Likert Scale)
4) For each person, there are math concepts that they would never be able to understand, even if they tried. (Likert Scale)

In addition to the MAPS survey, the design also invites students to provide feedback about their perceived experiences about the activity. Drawing on these constructs, the framework proposes activity structures that explicitly surface and reframe beliefs about error, struggle, and ability. For example, structured error-analysis experiences (e.g., a "Festival of Errors") are conceptualized as mechanisms for normalizing productive struggle and positioning mistakes as integral to mathematical reasoning. In this way, MAPS-informed constructs are embedded into activity design, aligning belief development with cognitive practice and structural support. The full activity illustration is provided in the Appendix as an example of how these principles may be instantiated in practice.

Learning Environments: The conceptual framework is designed to function across diverse STEM learning environments illustrating how growth mindset, error normalization, and STEM identity development can be supported in both formal coursework and informal co-curricular programming. In classroom settings, the framework can be embedded in credit-bearing courses that focus on developing students' mathematical problem-solving skills, metacognition, and self-regulated learning strategies [17]. In informal settings, such as STEM living-learning community events, the same principles can be applied to brief, interactive activities that foster engagement, collaboration, and identity-building in a low-stakes environment.

This multi-setting design highlights the scalability and adaptability of the conceptual framework. While specific tasks, entry points, and scaffolds may vary depending on students' mathematical backgrounds and the learning context, the underlying layers of beliefs, cognition, and instructional design remain consistent. Generative AI tools can support task contextualization and personalization across settings, demonstrating how the framework operationalizes theory into practical, adaptable design elements that enhance student agency, engagement, and STEM identity.

IV. Role of Generative AI in the Cognitive Layer Design

A generative artificial intelligence (GenAI) tool [12] was used as a design partner to support the creation of contextualized, algebra- and calculus-level challenges aligned with students' STEM majors, as part of the UDL methodology. Specifically, the tool was prompted to generate real-world problem contexts (e.g., engineering systems, biological growth, data trends) that preserved core mathematical structures while situating them within discipline-relevant narratives.

Both authors used AI during activity development, drawing on two different GPT-5–powered tools. One used a university-supported version of Microsoft 365 Copilot, optimized for professional knowledge-work such as drafting structured documents, creating presentations, and synthesizing instructional materials. The other used the free version of ChatGPT, which also runs on GPT-5 but functions as a general conversational interface suited for brainstorming, rapid drafting, and open-ended exploration. Although both AI tools rely on the same underlying model family, their differing features shaped how each author contributed to the design.

The authors neither discussed nor coordinated their choice of AI tools at the beginning of the design process, and neither author conducted a prior investigation of AI tool features. By coincidence, Author 1, a mathematics faculty member, initiated the activity design using ChatGPT during the early ideation phase. This proved to be a productive match because the tool responded well to iterative prompts and criteria that guided the brainstorming process. These exchanges supported the development of the exponential, gamified error-analysis framework. Author 2, a Women in STEM director, worked from the emerging framework and collaborated with Copilot to shape the contextual and human-centered elements. This also proved to be a fitting choice, since Copilot is well suited for synthesizing and refining instructional materials.

Both authors curated, edited, and validated all AI-generated content to ensure mathematical accuracy, cognitive appropriateness, and alignment with the intended learning objectives. An example from one author is described as follows:

“In reflecting on my interaction with AI during task design during the ideation phase, I questioned whether asking students to compute concentration at 8 hours—after determining it becomes ineffective at 6 hours—was pedagogically purposeful or an oversight. Within seconds, the AI articulated multiple rationales: reinforcing the continuity of exponential decay beyond contextual thresholds, supporting graphical reasoning through an additional data point, and distinguishing between mathematical zero and contextual ineffectiveness. This exchange was significant not because of speed, but because it surfaced layered instructional intentions embedded in a single modeling decision. In engineering education, where mathematical structures must align with contextual interpretation, such distinctions are critical. The AI functioned as a reflective catalyst, making explicit the conceptual, representational, and epistemic dimensions of the task. Rather than replacing design judgment, it expanded awareness of how a single numerical extension could support deeper modeling coherence.”

The primary strength observed in the use of generative AI was its ability to rapidly produce multiple contextual variations of a single task, which supported the development of a wide range of activity elements. This flexibility increased opportunities for relevance and student engagement without substantially expanding the design workload. Limitations were also documented. AI-generated problems sometimes required significant revision to address imprecise wording, inconsistent reasoning, or unintended assumptions. Human oversight and disciplinary expertise were therefore essential to maintain pedagogical quality. Even with these constraints, the approach shows strong potential for scalability and adaptation across STEM contexts because the underlying mathematical structures can be systematically recontextualized for different disciplines or learner groups. When applied as a co-design partner rather than an autonomous content generator, generative AI offers a promising and scalable way to support inclusive, contextualized, and learner-centered STEM instruction.

V. Cross-unit Collaborative Design Experience

Cross-unit collaboration proved to be a central strength of this project. The partnership between a mathematics faculty member and a woman in STEM student-success professional brought together distinct types of diversity that shaped the quality of the final activity design. Diversity of thought, disciplinary training, and professional context enriched the design process by allowing the authors to approach the same instructional goal from complementary perspectives. This interdisciplinary exchange supported a more holistic and engaging learning experience for students.

One author, a mathematics faculty member, typically teaches coordinated course structures that prioritize uniform pacing, standardized assessments, and tight content sequencing. These constraints can limit opportunities to transform abstract concepts into relatable life applications or to revisit problem solving approaches. In many mathematics classrooms, students may hesitate to participate out of concern for making mistakes, especially when instructional time is rigid and opportunities for low-stakes exploration are limited.

The other author, associate dean of Women in Science and Engineering, operates in a co-curricular environment with greater flexibility in format, timing, and design. Her work centers on high-impact practices and the creation of learning experiences that feel different from traditional lecture-based instruction. Because her students' presence and participation are voluntary, activities must be contextualized, relevant, and engaging to sustain participation. This setting prioritizes creativity and the translation of conceptual or theory-driven ideas into real-world narratives that resonate with students.

Collaboration between these two faculty/staff and settings introduced a novel framework that broadened the instructional possibilities of the design. The mathematical structure and problem-solving expertise of the first author combined with the contextual design experience and learner-engagement perspective of the second author. Together, the activity was designed to maintain mathematical rigor while also integrating human-centered and culturally responsive elements. This cross-unit partnership allowed the design to reflect both strong disciplinary foundations and a richer, more inclusive learning environment. The final product benefitted from the strengths of each collaborator and presents a model for how interdisciplinary teams can diversify STEM learning experiences for undergraduates.

VI. Discussions and Implications

This paper contributes to a conceptual understanding of how growth mindset and STEM identity can be operationalized in engineering education through layered pedagogical design rather than as standalone psychological interventions. By situating mindset theory within a framework of beliefs, learning processes, and instructional design, the work illustrates how theory can directly inform the structure and experience of learning activities.

The Festival of Errors exemplifies how error normalization can be treated as an epistemic practice rather than merely a remediation tool. By making mistakes visible, communal, and subject to reflective analysis, the activity demonstrates how growth mindset principles can be enacted in authentic engineering mathematics experiences. This extends current theory by linking affective constructs (self-efficacy, resilience) to observable student engagement in disciplinary practices, reinforcing the idea that productive failure is an integral component of STEM learning, rather than a discrete outcome.

The integration of generative AI as a scaffolding tool shows how cognitive load can be managed while maintaining conceptual rigor. AI-assisted problem contextualization provides personalized, discipline-relevant entry points, aligning with UDL principles and promoting metacognitive engagement. This example highlights a novel pathway for translating theoretical frameworks into scalable, inclusive instructional design. It also emphasizes the role of technology-mediated support in operationalizing cognitive and epistemic constructs, as well as time allocation for teaching faculty and staff whose main objective is not to design research or to publish papers.

Together, these examples demonstrate how a theoretically grounded, multi-layered framework can guide the design of interventions that are simultaneously psychologically informed, cognitively supportive, and structurally equitable. The implications for engineering education research include: (1) Extending growth mindset theory from attitudinal constructs to structured epistemic engagement, (2) Demonstrating the practical integration of UDL and gamification in conceptualizing STEM learning activities, (3) Showing how AI-supported scaffolds can operationalize theoretical principles while maintaining rigor and accessibility, (4) Providing a model for bridging formal and informal learning environments, illustrating how conceptual frameworks can inform cross-context pedagogical design.

In summary, this paper provides a theoretically grounded, practically adaptable model that bridges educational psychology and engineering pedagogy, offering new ways to conceptualize, design, and study learning in STEM environments.

VII. Limitations and Future Work

This conceptual paper presents a theoretically grounded framework for integrating growth mindset, productive struggle, and error normalization into STEM learning. As a design-focused work, it emphasizes the alignment of instructional layers, UDL principles, and AI-supported scaffolds with engineering epistemic practices. While the framework is broadly applicable, it is currently illustrated using examples from a supplemental mathematics course and a women-focused STEM living-learning community at a research-intensive university. Adaptation to other contexts, disciplines, or learner populations may require consideration of local constraints, disciplinary norms, and learner readiness.

The framework assumes active facilitation by instructors or peer leaders to ensure that AI-generated problem contexts and gamified activities maintain conceptual rigor and pedagogical alignment. Although AI can generate contextually rich problems, it cannot independently ensure cognitive appropriateness or alignment with theoretical principles. Effective implementation thus depends on instructor expertise, limiting immediate scalability without professional development or design support. Future work can explore scalable models for integrating AI-supported scaffolding across diverse course types, student populations, and institutional settings.

Further opportunities include examining additional epistemic practices such as collaborative modeling, iterative experimentation, or disciplinary design thinking, extending the conceptual framework to guide broader theory-informed interventions in engineering education. Empirical testing of specific components could complement the conceptual design by investigating how different layers interact with learner characteristics, promoting resilient STEM identities, and sustaining productive engagement. Empirical analyses examining the enactment of these propositions are currently underway and will be presented in a forthcoming companion paper, which focuses on implementation and outcomes in authentic learning environments.

By highlighting the theoretical and design principles in a replicable framework, this work provides a foundation for future research and practical applications that advance understanding of how instructional design can operationalize mindset theory, agency, and inclusive practices in STEM education.

References

[1] A. K. Koch and B. M. Drake, Digging Into the Disciplines I – Accounting for Failure: The Impact of Gateway Courses in Accounting, Calculus, and Chemistry on Student Success. Brevard, NC, USA: John N. Gardner Institute for Excellence in Undergraduate Education, 2018.

[2] E. Seymour and N. Hewitt, Talking about Leaving: Why Undergraduates Leave the Sciences. Boulder, CO, USA: Westview Press, 1997.

[3] N. Hatfield, N. Brown, and C. M. Topaz, “Do introductory courses disproportionately drive minoritized students out of STEM pathways?” PNAS Nexus, vol. 1, no. 4, Sep. 2022, Art. no. pgac167, doi: 10.1093/pnasnexus/pgac167.
[4] C. Riegle-Crumb, B. King, and Y. Irizarry, “Does STEM stand out? Examining racial/ethnic gaps in persistence across postsecondary fields,” Educational Researcher, vol. 48, no. 3, pp. 133–144, 2019, doi: 10.3102/0013189X19831006.
[5] J. Ellis, B. K. Fosdick, and C. Rasmussen, “Women 1.5 times more likely to leave STEM pipeline after calculus compared to men: Lack of mathematical confidence a potential culprit,” PLoS ONE, vol. 11, no. 7, Jul. 2016, Art. no. e0157447, doi: 10.1371/journal.pone.0157447.
[6] R. J. Daker, S. U. Gattas, H. M. Sokolowski, et al., “First-year students’ math anxiety predicts STEM avoidance and underperformance throughout university, independently of math ability,” npj Science of Learning, vol. 6, Art. no. 17, 2021, doi: 10.1038/s41539-021-00095-7.
[7] I. Lyons and S. Beilock, “Mathematics anxiety: Separating the math from the anxiety,” Cerebral Cortex, vol. 22, no. 9, pp. 2102–2110, Sep. 2012, doi: 10.1093/cercor/bhr289.
[8] C. S. Dweck, Mindset: The New Psychology of Success. New York, NY, USA: Random House, 2006.
[9] A. Meyer, D. H. Rose, and D. Gordon, Universal Design for Learning: Theory and Practice. Wakefield, MA, USA: CAST Professional Publishing, 2014.
[10] A. Bandura, Self-Efficacy: The Exercise of Control. New York, NY, USA: W. H. Freeman, 1997.
[11] A. Bandura, “Toward a psychology of human agency,” Perspectives on Psychological Science, vol. 1, no. 2, pp. 164–180, Jun. 2006, doi: 10.1111/j.1745-6916.2006.00011.x.
[12] OpenAI, “ChatGPT: GPT-5,” Generative Pre-trained Transformer, 2025. [Online]. Available: https://openai.com/chatgpt
[13] A. K. Henrich, E. D. Lawrence, M. A. Pons, and D. G. Taylor, Living Proof: Stories of Resilience along the Mathematical Journey. Washington, DC, USA: Mathematical Association of America, 2019.
[14] M. Khoshnoodifar, A. Ashouri, and M. Taheri, “Effectiveness of gamification in enhancing learning and attitudes: A study of statistics education for health school students,” Journal of Advances in Medical Education & Professionalism, vol. 11, no. 4, pp. 230–239, 2023, doi: 10.30476/JAMP.2023.98953.1817.
[15] P. C. Brown, H. L. Roediger III, and M. A. McDaniel, Make It Stick: The Science of Successful Learning. Cambridge, MA, USA: Harvard University Press, 2014.
[16] W. Code, S. Merchant, W. Maciejewski, M. Thomas, and J. Lo, “The mathematics attitudes and perceptions survey: An instrument to assess expert-like views and dispositions among undergraduate mathematics students,” International Journal of Mathematical Education in Science and Technology, vol. 47, no. 6, pp. 917–937, 2016, doi: 10.1080/0020739X.2015.1133854.
[17] S. Tabanli, “Fostering active learning and metacognitive skills in a cognitive-science based math course,” International Journal of Teaching and Learning in Higher Education, vol. 35, no. 2, Art. no. 19, 2024, doi: 10.7771/1812-9129.1018.
[18] L. Prendergast and E. Etkina, “Review of a first-year engineering design course,” Rutgers, The State University of New Jersey, 2014.

https://www.researchwithrutgers.com/en/publications/review-of-a-first-year-engineering-design-course.
[19] J. Kerrigan and L. Prendergast, "Flipped Pre-Calculus for Engineers: An Active Learning Course Transformation," PRIMUS, pp. 1–18, Nov. 2021, doi: https://doi.org/10.1080/10511970.2021.1993395.
[20] L. Prendergast, L. S. Joseph, and H. Bensetti-Benbader, "High Impact Experiential Learning – STEM Living Learning Communities for Women," *American Society for Engineering Education (ASEE) Annual Conference & Exposition*, 2025. [Online]. Available: https://peer.asee.org/high-impact-experiential-learning-stem-living-learning-communities-for-women.
[21] M. Kapur, "Productive failure," Cognition and Instruction, vol. 26, no. 3, pp. 379–424, 2008.
[22] J. Sweller, "Cognitive load during problem solving: Effects on learning," Cognitive Science, vol. 12, no. 2, pp. 257–285, 1988.
[23] J. H. Flavell, "Metacognition and cognitive monitoring: A new area of cognitive–developmental inquiry," American Psychologist, vol. 34, no. 10, pp. 906–911, 1979.
[24] National Academy of Engineering, The Engineer of 2020: Visions of Engineering in the New Century. Washington, DC, USA: National Academies Press, 2004.
[25] B J. A. Banks and C. A. M. Banks, "Equity pedagogy: An essential component of multicultural education," Theory Into Practice, vol. 34, no. 3, pp. 152–158, 1995.
[26] H. Farhood, M. Nyden, A. Beheshti, S. Muller, et al., "Artificial intelligence-based personalised learning in education: a systematic literature review," Discover Artificial Intelligence, vol. 5, art. 331, 2025.
[27] G. D. Kuh, High-Impact Educational Practices: What They Are, Who Has Access to Them, and Why They Matter. Washington, DC, USA: Association of American Colleges and Universities, 2008.
[28] S. Tabanli, "Three ways to teach college math with compassion (opinion)," Inside Higher Ed, Sep. 18, 2024. [Online]. Available: https://www.insidehighered.com/opinion/career-advice/teaching/2024/09/18/three-ways-teach-college-math-compassion-opinion

APPENDIX – Complete Activity Sheet

Fizz Factor!

Welcome, STEM Explorers. Today you are the recipe designers for an important mission. Middle-schooler, Serena, has a sensitive stomach, and club soda with just the right amount of baking soda helps her feel better between meals. She'll only drink homemade, so she knows the recipe is exactly right.


Eugenia Cheng

Mathematician and author of *How to Bake* π, known for using baking analogies to make math more approachable.

Your mission is to design a recipe Serena can create and trust. Inspired by the kitchen adventures of *How to Bake* π, you will discover how ingredients can shape what happens in an edible creation over time. Let's experiment, mix, and test through every step, even the messy ones.

Mission 1: Let's Concentrate

The concentration of ¼ tsp baking soda is expressed as: $\mathbf{C(t) = C_0\, e^{-0.2t}}$, where **t** is time in hours, and $\mathbf{C_0 = 100}$. The club soda is effective for Serena when the baking soda concentration stays above 50. Determine how long it remains effective for Serena and explain your reasoning.

Mission 2: Choose Your Fizzy Path

Serena eats her meals every 4 hours, so the club soda must stay effective for that duration. The recipe is very simple: 1 liter water, 1/8 tsp salt, and ***1/4 to 1/2 teaspoon baking soda***. How much baking soda should be used? Choose Path A, B, or C and use the table below.

Baking Soda	C_0	C(4)	Effective?
¼ tsp	100		
⅓ tsp	133		
½ tsp	200		

Path A: Algebra / Precalculus Explorer

- Will all the baking soda measurements work after 4 hours?
- Use words, sketches, or simple calculations.
- How does the concentration change over time?

Path B: Calculus Navigator

- Find C'(t) and interpret how fast the concentration is changing at t = 4 hours
- What does the rate tell you about the club soda's effectiveness?

Path C: Conceptual Thinker

- Describe what happens to the concentration over time
- Why are remedies taken at regular intervals?

🕵️ **Mission3: With other STEM Explorers - Detect the best solutions.**

3a: Another explorer wrote: "After 4 hours the concentration will be 92 because 100 – 4×0.2 = 92."

1. Identify what was done correctly.
2. Find the mistake(s).
3. Explain the correct reasoning.

3b: Compare your Mission 1 and Mission 2 solutions.

1. Compare effectiveness results of the baking soda measurements.
2. Identify key similarities and differences in reasoning.
3. Agree on the clearest beginner-friendly explanation for Serena.

🌟 **Mission 4: Heroes and Heroines of STEM**

Pick a STEM professional who inspires you. Share who you chose, what they are known for, and how their journey—through innovation, challenges, or persistence—motivates you.

✅ **Mission 5: How did we do?**
Consent + Survey

The PRIZE: Let's Make Club Soda

Ingredients

- 1 liter cold filtered water
- 1/4 to 1/2 tsp baking soda
- 1/8 tsp table salt
- Simple syrup (optional)
- Food Coloring (optional)

Instructions

- Mix the baking soda and salt into a small amount of water first to avoid excessive fizzing.
- Add the rest of the water, simple syrup, and food coloring
- Pour the mixture into the soda stream.