Characterising STEM Ways of Thinking in Engineering Design (ED)-based tasks.

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Investigating students' thinking in routine classroom tasks, especially in science and engineering, is crucial. Given the rising interest in STEM Ways of Thinking (SWoT), in this exploratory study, we focus on two multi-week Engineering Design tasks within an undergraduate physics laboratory. Given that the term 'ways of thinking' has varied interpretations, we aim to further the discourse by identifying four SWoTs: Design Thinking, Physics Concepts, Mathematical Constructs, and Metacognitive Reflection. Analyzing discussions from 14 student-groups reveals notable differences in how students solve an instructor-assigned challenge given earlier in the semester and a student-generated challenge later in the semester. Students considered physics concepts more frequently and combined mathematical and physics concepts in more detail in the latter task. Our findings underscore the value of small-group discussions in understanding and operationalizing SWoT. We acknowledge the need for diverse frameworks and believe our study can benefit educators and researchers exploring similar strategies.

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I. INTRODUCTION

In preparation towards STEM careers, students must develop strong understanding of disciplinary core ideas, interdisciplinary crosscutting concepts, and key science and engineering practices [1]. Embedding Engineering Design (ED) into physics laboratory tasks is a promising approach to achieve these objectives [2–5]. The ED process model in the context of this study involves six interactive phases for solving 'ill-structured' [6] problems. Student groups identify the problem, generate ideas using relevant physics, create and test plans, record results, and explain outcomes using scientific knowledge. They then share ideas, gather feedback, and revise and retest their models accordingly [7, 8].

Research suggests that science education should emphasize disciplinary 'ways of thinking' (WoT) [9–13] in addition to mastering abstract concepts and problem-solving [14]. WoT, in the context of this study, is about how students "think, act, and engage in their projects and make decisions" [9]. Earlier studies examined students' thinking while solving a real-world instructor-assigned ED problem [15, 16]. The current study aims to compare students' thinking between instructor-assigned and student-generated ED problems.

Our research question is: *How do student-groups' ways of thinking compare while engaging in two multi-week ED tasks - an instructor-assigned task and a student-generated task?*

We aim to further the discussion on 'STEM Ways of Thinking' (SWoT) [9–13], that would be of interest to STEM educators and researchers.

II. LITERATURE REVIEW

With the advent of the Next Generation Science Standards [1] there have been calls to update our expectations about what students should learn in college-level introductory STEM courses [17]. One approach [18] is to structure learning experiences that infuse Engineering Design (ED) into science classrooms to bridge 'tactics and strategies' (Engineering Design) with 'practices and the nature of science' (Science Thinking) [1].

Research has shown that by observing what students are doing, such as engaging in peer interactions, it is possible to ascertain how they are thinking [19]. Peer interactions enable learners to leverage diverse expertise, encounter varied viewpoints, question, explain, exchange ideas, and articulate their reasoning [20, 21]. Small-group discussions help students "explore their ideas and move from understandings that may often be naive to towards more valid scientific ideas and explanations" [22], apart from contributing to STEM achievement, motivation, engagement, and problem-solving [23].

The focus on SWoT has been underscored by several studies [9–13]. Efforts have been directed towards developing theoretical frameworks to delineate and characterize these ways of thinking (WoT) [9, 11]. While emphasizing the importance of exploring WoT, it is acknowledged that the field is "still at a nascent stage" [9], signaling the necessity to move beyond intuitive or 'common sense' understandings of what WoT may entail [24]. Our analysis has some commonalities with the SWoT framework suggested by English [13], and we intend to elaborate in an extended publication.

Our earlier studies [15, 16] reveal that capturing students' 'in-the-moment' thinking provides rich data on their approach to the ED challenge. Although group discussions alone may not fully capture students' thinking entirely, they offer valuable insights into students' "interthinking" [25] in naturalistic settings. We aim to address our research question by analyzing these discussions.

III. METHODS

This study is situated in a large-enrollment, first-semester, calculus-based, undergraduate physics course at a large U.S. Midwestern land-grant university. This course has an annual enrollment of about 2500 students, of which about 85% are engineering majors and the remaining are science majors.

The course adopts the principle-based approach [26], with content divided into three units each focused on a fundamental principle: momentum, energy, and angular momentum. Common threads include a focus on systems thinking, modeling, and making assumptions and approximations. The weekly schedule includes two 50-minute lectures, one 110-minute laboratory, and one 50-minute recitation focused on problem-solving.

This study centers on the 14-week laboratory experience in the course. Student-groups of sizes two or three, in weeks 01-06, completed labs related to the Momentum principle. In addition to the laboratory experiments each week, student-groups also completed an instructor-assigned ED challenge (ED1) (Fig.1).

FIG. 1: Instructor-assigned engineering design challenge (ED1) statement. Plan-view of the warehouse provided to the students is not produced in this paper.

> "A partner shipping company is requesting your team to develop an algorithm to remotely control its Automated Guided Vehicles (AGVs) at the warehouse in a timely and safe manner. Provide a written or visual description of how it works and any additional information that you consider relevant. They will review your proposal and send the algorithm to a team of expert programmers who will implement it. The parameters of AGV robots are: Mass (no load): 145 kg; Dimensions: 75×60×30 cm; Maximum load: 340 kg; Maximum momentum: 220 (kg m/s). The layout of the warehouse area provides 25 × 25 sq m space for AGVs to operate. The size of each work station is about 2 x 2 sq m."

Labs related to the Energy principle were completed in weeks 07-09, and those related to the Angular Momentum principle were completed in weeks 10-14. In weeks 08-14, student-groups completed a student-generated ED challenge (ED2). Student-groups framed their ED challenge considering aspects such as: identifying the clients and stakeholders, stating the metrics, outlining the criteria and constraints, and making trade-offs. Teaching assistants (TAs) did not influence students' choice of the ED challenge, but guided students to progress towards a solution iteratively.

The participants in our study were 14 student-groups in the laboratory section for which the first author was the Graduate TA. At the end of each ED task, in response to written prompts provided in the lab write-ups in weeks 06 and 14, students were prompted to discuss and record: relevant physics and math concepts and their application to the ED problem, and the evolution of their ideas through multiple iterations of their design solutions. They were encouraged to engage in "free-flowing" [27, 28] discussions lasting about five minutes per task.

The audio recordings of the discussions, our primary data source, were manually transcribed, and qualitatively coded inspired by an earlier study [15]. Students recorded discussions in the laboratory or corridors, and the resulting background noise made it extremely challenging to uniquely associate conversation segments with individual speakers. Consequently, this study does not explore individual students' ways of thinking, but that of the group. In the transcripts, textual segments of varying lengths were chosen as coding units, a decision that may invite criticism for potential subjectivity and bias. However, this flexible approach was adopted after careful consideration of factors such as the complexity of student discussions and unique conversation styles within each group [29]. We are of the view that choosing a fixed text length would not capture the diversity and richness in students' approach to discussions, in addition to not being respectful to their communication styles. Multiple codes may be attributed to the same textual segment.

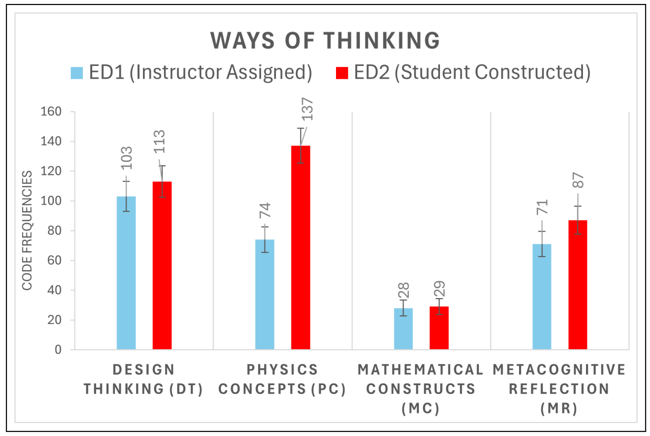
For 'trustworthiness' and 'dependability' of our analysis, we were guided by Lincoln and Guba [30, 31]. The lead author performed the initial coding. Another experienced TA coded seven transcripts per task based on code definitions and multiple examples. The two coders discussed, reviewed, and 'coded to consensus' [31]. The lead author then re-coded the remaining transcripts.

IV. FINDINGS & DISCUSSION

The four emergent codes were: Engineering Design Thinking (DT), Physics Concepts (PC), Mathematical Constructs (MC), and Metacognitive Reflection (MR). Descriptors (tailored to reflect the study's context) and example quotes for each code may be seen in Table I.

The code frequencies for each code are shown in Fig.2. As shown in Fig.1, the instructor-assigned ED task (ED1) was about the motion of an automatic guided vehicle (AGV) in a warehouse. In contrast, the student-generated ED task (ED2) encompassed a diverse array of real-life problems such as: designing golf-carts, enhancing traction in race cars, creating toy catapults, and improving roller skates, among others. A more complete description of the variety of student-generated ED challenges may be seen in [35]. The fact that no two groups worked on the same problem suggests that student-groups explored independently and genuinely pursued their own ideas.

FIG. 2: The bar graph displays code frequencies vs the codes. The blue and red bars represent the instructor-assigned (ED1) and student-generated (ED2) engineering design tasks respectively. Error bars depict the standard error of mean.



The following themes were emergent from our analysis.

A. Is 'agency' playing a role?

Although we had asked students to keep their discussions to around five minutes, we found it striking that the duration was notably longer for the student-generated task (ED2) in all the groups. A paired t-test shows that the difference is statistically significant with a p value of 0.0090. Further, the number of times students used physics concepts (PC) was significantly higher in ED2 as seen in Fig.2. While these observations may seem predictable given that the student-generated (ED2) task occurred later in the course, we wonder whether students' 'sense of authorship' or 'agency' [36] could have influenced the outcomes, a view supported by research which shows that providing students with agency can lead to higher levels of motivation and engagement [37–40].

B. Everyone can design

We found no significant differences in students' engineering design thinking (DT) between the two tasks. Within each team, instances of design thinking were spread throughout their conversations. This finding is consistent with the view that "everyone designs and can design", and that students have innate enthusiasm towards designing and making their creations, taking things apart, and figuring out how things work [41, 42].

TABLE I: The table below shows the codes for Types of Thinking, code descriptions, and example quotes. DT-Design Thinking; PC-Physics Concepts; MC-Mathematical Constructs; MR-Metacognitive Reflection.

Code	Code Description	Example Quote
DT	State the problem; identify criteria and constraints; brainstorm multiple solutions; iterate, select the best solution; consider design aspects; prototype the solution; communicate. [32]	We will focus on the batter's perspective and calculate the exact time, position, and technique that should hit the ball in order to get the best outcome. We will explore the specific question: what are the optimal conditions for a baseball player to hit a home run.
PC	Identify related physics terms, concepts, or principles; cause and effect; system and surroundings; scale; change and rate of change. [33]	The physics concept was Newton's II law. We used that so that we'll know the constant speed over time which means there will be no acceleration.
MC	Mention a formula, equation, or a mathematical concept; refer to a scientific statement in terms of a relation among several variables and constants; proportional reasoning; units analysis; use of explicit equations.	One of the math concepts for this lab was relabeling x and y coordinate vectors or having them in a different position. This is like linear algebra where we are rearranging coordinate vectors as basis vectors.
MR	Reflect on their design and science ideas and progression towards the solution [34].	In our first iteration attempt to solve this problem, we did during lab 11 but this problem did not have... we had too many variables which we didn't know and it made it too hard to solve this problem.

C. Opportunities for Design Thinking

Almost all teams clearly articulated their problem statements within their conversations. Fig.3 captures a portion of the conversation from Team-X. In addition to identifying clients and stakeholders, providing metrics, and integrating physics ideas, this team adeptly kept the problem simple, yet authentic. Most teams, in contrast, opted for far more complex problem statements, which potentially created challenges in their progress towards a solution [43, 44]. The student-generated ED task (ED2) created a direct opportunity for students to engage in problem framing, an important aspect of Engineering Design (ED) thinking [45].

FIG. 3: Example for an ED2 problem statement.

> We are the toy catapult group, and we are being commissioned by Dunkins toy chest. We are creating a safe and fun toy catapult for this toy company to make a better and safe toy for their product line. They have given us a few specifications including that the toy catapult must not launch a projectile above 6 feet so that the toy catapult could be used indoors. Also they have given they will be using a spring with a given spring constant. We need to ensure that this toy is safe and fun and is able to launch a soft small beanbag projectile of a weight of 0.04 kg."

D. Few Mathematical Constructs deployed

Mathematical Constructs (MC) had the lowest overall representation in both tasks, consistent with an earlier study [15]. Despite prompts for discussing mathematical ideas, teams often used lengthy, occasionally repetitive sentences for scientific concepts, with only a few employing mathematics for concise, detailed statements.

E. Interplay of Physics and Mathematics

There were significantly more instances of teams weaving together mathematics (MC) and physics concepts (PC) in ED2 than in ED1. Team-Y, which had identical code frequencies for ED and PC in both tasks, states: "One of the main concepts for this design was the momentum update which is final momentum = initial momentum + Fnet x delta t. And we used this to calculate the momentum of the AGV by finding the load and net force and the time it takes to reach the other side of the map." In ED2, working on YoYo design, the same team states: "we can find the angular acceleration using the angular momentum principle. We are going to use the relation that torque = I x alpha and torque = r x F ...then we're going to use the fact that the angular acceleration = torque / I. That will give us the angular acceleration and the angular velocity of the YoYo which tells us how fast the YoYo is moving and how fast it is speeding up." The team employs a mix of formal mathematical reasoning coupled with conceptual observation, despite the constraints in 'talking' mathematics and not putting it down in writing. We believe this merits a more detailed and layered analysis [46].

From the ways teams used math and physics, one wonders if there is any difference at all between the two. Our findings reinforce the view that physicists not only use math in doing physics, but also use physics in doing math [47].

F. Design Thinking complements Science Thinking

All teams had several textual units coded for both DT and PC, highlighting how students intertwined design aspects and physics concepts. For example, in ED1, Team W states: "We also needed to figure out friction so that we'd be able to slow down the vehicle so that the boxes would not go flying off and because the boxes are not necessarily stuck to the AGV." Similarly, in ED2, Team-XX states: "we additionally solved for the height that the axe could reach at a range of different angles of projection in the approximate range where the user would throw the axe... We used the velocity found earlier after the throw to find these values and provide the client with the range of possible angles that the axe could be thrown at. With the height and range values calculated we were able to come up with the recommendations for our client."

G. Design Science gap - opposite trends

Almost all teams coded higher on physics concepts (PC) in the student-generated task (ED2) compared to the instructor-assigned task (ED1). Many teams discussed physics concepts in greater detail in ED2. Surprisingly, the use of physics concepts (PC) was more frequent than design thinking (DT) in the student-generated tasks (ED2). Studies on 'design-science gap' [48–51] reveal that students tend to adopt 'trial and error' approaches, or 'gadgeteer' [52] their way to a solution without making detailed use of science and math concepts. While studies [48–50] show that design thinking tends to dominate science thinking, in the student-generated tasks (ED2), intriguingly, we saw a reversal of this trend.

V. SUMMARY & CONCLUSION

Despite being limited to ED-based laboratory tasks, we posit that this study can further the discourse on developing and operationalizing 'WoT' frameworks [13], particularly in integrated STEM contexts, potentially moving towards 'converting the classroom into a community of inquiry' [44].

In our analysis, we often debated if science, engineering, and technology are indeed distinct. Owen [53] views "Design thinking as a complement to science thinking." To muddy the debate further, Radder [54], in his thought-provoking philosophical essay states that the differences "will be a matter of degree and that they do not add up to an unambiguous contrast between science and technology."

The lack of mathematical constructs in both types of ED challenges is concerning. Though one may acknowledge the difficulty and apparent unnaturalness of incorporating mathematical equations in discussions, students must be "encouraged to discuss and explain the mathematics which they are doing" [55]. The view: "Learning science means learning to talk science" [22, 56] would certainly be applicable to mathematics so as to foster diverse ways of thinking. Given the view that all our thinking, including mathematical thinking, is essentially discursive [57], educators need to look strategies that encourage students to actively deploy mathematical thinking while solving ill-defined problems [58].

We did not observe significant differences in students' metacognitive reflections (MR) between the two tasks. Given that effective use of metacognitive strategies can enhance learning [59], we speculate that the nature of the prompts may have influenced the outcomes.

In summary, we find notable qualitative differences in students' ways of thinking in the two tasks. Specifically, in the second engineering design task (ED2), students not only exhibited a higher frequency of physics concepts but also demonstrated a more intricate integration of physics and mathematics. Intriguingly, we find a reversal of the 'design-science gap' in the student-generated task (ED2), in that the use of physics concepts (PC) is more prevalent than design thinking (DT). It probably suggests that the open-ended nature of the student-generated task (ED2) fostered a greater discussion of the underlying physics concepts. Our findings merit further investigation.

VI. LIMITATIONS & FUTURE WORK

While group discussions are rich sources of 'in-the-moment' thinking, they often lack the depth and cogency of thought found in written work. Also, large enrollment courses, overseen by multiple TAs with varying styles, introduce uncontrollable variables. Our analysis does not delve into the variations in thinking among individual group members, nor does it account for group dynamics – another hidden variable. Any differences that we find between the instructor-assigned (ED1) and student-generated (ED2) tasks could be partly due to the fact that ED2 occurred later in the semester. Our findings are specific to the instructor-assigned task which may influence student motivation and engagement. The 14 groups of students selected for the study may not be representative of the entire student population. Further, our findings are dependent on how student-groups may interpret the term 'free-flowing' in the prompts. Similarly, definitions of 'science', 'technology', and 'engineering' continue to be debated [54]. Moreover, the ways of thinking presented here are not mutually exclusive. Human learning is a complex, continuous process occurring through our interactions with the world, influenced by our prior knowledge, and ongoing reflection [20, 60].

While students used Python for coding, our study reveals nothing about their coding skills. Future research will analyze students' written reports for insights into their mathematical thinking and Python coding skills, addressing Computational Thinking as a fifth dimension to WoT. [11, 61].

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ChatGPT-3.5 was employed only to 'wordsmith' passages, but not for any analysis. Thanks to Dr. Amogh Sirnoorkar for his insights on qualitative analysis. This work is supported in part by U.S. National Science Foundation grant DUE-2021389. Opinions expressed are of the authors and not of the Foundation.

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