

Characterizing the ‘design-science gap’ in an engineering design-based laboratory unit in an introductory physics course for future engineers

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It is essential to equip the next generation STEM workforce with skills that are crucial to solve real-world problems. The success of this preparation rests largely on the instructional innovations in science classrooms for postsecondary students. Reform documents and research suggest that integrating engineering design (ED) experiences add value to science courses. In this study we explore the ways in which students in an introductory physics course developed a solution to a prescribed real-world problem. By carefully analyzing students' lab reports, we attempted to gain an understanding into the design science connection in their solution. We coded for five aspects to gain insights into the effectiveness of the scaffolds we had provided to guide the students through the task. Results of this study have implications on how to provide appropriate scaffolds, particularly in ED based tasks to maximize science learning.

I. INTRODUCTION

In preparation towards STEM careers, students need to develop strong understanding of scientific and mathematical principles; think creatively, reflect and iterate on their ideas; and process information from a variety of sources [1, 2-5, 6]. One way to achieve these goals is by integrating science concepts and engineering design (ED) through real-world problems [5, 7]. Design challenges lend a motivating context for students to learn and apply science concepts. The iterative process of working through a design challenge provides students opportunities to learn new concepts, evaluate their approach and revise their thinking [8]. However, students often apply trial and error and other heuristics to solve a design challenge that does not necessitate the learning of science, resulting in what is called the “design-science gap” [9].

The goal of this study is to operationalize the ‘design science gap’ in an introductory undergraduate physics course for future engineers. Though there may not be a unique way of characterizing the design-science gap, we develop a procedure to gain insights into the depths to which students are able to apply physics concepts to their design. Our study explores the extent to which students use principles of physics in their ED challenge. Our research question (RQ) is:

RQ. With what level of completion and correctness do students apply physics concepts to their ED challenge? What evidence, if any, do we find for a design-science gap?

This study is a preliminary investigation to understand the design-science gap in a calculus-based mechanics course at the undergraduate level.

The results of our study have implications for educators to appropriately scaffold science learning through engineering design.

II. LITERATURE REVIEW

Research has shown that integration of engineering into learning science can provide an authentic context for understanding and application of science [10]. However, students do not necessarily rigorously apply science concepts while solving an ED problem [11, 12]. Despite pedagogical innovations aimed to integrate ED and science learning, students often have difficulties in connecting their design challenge with the underlying science [13]. It is incumbent on educators to bridge this design-science gap. One way this can be achieved is by designing activities with appropriate scaffolds, and pedagogical strategies [14].

In this context it may be worthwhile to consider if science and engineering are indeed different. Radder [15] is of the view that any attempt to define and differentiate science and engineering would be debatable since science and engineering have as much similarities as differences.

Meaningful differences between science and engineering are not in terms of their practices (e.g., asking questions, observing, experimenting) but more in terms of their purpose and motives [10]. For the data analysis of this study, we will adhere to the framework provided by the Next Generation Science Standards (NGSS) [6]. Even here it may be noted that NGSS emphasizes the difference between science and engineering in only two of its eight practices.

III. CONTEXT OF STUDY

This study is situated in a large-enrollment, first-semester, calculus-based undergraduate physics course at a large U.S. Midwestern land-grant university. A significant reform in this course over the last two years has been integrating ED into the laboratory component of the course. This course has an annual enrollment of about 2500 students, of which about 85% are engineering majors and the remaining are science majors. Engineering majors are concurrently enrolled in a first-year engineering course focused on ED, which creates a unified engineering design experience for these students spanning multiple courses. Non-engineering majors are provided tutorials on ED prior to starting the ED challenge.

The course adopts the principle-based approach [16] such that the content is 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. The laboratory segment had 13 sessions, encompassing three multiweek ED challenges.

In weeks 6 through 10, student groups worked on an ED challenge focused on the energy principle. In week 6 they engaged in problem scoping and solution generation. In weeks 7 - 9 they completed inquiry-based activities, which were related to the ED challenge, by using hands-on equipment, *VPython* code and *PhET* simulations to help build conceptual and computational models for (i) launching a payload along an inclined ramp using a spring-loaded device (week 7), (ii) dropping a coffee filter or firing a projectile under the influence of air drag (week 8), and (iii) bouncing a falling object off a hard surface with a certain coefficient of restitution (week 9). Each week, groups were asked to revisit the ED challenge and audio record their group discussions on ideas for solving the ED challenge. This study is based on the final lab report the students submitted in week 10.

A. Participants

The participants were 27 student groups of three students each, enrolled in the two laboratory sections for which the

first author was the teaching assistant (TA). The lab groups were formed based on the CATME (www.CATME.org) Team-Maker Survey [17] given to the students at the beginning of the semester. There was no statistically significant difference between the average performance on exams of these groups and the overall class performance.

In this study, we analyzed students' final (week 10) report in response to a prescribed engineering design (ED) challenge problem. Though students worked in groups, they individually submitted weekly lab reports. One lab report per group was randomly selected and qualitatively analyzed for this study. We investigated the design approaches students adopted, to what detail they were able to justify their design decisions, the science connections they made to the lab activities which were partly intended as scaffolds, how well they were able to justify the assumptions and approximations in their design solutions, and whether they were able to identify the limitations in their solution. This analysis would address the overarching question: To what extent did students appropriately use physics concepts and principles in the solutions of their ED challenge?

B. Engineering design challenge

Seven essential ED characteristics [18] guided the development of our challenge. Students worked in teams to first identify the overall context of the problem and then generated possible ideas or solutions using what they knew about the problem as well as using relevant physics knowledge. The teams created and tested their plan, recorded results, and used their current scientific knowledge to explain their design. They shared their ideas and gathered feedback from other teams and the graduate teaching assistant (GTA) and used this information to revise, improve, and retest their original model. Professional development was provided to GTAs to facilitate the design challenge in the lab.

Although the ED challenge was situated in the laboratory component of the course, it was not confined to the lab alone. 'Expansive framing' was used to integrate and scaffold it with other learning experiences in the course [19]. In the lecture, the instructor asked students to reflect on how physics concepts presented therein might be relevant to the ED challenge. The weekly recitation problems that students solved tied into the ED challenge. In lab, to facilitate integration of science in ED, we modified the ED cycle [20] by taking a 'detour' into inquiry-based lab experiences using hands-on equipment and *VPython* to investigate the science concepts and reflect how these concepts apply to the ED challenge [21].

The ED challenge problem [21] presented to the students read as follows: "Pristine natural habitats of endangered species such as the gorillas in the Congo River basin are becoming increasingly rare. Today, these habitats and the endangered species that inhabit them need to be not only protected but even sustained by humans. As a member of a

team of engineers volunteering for a non-profit organization, you are asked to design a system that can launch a payload of food to an island in the Congo River and land it safely for the gorillas. Each payload is about 50 kg, and it must be delivered to a habitat area located on an island in the Congo River that is about 150 m away from the riverbank. To avoid contributing to global warming, the client wants you to use a means that would minimize the carbon footprint of the delivery. Furthermore, the client also wants to ensure that the habitat remains pristine, so that neither humans nor a robotic machine must disturb the flora and fauna of the habitat while delivering the food".

IV. METHODS

A. Data collection

Our main data source was the students' lab reports submitted in week 10, after completion of the ED challenge. We specifically examined students' responses to four tasks (1 – 4) below.

Task 1. From the previous labs, what are the solutions (or iterations of the solution) you have explored?

Task 2. Based on the solutions/iterations you have, what would your final solution be? Describe in words the ideas you are using from any of the previous labs and how you would combine them into this final solution.

Task 3. Present your final design in a diagram/sketch. Provide a labeled sketch to better explain all possible aspects (physics and engineering design) of your final solution.

Task 4. What are some of the limitations of your final design? Think about possible physics related limitations of your design. Additionally, explore possible limitations that are not related to the physics concepts.

B. Data analysis

Student responses to Tasks 1-4 were qualitatively coded through several rounds of open coding by the first author. Five inter-related themes emerged from our analysis: *Physics Concepts* (PC), *Design Solution* (DS), *Making Assumptions and Approximations* (AA), *Recognizing Limitations* (RL), and engaging in *Iterative Thinking* (IT).

We coded for each of these dimensions on four levels of performance. Additionally, five of the 27 reports were independently coded by another trained rater for inter-rater reliability (IRR). Codes were compared and reviewed by the raters until a consensus was reached. The first author re-coded the remaining transcripts post the IRR test. The levels of performance for each dimension are described below.

Design Solution (DS): Levels of performance of the design solutions as shown in Table I. We also separately categorized the type of solution to the challenge.

TABLE I. *Design Solution (DS)* levels

Level	Description
Level 0	No meaningful detail of solution provided
Level 1	Detail about <i>what</i> material is used
Level 2	Detail about <i>how</i> the material is used
Level 3	Justification about <i>why</i> the material is used

Here is an example for a Level 3 DS response. The solution approach has details on what materials are used, how and why, along with a justification.

“The final solution involves a payload sitting on a ramp. The payload would be launched using a spring. The properties of the ramp, spring would be used to calculate its initial velocity and the maximum height it would reach. Once the payload reaches maximum height, a parachute will launch to increase its drag force. The payload will fall onto the sand bar located at the shore of the river on the other side, contributing to a lower coefficient of restitution and making the payload bounce less. Landing on the shore would also not affect the wildlife in the area.”

Iterative Thinking (IT): Students were asked to iterate their design based on the hands-on tasks and simulations that they worked on in the lab, which in turn was related to new concepts and problems addressed in the lecture and recitation. Levels of performance (Table II) were based on the extent to which the design iterations made connections to the lab experiences each week.

TABLE II. *Iterative Thinking (IT)* levels

Level	Description
Level 0	No evidence of any iterations
Level 1	Iterations, <i>no</i> connection to labs experiences
Level 2	Iterations, <i>some</i> connection to lab experiences
Level 3	Iterations <i>justified</i> based on lab experiences

Recognizing Limitations (RL): The goal was for students to progress toward the design solution by applying relevant physics concepts. In the process, it was important that students were aware of the limitations of both the design and physics. Levels of performance shown in Table III were used to rate the design limitations.

TABLE III. *Recognizing Limitations (RL)* levels

Level	Description
Level 0	No meaningful limitations described
Level 1	At least one related to <i>design</i> , none for physics
Level 2	At least one related to <i>physics</i> , none for design
Level 3	At least one related to <i>physics</i> , one to <i>design</i>

Assumptions and Approximations (AA): We emphasized to students that real-world problems are complex and encouraged them to simplify the problem by making appropriate assumptions and approximations. Levels of performance shown in Table IV were used to rate the identification of assumptions and approximations.

TABLE IV. *Assumptions & Approximations (AA)* levels

Level	Description
Level 0	None stated
Level 1	Vaguely stated with no justifications
Level 2	Clearly stated: incorrect, vague justifications
Level 3	Clearly stated: correct, detailed justifications

Physics Concepts (PC): We expected students to invoke at least the linear momentum and energy principles in their design in some form. Spring force, energy conservation, projectile motion, drag force, collisions and coefficient of restitution are a few of the concepts we expected them to apply. The levels of performance are shown in Table V.

TABLE V. *Physics Concepts (PC)* levels

Level	Description
Level 0	None stated
Level 1	Identified but unclear, significant errors
Level 2	Clearly identified, some detail, minor errors
Level 3	Clearly stated: correct, detailed justifications

Here is an example for a Level 1 response for PC. A set of physics concepts has been merely listed or identified.

“Spring force, momentum principle, energy principle, air drag, collision”.

V. RESULTS & DISCUSSION

To find answers to our research question we conducted a quantitative analysis of the code frequencies which emerged from the qualitative analysis of students’ written work. In particular, to gather evidence for any design-science gap, a McNemar’s Chi-square test was performed to examine the relation between the Design Solution (DS) and the Physics Concepts (PC) used. The test showed a statistically significant difference ($p = .013$, 2-sided) between the proportions of students who scored high (Level 2 or 3) in DS compared to PS, providing evidence of the design-science gap.

The prevalence of the five emergent themes is shown in Fig. 1.

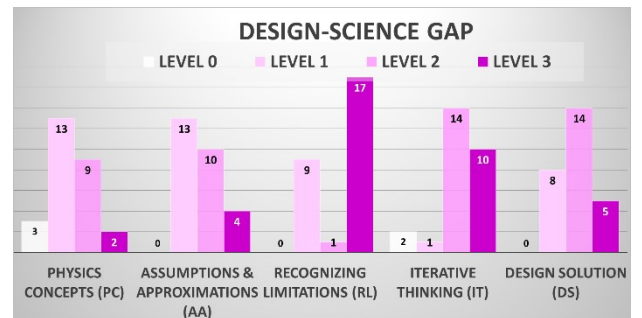


FIG. 1. Performance level on emergent themes in the ED tasks.

The design-science gap is evident in that a larger fraction of groups (19 of 27) scored at the higher performance level (Level 2 or 3) for the *Design Solution (DS)*, compared to a smaller fraction of the groups (11 of 27) for the *Physics*

Concepts (PC). A comparison of the codes bears out some interesting trends highlighting the design-science gap, in that a high score for *design solution* (DS) does not correlate with a high score for *physics concepts* (PC). This could be due to the nature of the scaffolds provided. In Task 1 we only asked the students to ‘list’ the science concepts related to their design. If we had rather asked students to ‘elaborate and explain’ how the physics concepts would apply to the design, we believe the scores would have shifted to higher levels for PC. This reinforces the importance of structuring our instructional scaffolds well. The data also shows that a high score on the *physics concepts* (PC), in most cases, leads to a strong *design solution* (DS), but the converse is not true, which is consistent with literature [6, 15].

A large fraction of the groups (24 of 27) scored at a higher level (2 or 3) for the aspect of *Iterative Thinking* (IT). This is expected as students were specifically asked to iterate after each lab. Further, a higher score on *Iterative Thinking* (IT), by the nature of the scaffolds, seems to yield a higher score on the *design solution* (DS). Although the iterations were regarding their design, it appears that the students were motivated by the new physics concepts they may have learned from the labs.

Only about half the groups (14 of 27) scored at a higher level (2 or 3) *assumptions/approximations* (AA). This is interesting because assumptions and approximations are highlighted in the Recitation aspect of the course. It appears that students were unable to expansively frame their experiences in the Recitation to the design challenge in the laboratory. The levels on *assumptions/approximations* (AA) are more closely aligned with level of *physics concepts* (PC) than the level of the *design solution* (DS).

A large proportion of groups did well in *recognizing limitations* (RL) with a significant number (17 of 27) citing both physics and design limitations. Consequently, a high score on *recognizing limitations* (RL) seems to overlap with a high score on both *physics concepts* (PC) and the *design solution* (DS).

Finally, only two of the 27 groups scored a maximum (Level 3) on all aspects, by providing highly detailed ED descriptions and by applying physics concepts. These two groups also drew connections to the *VPython* and *PhET* simulations, making it clear that they made the best use of the scaffolds provided.

VI. LIMITATIONS

Though all students submitted their reports, we selected only one report per group. This study does not delve into the variations one may expect within a single group. We believe some students did not quite understand what was exactly expected out of them while responding to the prompts. It is natural that different students interpret terms differently. For example, there is not a unique way in which the terms ‘assumptions’, ‘approximations’ and ‘limitations’ may be interpreted. Presenting the students with a glossary of terms

with specific and clear descriptions of the terms involved in the prompts would have helped to elicit more concrete responses. We had asked the students to ‘list’ the various science concepts they may invoke for their design. If we had asked them to ‘explain and elaborate’ instead of merely listing the concepts, we could have obtained a more detailed response from the students. Finally, as much as an understanding of physics concepts is important for a superior design solution, so are mathematics and computing skills. The design solutions presented by our students may have been richer had scaffolds been provided for these aspects.

The results of our study are specific to the given ED challenge. They may vary if a different ED challenge had been provided, or if students were allowed to choose their own ED challenge.

VII. CONCLUSIONS AND IMPLICATIONS

We explored the design-science gap in the context of a multi-week laboratory ED challenge in a first-semester calculus-based physics course. As may be evident, this study is based on only the written reports submitted by the students at the end of the multi-week ED challenge. We are currently working on expanding on this preliminary investigation by analyzing the students’ work in all the weeks of the ED challenge.

We found that while students mostly closely followed the scaffolds provided through the accompanying lab activities each week in inventing a solution to the design challenge, a significant fraction pursued alternative design strategies. This indicates that providing students with scaffolds that may suggest a particular design solution does not necessarily limit their ingenuity in coming up with their own design solution. In addition, we found mixed results on the extent to which students apply their physics concepts to the ED solution. Students who scored highly on the physics concept aspect of their design task also scored highly on their design solution, but not vice-versa, showing evidence of a design-science gap in that the evidence of an effective design solution does not imply a sound knowledge of the underlying physics.

In summary, this study has revealed several interesting leads into students’ understanding of ED and physics. It appears that if students demonstrate an understanding of physics concepts in their design solution, their design is rich and detailed. However, the converse is not supported by the data: strong design solutions do not always reflect a strong grasp of science. It seems that the successful use of ED as a context to learn physics rests on providing students with appropriate scaffolds to integrate their learning of physics concepts into their ED challenge, so as to enhance the design science connection.

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