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Abstract

In recent years, there has been a demand to teach engineering in high schools, particularly using a challenge-based curriculum. Many of these programs have the dual goals of teaching students the engineering design process (EDP), and teaching to deepen their understanding and ability to apply science and math concepts. Using both quantitative and qualitative methods, this study examines whether a high school design engineering program accomplishes each of the two goals. During the 2010–2011 school year, over 100 students enrolled in the same design engineering course in seven high schools. Evidence of learning and application of the EDP is accomplished by triangulating student interviews with pre-/post-tests of EDP-related questions and a survey of design engineering beliefs. To determine whether students could apply science and math concepts, we examined content test questions to see if students used science and math ideas to justify their engineering work, and triangulated these results with student interviews. The results are mixed, implying that although there is some learning, application is inconsistent.

Keywords: design-based instruction, challenge-based instruction, high school engineering, K-12 engineering, secondary engineering, design engineering, STEM concepts

Introduction

Recently, engineering education has shifted away from treating the science of engineering and engineering design as different domains and is starting to integrate them (Tate, Chandler, Fontenot, & Talkmitt, 2010). In fact, in a synthesis of the state of K-12 engineering education, the National Academy of Engineering and National Research Council (2009) concluded that students should both engage in engineering design and "incorporate important and developmentally appropriate mathematics, science, and technology knowledge and skills" (p. 5). In addition, we see a movement to address

these learning goals through Challenge-Based Instruction (CBI) (Klein & Harris, 2007; Krajcik, Czerniak, & Berger, 1999; National Academy of Engineering & National Research Council, 2009; Sadler, Coyle & Schwartz, 2000; Tate et al., 2010). The proposed study examines the combination of these goals asking what science/math and engineering content students learn in the context of a challenge-based approach to high school engineering.

Background

In the past two decades, engineering educators have used lessons learned in science education and the learning sciences to improve engineering courses at both the collegiate (Klein & Harris, 2007; Tate et al., 2010) and pre-collegiate (National Academy of Engineering & National Research Council, 2009) levels. Engineering modules that emerge out of this work typically employ a version of project-based learning (Krajcik et al., 1999), in which students are posed problems or challenges that motivate exploration of the desired engineering science content. In engineering education, this is often called challenge-based instruction (CBI). Synthesizing across this work, we have identified three different challenge types: problem-based, engineering-design, and STEM-design. Although these different approaches overlap significantly in practice, they place different emphases the various learning goals. For example, problem-based challenges foreground science and math learning goals over engineering, while engineering-design challenges emphasize engineering learning goals over science and math. As such, we find it instructive to consider the different possible foci for challenges when designing CBI courses.

Problem-Based Challenges

CBI that foregrounds science and math learning goals— "engineering science"—over engineering learning goals are often designed around challenging *problems* in which students are given large complex problems that can only be solved through the application of concepts they are learning in the course. Many of the CBI modules that came out of VaNTH's research and curriculum development endeavor (Cordray, Harris, & Klein, 2009; Klein & Harris, 2007; MartinRivale, & Diller., 2007) exemplify this approach. For example, Linsenmeier, Harris, and Olds (2002) challenged students to determine "how much food is needed by an astronaut per day for a two week space mission in order to satisfy metabolic demands and not gain or lose weight" (p. 213). In this case, students who learned the content in the context of the challenging problem were better able to apply the concepts to novel situations and were more engaged than students who received more traditional instruction and laboratory activities. More broadly, students in engineering classes that enact VaNTH's problem-based

challenges have been shown to develop standard content knowledge like students in more traditional engineering classes. However, the VaNTH students were better able to apply the content in innovative ways (Cordray et al., 2009).

Engineering-Design Challenges

CBI that emphasizes *engineering-design challenges*, in contrast, emphasize learning goals associated with the practices of engineering and have fewer explicit goals that address traditional math and science content. As such, these challenges focus on engaging students in the design work of engineers, and the science and math concepts that underlie the challenge are not the primary focus; students clearly must work with those concepts in order to complete a design challenge, but they are more focused on employing the engineering design process (EDP). This approach purports to teach "engineering design," to augment typical "engineering science" (Tate et al., 2010) curricula.

This emphasis on engineering design in either introductory or capstone courses is seen in numerous engineering programs across the country. Engineering Design and Communication, a freshman/sophomore course at Northwestern University, exemplifies this approach. In this two-term course, students learn core communication strategies, problem-solving approaches, and engineering processes through a series of design challenges that are increasingly student-driven (Hirsch, Schwom, Yarnoff, Anderson, Kelso, Olson, & Colgate, 2001). This strategy is seen in pre-collegiate education as well. For example, the popular high school engineering program *Project Lead the Way* (2011) begins with a course in which students learn and engage in an EDP.

STEM-Design Challenges

STEM-design challenges are the third design challenge type that emerges in this literature. These challenges engage students in engineering design—like the engineering-design challenges—but include an emphasis on science and math learning goals—like the problem-based challenges. As such, we call these challenges *STEM-design* challenges. In these contexts, successful design requires the purposeful application (and likely, learning) of engineering principles as well as relevant math and science concepts. For example, Wojcik, Clayton, Radinska, and Comolli (2011) argue for using short "impromptu" design challenges in traditional engineering science courses that can reinforce that content. At the pre-collegiate level, we also see this sort of integration between design challenges and science/math content goals in science courses (Burghardt & Hacker, 2004; Fortus, Dershimer, Krajcik, Marx, & Mamlok-Naaman, 2004; Kolodner, Crismond, Gray, Holbrook, & Puntambekar, 1998; Lachapelle and Cunningham, 2007; Sadler et al., 2000).

For example, Fortus et al. (2004) created a number of units in which students were engaged in "Design-based-science," such that the ability to design the target artifact required that they learn and apply the desired content.

This Study

There is an increasing call for students to engage in these types of STEM-design challenges in which they learn and apply math and science content while engaged in an engineering challenge (National Academy of Engineering & National Research Council, 2009; National Research Council, 2011). The current study adds to the growing body of research exploring the successes and challenges associated with integrating science, math, and engineering learning goals through STEM-design challenges (Burghardt & Hacker, 2004; Fortus, et al., 2004; Kolodner, et al., 1998; Lachapelle and Cunningham, 2007; Sadler et al., 2000). In particular, we explore student learning around engineering *and* more traditional science and math content. We had two primary research questions to focus our investigation of students' learning in the STEM-design approach to CBI:

- Are students learning the engineering practices?
- How are students learning to apply relevant math and science principles to their design work?

Methods

Participants

Students in this study were all enrolled in engineering courses that were implementing a pilot version of the UTeach*Engineering* created high school curriculum during the 2010–2011 school year. Over 100 high school students in nine engineering classes across seven schools participated. The schools spanned three districts in urban and suburban settings surrounding a major city in Texas and include both high and low socio-economic status populations. A summary of the demographics of each school is displayed in Table 1.

Project Curriculum

The first version of the UTeach *Engineering* created curriculum—*Engineer your World*—was a collaborative effort between University of Texas engineering faculty and high school teachers. The same teachers who helped write the curriculum also taught it during the 2010–2011 school year. The course is currently being revised to address challenges and successes that emerged through the pilot enactment.

This curriculum entails four units, each of which is centered around a STEM-design challenge.

- Energy unit: Students learned about various methods of energy generation and completed a project in which they designed, built, tested, and optimized blades for a wind turbine. Through this, students enacted all phases of an EDP developed by the project team and shown in Figure 1. This EDP was then used throughout the remaining units.
- Reverse Engineering unit: Using a common household product (e.g. hair dryer), students performed a needs analysis and wrote performance metrics. The students were asked to predict the inner workings of the product and then to compare their predication against a disassembled device. Requirements specification and product design were the focuses of this unit.
- Robotics unit: Students learned how to use LEGO MINDSTORMS™ to perform various tasks. Students started from basic physics and mechanical engineering concepts (e.g. torque, gear ratios) and progressed to using LABVIEW™ to program the microcontroller to activate sensors and motors.
- Final design project: Over several months, students worked on a group project that was largely student directed. Depending on the school, students either optimized a construction helmet to maximize impact protection or designed an emergency shelter.

These challenges were designed with the hope that students would learn the EDP, while learning and applying traditional math and science content. For example, in the

Table 1
Demographics of schools participating in study

School	District student population	School student population	School setting	Economically disadvantaged school population	Minority population of school	Number of students participating in study
A	~85,000	~2900	Urban	~15%	~46%	24
B		~1600		~65%	~83%	18
C		~1800		~43%	~58%	16
D		~800		~91%	~98%	10
E		~400		~90%	~99%	5
F	~45,000	~2500	Suburban	~37%	~65%	43
G	~5,000	~1200	Suburban	~7%	~17%	43

THE ENGINEERING DESIGN PROCESS

UNDERSTAND
the problem
problem identification
market analysis
customer needs analysis

QUANTIFY
the need
specifications
competitive benchmarking

ENGINEER
the concept
functional modeling
concept generation
concept selection

EMBODY
the concept
geometry, materials
manufacture
sw design

IMPLEMENT
the design
prototyping
testing

FINALIZE
the design
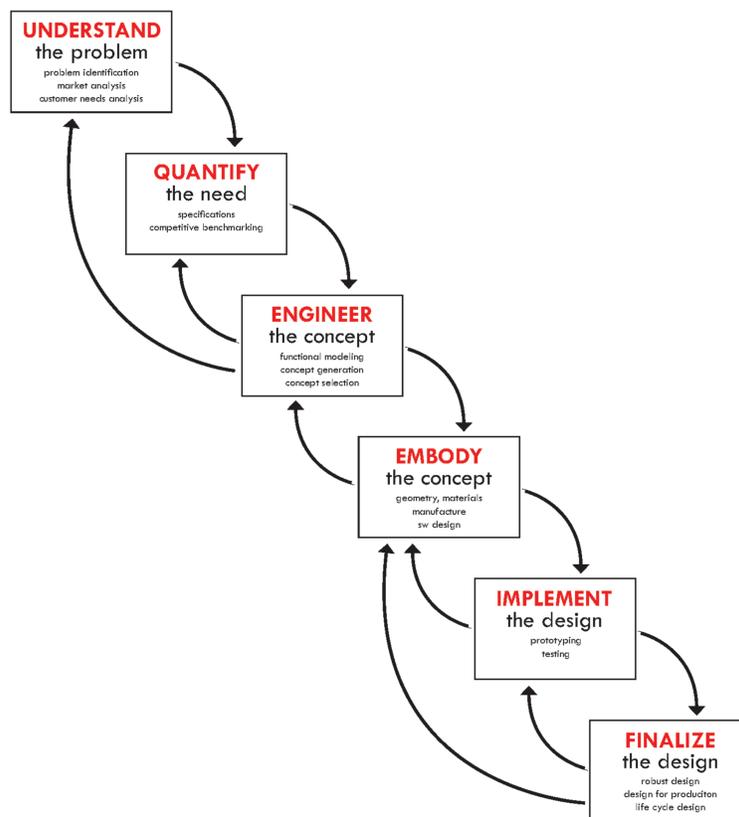robust design
design for production
life cycle design

Figure 1. The EDP used in the curriculum.

Energy unit, students explored energy transformations, whereas in the robotics unit they learned computational thinking.

Data Sources and Measures

We combined quantitative pre-/post-measures and semi-structured interviews to explore student learning of both engineering practices and relevant math and science content.

Quantitative Engineering Practices Measures

For our examination of student understanding of engineering practices, we focused on their use of the EDP. Two different pre- and post-measures had a twofold focus: The Design Survey and the Reverse Engineering test.

The Design Survey was designed by Mosborg, Adams, Kim, Atman, Turns, & Cardella (2005) to assess engineering design expertise and attitudes associated with this expertise. This measure consists of 27 Likert scale statements regarding student beliefs about engineering design. The scale ranges from strongly disagree to strongly agree on a 5-point scale. Given our particular research

focus on student understanding of the EDP, this study analyzed nine items that most directly pertain to that process (see Appendix A for complete list of the nine analyzed items). Sample items are outlined below.

- In design, one of the main questions that needs to be answered is "who will be using the product?"
- Design begins with figuring out what is needed and ends with a product or system in the hands of a user.
- Design is a goal-oriented, decision-making activity, with many requirements to meet.

The goal of this assessment was to explore whether an extended design experience would change students' beliefs about design and the EDP. As the "capstone" design project was scheduled to occupy the majority of the spring semester, we planned the pre-test to occur late in the fall semester and the post-test at the end of the spring semester. To minimize disruption in the classroom schedule, we needed to work with the teachers to find mutually agreeable times to give the tests. The result is that while all students in the same class were tested at the same time and point in the curriculum, there is some difference between classes. All students completed the pre-test in October–November and were either nearing the end of Unit 2 (Reverse Engineering) or had recently completed it. All students completed the post-test as they

were finishing the final design project in May. These testing periods fulfilled our goal of testing students before the final project started, and near the project's completion. One main limitation of our methodology is that students developed some familiarity with the EDP through their course work in the fall, prior to the first administration of this survey. To capture the entire learning process, we would have added an early fall administration of the Design Survey to the existing test periods in the late fall and late spring semesters.

The Reverse Engineering test was developed by the project team and consisted of four constructed-response items all focused on reverse engineering and improving of vending machines. The test was given immediately preceding and immediately following the second unit of the course. Questions 1, 2, and 3 focused on describing how the vending machines function and identifying possible innovations. Question 4, asked students to describe the process they would go through in order to decide "what sorts of improvements to make to the current design [of a vending machine]." We focus on the fourth test item for the current analysis because it designed to elicit student descriptions of two particular steps of the EDP: understanding a problem and quantifying a need. Two researchers scored each response to this question on a 0–2 point scale. Disagreements were discussed and consensus reached. Sample answers for each level are provided in Table 2.

Quantitative Measures of Math and Science Content

We used the pre- and post-measures from two of the units in the course—the Energy and Robotics units—to examine students' understanding of relevant math and science content. The Energy test consisted of two questions in which students were expected to apply what they learned from designing and testing a wind turbine to design a hydraulic turbine. As such, this test was designed to identify the science and math concepts that students found relevant to turbine design. The Energy test was given on the first and last days of the Energy unit.

One question asked students to speculate about how underwater turbine blades would differ from above-ground blades and to explain their hypotheses. Students were scored on a whether they explained how both the blade shape and blade length might be affected when the turbine was under water. For example, one student answered the question by stating:

"I would expect them [underwater and wind turbine blades] to be about the same because their [sic] both using something to spin the blades. I would expect the tidal turbine blades to be thicker because it needs to be more study to go through water."

In this response we see students not considering questions of blade length at all. They are, however, considering how the density of the water would affect the blade design. Another student stated:

"I would expect the tidal [underwater] turbine blades to be shorter, but much wider than wind turbine blades. These changes are because tides have a lot more force than winds do, so longer blades would be easily damage."

In this response, we see the student considering both length and shape, but only providing an explanation for why the length of the blades would need to change. In both of these cases, the students received partial credit: they were able to provide a scientifically based explanation for why one characteristic would change, but not the other.

The other item on this test asked students to identify factors that would affect the design of the underwater turbine. For example, students discussed environmental factors such as the speed and direction of the current, depth of the water, and presence of debris in the water.

The six-question Robotics test was designed to assess student understanding of programming terminology as well as their basic flow-charting abilities. The test items asked students to define and exemplify computer science and control engineering concepts such as the use of sensors, and open and closed loop systems. In addition, students were asked to construct a flow chart. We categorize this test as assessing math and science content knowledge because it examines student understanding of the computational literacy principles that were relevant to their robotics design.

Table 2

Exemplar student responses to test item: "How would you go about deciding what sorts of improvements to make to the current design [of vending machines]?

Score	Exemplar student responses
0	<Blank> or I don't know
	(off topic responses) "You would find ways to make it more convenient or harder to 'cheat,' and improve it.
1	"By doing research on the customers' likes/dislikes about it."
	"Surveys"
2	"I would calculate whether the cost of the changes would be worth the improvements."
	"Analyze what we currently have made and break down certain aspects that can be changed, and interview customers' opinions and behaviors.

Semi-Structured Interviews

In addition to the quantitative measures, we conducted 19 interviews to develop a deeper understanding of how students were thinking about the EDP and relevant math and science concepts. Students in six of the seven participating classes were interviewed—students in the seventh class were not interviewed owing to logistical constraints. We worked with classroom teachers to identify students to interview in each class. Teachers selected students based on their willingness, class work status (e.g., students that were behind on their work were unable to spend class time on interviews), and teacher expectation that students would engage with the interviewer rather than supplying minimal responses. Owing to time constraints and student preferences, we interviewed 2–5 students in each of the six classes. Seventeen of the interviews were conducted one-on-one, the remaining two included one interviewer and 2–3 interviewees. These pair interviews were conducted in response to student requests. (Note: In the group interviews, one student often dominated the conversation or all students would agree and co-construct a response. This made it near impossible to reliably attribute beliefs to individual students. As such, we collapsed across the students in the group interviews and reported patterns as emerging from the interview rather than an individual student.) All interviews lasted 10–30 minutes, depending on how talkative the student(s) was. The lead researcher on this study conducted the first interview to serve as a model for the rest of the interviews. Graduate students conducted the remaining interviews. Interviews were video recorded and transcribed.

The interviews were semi-structured: interviewers were given a set of topics on which to focus and sample questions. The expectation was that interviewers would engage in a conversation with the interviewee in which the interviewer worked to elicit student's thoughts about, among other things, the EDP they used and the relevance of math and science concepts for their engineering work. We consider the interviews a "negotiated text" (Fontana & Frey, 2003, p. 663) that was co-constructed through the conversation between the interviewer and interviewee(s).

The goal of our interview analysis was to describe student perceptions around the two types of learning goals upon which this study focuses (i.e., student understanding of the EDP, and student understanding and application of science and math concepts). The process began with identifying segments of each interview in which these two topics were discussed. In doing this, a segment was defined as the entire interviewer-interviewee exchange in which the topic was discussed in addition to any contextualizing discourse that supported the interpretation of that exchange (a segment typically ranged from 2 to 10 turns-of-talk). This process was fluid—a single utterance could speak to both topics and each topic could be addressed multiple times throughout the

interview. The lead author on this paper identified these interview segments by first focusing on places in which the interviewee was responding to a prompt designed to elicit their thoughts on a focal topic (i.e., flagging student responses to questions like "talk to me about the process you used to complete the wind turbine challenge"). This captured the majority of the segments that related to our research questions. Additional segments were identified through a close read of the remaining discussion to find segments in which focal topics (i.e., EDP and use of science and math concepts) were mentioned in other contexts.

Once the topic segments were identified, a researcher summarized the ideas being expressed in each one. All summaries within a single topic were then compared in order to identify the central ideas that emerged across the interviews. Interview sections were then analyzed a third time to apply those emergent codes. Each segment could have multiple codes applied to it. The same code was only applied once in a single segment because our goal was to identify whether students discussed specific ideas, not the frequency with which they did so. These codes were used to identify patterns in the student understandings of the EDP and science and math content. Although variation across individual students clearly exists, analyses of the interviews reveal general trends. We report these trends in the following sections. All patterns were discussed with the graduate students that conducted the interviews to ensure consistency with their interpretations and understandings. This process is consistent with grounded theory data analysis (Charmaz, 2003) methodologies that emphasize the use of open coding and iteration.

Findings

Our findings are organized around the two areas on which this work focuses: (1) students' understandings of the EDP and (2) students' identification and application of relevant math and science principles in their design work. For each, we discuss the pre-/post-test results as well as relevant interview responses.

Understandings of Engineering Design Process

Design Survey Results

We analyzed the nine items from the Mosborg et al. Design Survey (2005) that reflected beliefs about the nature of EDP using a repeated measures Analysis of Variance (RM-ANOVA) with one within subjects factor: time (pre-test, post-test). There were 106 students from the seven classes that responded to both the pre- and post-survey. Overall, student beliefs about design did not change from the pre- to post-administration of the survey (pre-survey: $M = 4.00$, $SD = 0.45$; post-survey: $M = 4.03$, $SD = 0.47$); there was no significant main effect of time, $F(1, 105) = 0.36$, $MSE = 0.18$, $p = 0.55$. This lack of change is not surprising

given already high scores found during the first administration of the survey. Moreover, given that students were engaged in design work before the administration of the pre-survey, it is difficult to ascertain whether students entered the course with these sophisticated beliefs about the EDP or these beliefs developed through their participation in the early units of the course. Regardless of the source, it is clear that, by the conclusion of the course, students' beliefs about the EDP aligned with those of professional engineers.

Reverse Engineering Content Test Results

Seventy-six students from across the seven participating classes were present during the administration of both the pre- and post-administration of the Reverse Engineering test. For the purpose of this study, we chose to analyze only the fourth question on the test—the one asking students *how* they would decide how to redesign a vending machine—because it was most closely related to EDP. With a sample size of $N = 76$, we performed a RM-ANOVA with one within-subjects factor: time (pre-test, the post-test). The test scores exhibited an insignificant increase from pre- to the post-test, $F (1, 75) = 2.36$, $MSE = 0.23$, $p = 0.13$. Unlike the high student performance on the Likert survey, their scores on this item were generally low: pre-test ($M = 0.71$, $SD = 0.59$), the post-test ($M = 0.83$, $SD = 0.66$).

The survey results and the students' responses to the Reverse Engineering item reveal that the students had a general sense of how engineers work. For example, they know that engineers attend to user needs and work to meet design requirements. However, they did not seem to develop deeper understandings of *how* to do those sorts of things (in this case, we saw that the students did not develop understandings of how to identify users or how to investigate user needs).

Interview Results

Students exhibited understandings of the EDP most often when responding to questions such as:

- Can you tell me about the process you went through to solve the wind turbine challenge?
- Did the different challenges relate to one another at all?

Sixteen of the 19 interviewed students discussed the EDP: Of those, students in 13 interviews discussed the EDP when describing their work on the wind turbine challenge. Eight of the 13 described it in general terms that abstracted across multiple STEM-design challenges and five students discussed it in both contexts. The three students that did not discuss the EDP responded to question prompts such as those above by discussing specific activities in which they engaged (i.e., cutting cardboard, figuring out what to measure) without abstracting their work to discuss a process. As such, it was quite difficult to determine what

these 3 students understood about the EDP, either as it was applied to their wind turbine challenge or how it worked more generally.

The 16 students that discussed the EDP all emphasized the general processes of designing, building, and testing. For example, in response to the interviewer's prompt: "Is there a general design process, you think?", Anthony stated (Student names changed to protect anonymity):

"And we just like come up with an idea first, you know, and then see if it'll work out. Then we do it and just test it. And that would be it pretty much."

Similarly, when discussing his work on the wind turbine challenge, specifically, Dylan stated:

"we were just getting started and we didn't know what to expect in class. So, we were just like, you know, when were thinking about designing the [wind turbine] blades, which was most of it, because the gear ratio and all that was obvious. You just use the biggest gear. We figured that out pretty easily. I don't know. It was just a lot of trial and error, and you'd see some blades that you'd think would work, not work, and some other blades that you really didn't expect to work worked well…"

In this response, it appears that Dylan found the final stages of the challenge work in which he and his group engaged in trial-and-error in order to construct a functional wind turbine the most compelling aspect of the EDP.

Across these interviews we see that the students never offered the standardized EDP that was taught in the curriculum (see Figure 1). Instead, they used everyday language to describe the most actionable steps of their work (i.e., they rarely discuss "describing the need" or "characterizing the system"—steps that have little in the way of a product and instead focused on designing, testing and building).

Looking across the different measures of their understandings of the EDP, reveals a consistent picture: In all three measures we see that the students have a solid sense of what engineers do (i.e., identify user needs, design, test, build and iterate), but that they lack details (i.e., the need to model the system they are designing, ways to identify potential users or stakeholders, or how the importance of communication).

Application of Math and Science Concepts

Energy Unit Test Results

Students designed a model wind turbine during the Energy unit. The unit test asked students to apply concepts from a wind turbine design to the design of a hydrolic turbine (an underwater tidal turbine). Seventy-one students completed both the pre- and the post-test for the Energy unit. For this study, we wanted to know if students evidenced an increase in their application of math and science knowledge over the course of the Energy unit. To that end, we focused on two test items. In one item,

students were asked to apply their knowledge of above ground turbines to identify factors that would affect the design of underwater turbines. The other item prompted students to sketch their ideas regarding the blades of an underwater tidal turbine, specifically addressing how the length and shape of the blades would compare with that of wind turbine blades.

Across the pre- and post-tests, students typically named the following as factors that would affect design: placement in the water, speed of the water current, existence of debris in the water, need to access and repair the turbine, density of water, etc. We graded responses on a scale of 0 to 4 based on the number of relevant factors students listed (0 = no factors, 1 = 1 factor, 2 = 2 factors, 3 = 3 factors, 4 = 4 or more factors).

The other test item analyzed for this study focused on whether students identified and explained how two turbine characteristics—blade length and blade shape—would be affected by the change in environment (i.e., from land to water). We rated students' answers on a scale from 0 to 4 for each of these parts on both the pre-test and the post-test. The average scores and standard errors for the number of design factors listed and the blade length and blade shape prompts from pre- to post-test may be found below in Table 3.

As each of the three questions on the Energy test were graded on a 0–4 scale, a 12 was the highest possible score a student could obtain. The means and standard errors for the students' test scores are listed in Table 3. We analyzed the Energy unit test using a RM-ANOVA with one within-subjects factor: time (pre-test, the post-test). The test scores showed a significant increase from pre-test to post-test, $F (1, 70) = 22.54$, $MSE = 5.00$, $p = 0.00$. Across these items, students improved in their identification of relevant design factors and their use of these factors when thinking about designing turbine blades. As such, we see these students improving in their application of the relevant science concepts over the course of the unit.

Robotics Content Test Results

Ninety-eight students took the Robotics test at both pre- and post-administrations. We analyzed the tests using a RM-ANOVA with one within-subjects factor: time (pre-test, post-test). Students exhibited significant improvement in their scores, $F (1, 97) = 37.27$, $MSE = 0.18$, $p = 0.00$. This increase suggests that the students developed deeper understandings of these fundamental computer science principles through their work on the Robotics challenge.

Across the two pre-/post-measures of relevant content knowledge examined in this study, we see an increase in performance: students were generally better able to identify and apply the relevant math, science and programming knowledge on the post-test than on the pre-test.

Interview Results

The interview was designed to explore student learning and application of the relevant math and science content further. To that end, students in all interviews were asked to describe instances in which they remembered using math and science while engaged in their designs. In addition, we asked them to describe how their team resolved disagreements about their designs. In both instances, we encouraged students to describe particular instances in their group's work together. Students answered these questions using examples from the Energy and Reverse Engineering units most frequently.

As would be predicted by the pre-/post-measures, the interviewed students consistently portrayed the math and science concepts that directly related to their design work as relevant and important. However, a detailed examination complicates this general finding. In particular, while students frequently identified relevant math and science principles, when asked to describe specific instances in which they used those ideas, many students answered in vague ways, suggesting that they did not remember doing so. In addition, some students described engaging in math or science activities (i.e., collecting data or performing calculations) but not using the results. And, when specifically asked how they resolved disagreements, the students reported a reliance on the underlying math and science as well as other factors, such as social relationships. Each of these responses suggests that, while students recognized the importance of the math and science

Table 3
Energy unit test scores means and standard errors

		Pre-test	Post-test
Factors affecting design of underwater vs. above ground turbines (0–4 points)			
	M	1.23	1.59
	SE	0.12	0.13
Effect of environment change on turbine blade length (0–4 points)			
	M	2.90	3.52
	SE	0.16	0.11
Effect of environment change on turbine blade shape (0–4 points)			
	M	2.06	2.85
	SE	0.17	0.14
Total Score (0–12 points)			
	M	6.18	8.00
	SE	0.32	0.27

concepts, they did not consistently apply those concepts to their work. We exemplify all of these responses in this section before discussing their implications for whether and how these units supported student learning and their application of the relevant math and science.

When discussing the wind turbine challenge, students in 14 of the 19 interviews describe vague connections between their work on the challenge and the math and science. For example, in response to the question: "did you use some math and science to describe what you were doing or predict what might happen?" Michael stated:

> *"Yea, I…we had a lot of science-y stuff. …like I remember designing my version, the dimensions and shape had to get the drag, to minimize drag and everything."*

Throughout these 14 responses, we saw students referencing some of the topics that emerged in the post-test described above. In particular, students mentioned the importance of radius in their interviews, which relates to their stated concern that the blade lengths not exceed the height of the stand, or depth of the water. These interview responses suggest that students were aware of the math and science concepts that were relevant to their engineering work, but it is unclear how much they used these concepts when making design decisions.

When asked how they reconciled disagreements, students in 16 of the 19 interviews reported relying on information other than the relevant math and science. Instead, they discussed topics like their intuition, wanting to reflect the real world, and logic. For example, when asked how she and her partner resolved disagreements, Isabel stated that:

> *"When he [my partner] wanted to just use the basic square blades, I said, 'It's not going to work, it's not going to work.' He was like, 'Well, I'm getting too frustrated with the other ones.' And I was like, 'Ok, well, whatever.'"*

In this case, it is clear that Isabel and her partner based their blade design on creating something that was simple to make (i.e., "basic square blade"), and personal persuasiveness. That is, although Isabel did not agree with her partner, she followed his lead without clearly ascertaining whether his ideas were more scientifically accurate.

However, earlier in the interview, Isabel has reported using the science information in teacher-provided packets to figure out how to "cut [the turbine blades] if we want more drag or less drag." This statement suggests that Isabel and her partner based their designs on principles of aerodynamics. However, she is vague leaving open the possibility that these students simply copied designs rather than internalized information to construct their own

designs. As such, we see that Isabel recognized the relevance of the science concepts—or the principles for affecting drag—but it appears that she did not consistently apply them to her design work. In fact, students both discussed the relevance of particular math and science concepts and identified non-science/math criteria in their decision making process in 12 of the 19 interviews, suggesting a tension or ambivalence regarding the role of this content, on the part of the students.

Jacob provides an additional example of this tension between recognizing the relevance of the math and science concepts while describing design decision making processes that do not apply those concepts. In Jacob's case, he recognized that it was important for him to do mathematical calculations when designing his wind turbine, but he rarely did this work. Instead, Jacob relied on his partner to determine the specific dimensions needed to construct his idea:

> *"When it comes to engineering in this class, I'm not really too big on finding out like the math stuff of what we need to do. I mainly come up with the main design idea. And then it actually worked out perfectly with Andrew, because I came up with the design idea of what we should do, what type of blade design we should use, and then he did the math, found out what size it had to be, and then I built it."*

Isabel and Jacob exemplify the trend found throughout these interviews (recall, we see a similar pattern in 12 of the 19 interviews): while students recognize that their engineering work should build upon scientific principles and/or mathematical calculations, they report rarely using it in their own work. Instead, they mention other criteria such as reliance on a classmate (as seen in Isabel and Jacob's respective quotes). In addition, students explicitly discussed basing their designs on a process of trial-and-error in eight of the 19 interviews. For example, when explaining how he resolved disagreements with his group, Christopher stated:

> *"Usually it was just trial and error. See who's right. Friendly like, 'Okay, I bet you that this one will work this time.' It was like, 'No, I'm pretty sure it's going to work this way.' So, we'd try it one way. If the first way works, then fine, that person wins."*

In addition to emphasizing trial and error, in seven of the 19 interviews, students explicitly stated that they did not use the calculations they performed, science concepts the class discussed, or data that they collected. Instead, they would engage in that prototypical math or science work and then turn to their designs, without connecting the two. For example, Daniel stated:

> *"We figured out how much like one rotation was for energy, whatever, that we could do with our thing. And*

we ended up getting like some big numbers, but we never got close to them.”

In this case, it appears that Daniel calculated the power that his wind turbine should have produced and found that calculation to be unrelated to the actual output. In the interview, Daniel gives the impression that he did not attempt to resolve or explain this discrepancy and, instead, simply accepted it.

Jason similarly stated that the mathematical model he did of the wind turbine was unrelated to the output produced by the turbine he built in class. In this case, Jason explains this in terms of limitations of the materials:

“It [constructing the mathematical model] wasn’t really like building it [the wind turbine]. It was just mathematics…I think the theoretical one [the mathematical model] was just to see how much energy you could produce if you had your own, like, actual commercial-size wind turbine. And the one with the—what we did in front of the fan, that was just testing the blade designs to see which blade design was better for getting the most energy out of it.”

As seen here, Jason appears to recognize that the science concepts and mathematical calculations were related to the theories of wind turbines but possibly not relevant to his own design work.

Even though this tension is apparent in the majority of interviews, students explicitly mention instances in which their design decisions were based on science concepts and/or mathematical calculations in 8 of the 19 interviews. For example, Wes stated that:

“We did some research on the types of fan blades that were effective by measuring the pitch and the way the blades were shaped. And so we came up with a design that we believed to be effective to meet the end of getting rid of draft and—reducing the draft, I mean, and causing more spin and more friction between the motors.”

Moreover, in six of the eight interviews in which students reported basing decisions on science and math concepts, they also responded to other questions by reporting instances in which they based their decisions on other criteria such as the persuasiveness of a peer, trial-and-error, or logic. As such, these six students reportedly used the math and science concepts at some points in their design process and not others. This duplicity is sensible and parallels professional practice: There are instances in which it is most prudent and effective to base a design on the underlying math and science concepts and others in which alternative criteria are most relevant.

Combining the pre-/post-tests and the interviews suggests that students learned which math and science concepts were relevant to design challenges. In addition, the Robotics test provides clear evidence that they developed a deeper understanding of these concepts through their design work. However, we see mixed results with respect to the frequency with which students applied their understanding of the relevant math and science concepts. In the case of the Energy post-test we see students improved their application of science ideas to considering the design of turbines and, in the interviews, we see that students reported using math and science ideas *sometimes* but often relied on other considerations such as trial-and-error or social pressures. We explore the implications of these mixed results in the discussion section.

Discussion and Implications

Throughout these interviews and quantitative measures, we see mixed results with respect to student learning of engineering practices (as reflected in the EDP) and relevant math and science content. In the former case, it appears that the students left the class with a general sense of the work of an engineer; however these understandings lacked detail. With respect to the learning and use of content knowledge, we see that students increased in their understanding of the ideas that were relevant to the various challenges, but that they inconsistently applied these ideas to their own work.

Combining across the measures of student understandings of the EDP and science and math content suggests a relationship. When discussing the EDP, students emphasized the trial-and-error aspects of design while rarely mentioning steps related to modeling, quantifying, or evaluating the system. However, it is these missing steps that deeply rely on application of math and science. That is, whereas it is often possible to “gadgeteer” a design solution by engaging in trial and error, this does not necessitate that students apply the math and science. In contrast, developing a mathematical model of the system, predicting how a design will perform, explaining what does and does not work, etc. do require that application.

In fact, this idea that different stages of the design process differentially necessitate an application of math and science concepts is apparent in the interviews in which about one-third of the interviewed students reported basing their decisions on both math and science concepts *and* alternative criteria (i.e., trial-and-error, persuasiveness of a peer, etc.), at different points in the interview. This finding suggests that the relevance of the math and science concepts shifts depending on where the students are in the design process.

The possibility that different phases of the EDP will elicit different decision-making criteria—and different reliance on math and science concepts—offers guidance to engineering educators. In particular, while we set out to integrate math and science concepts into engineering challenges, it is important to recognize that the math and

science concepts will be differentially relevant at various points in the process. This is something the students in this study recognized and something that is true throughout professional practice. Moreover, this study suggests that the students did not develop a solid understanding the steps of the EDP that make the math and science most relevant, such as the characterizing/modeling the system step.

Consequently, if we expect students to engage in authentic engineering design processes, in which they are applying relevant math and science concepts, we must: (1) develop activities that motivate and explain the value of the more mathematical and scientific steps of the EDP and (2) reinforce the desired math and science concepts when they are relevant, but teach alternative decision-making processes and criteria for when they are not. For example, educators might support the application of math and science principles as students are evaluating initial concepts—modeling the system and selecting a design to build. Then, as students move to testing their designs and are taking in data, it might be largely unrealistic to expect them to return to those underlying math and science concepts. Instead, educators might support students in making sense of the incoming data to optimize their results. Finally, as students communicate their final decisions and explain what worked, they might be supported in returning to the underlying math and science concepts as a way of explaining those results. Future work should explore these hypotheses examining whether students perceive math and science concepts as differentially helpful at the various points in the EDP and, if so, how that can be best exploited.

Limitations

As an exploratory analysis of pilot curriculum, this study has a number of potential limitations. For example, all four quantitative measures (the Design Survey, Reverse-Engineering test, Robotics test and Energy test) used relatively few items to gain insight into students' understandings. Interview-based research carries with it concerns regarding the influence of the interviewer on the participant responses (e.g., Russ, Lee, & Sherin, 2012) and researcher bias when analyzing qualitative data. Finally, as with much classroom-based research, this study was dependent on teachers enacting the expected curriculum and on students being present and willing to participate in the tests and interviews. Therefore, there are concerns with missing data and self-selection biases. As discussed throughout the paper, we worked on mitigating these limitations through carefully implemented analysis procedures.

A strength of this work rests in our ability to triangulate—to compare patterns across multiple data sources. This triangulation addresses the limitations discussed above as it demonstrates consistency in the findings. For example, the quantitative analyses reveal that students' understandings of engineering practices lacked

depth at the conclusion of this course. While one might question individual ways in which these quantitative measures were administered or analyzed, the interview analysis bolsters the reliability of this finding. In particular, interviews revealed students consistently simplifying the engineering design process by emphasizing the active steps (i.e., testing and building) over the analytical steps (i.e., identifying users or modeling the system). Similarly, the triangulation of quantitative and qualitative data converges on a single pattern regarding student learning of math and science content: participation in this course appeared to support students in identifying math and science concepts that were relevant to their design work, but students did not consistently apply these ideas. The triangulation across the qualitative and quantitative data sources presents a robust picture of student learning in a high school STEM-design challenge-based engineering course.

Acknowledgments

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Appendix A
Mosborg et al. (2005) Design Survey Items Used in Analysis

The Mosborg survey consists of 27 items designed to elicit student beliefs about the nature of engineering design writ large. Students took the entire survey. However, given the research focus on student understanding of the engineering design process, this particular study analyzed only the following nine items that most directly pertain to the EDP. Items were answered on a scale of A (strongly disagree) to E (strongly agree).

1. Good designers get it right the first time (Item 1 was reverse-coded in the analysis to maintain consistency with the other items.).
3. In design, one of the main questions that needs to be answered is "Who will be using the product?"
5. Engineering design is the process of creating a system, component or process to fulfill a need.
7. Design begins with the figuring out what is needed and ends with a product or system in the hands of a user.
16. Often, the designer will suggest different solutions in order to better understand the problem.
18. Design is a goal-oriented, decision-making activity, with many requirements to meet.
25. Designers use drawings, diagrams, and models to help generate ideas and create form.
26. Information is central to designing.
27. A key part of design is iteration.