AC 2012-4182: STUDENT RESPONSES TO CHALLENGE-BASED ENGINEERING CURRICULA

Dr. Leema Kuhn Berland, University of Texas, Austin

Leema Berland is an Assistant Professor of science education at the University of Texas, Austin. She earned a Ph.D. in the learning sciences from Northwestern University in 2008 and was a Doctoral Fellow with the NSF funded Center for Curriculum Materials in Science (2003-2008). Berland is broadly interested in facilitating and studying students as they engage in complex communication practices. She is currently focused on exploring the dynamics of how and why students are able (or unable) to productively communicate in engineering classrooms, in the context of UTeachEngineering high school classrooms.

Mr. William F. McKenna, University of Texas, Austin

Bill McKenna received his master's of mathematics from the University of North Texas about 10 years ago, and, after a brief career in acoustical test enclosures, he is working towards a doctorate in science, technology, engineering, and mathematics education. McKenna's current research focuses on high school engineering students. In this work, he strives to connect student participation in authentic discourse practices, student understandings of the content under study and the process of effective communication, and the products they are designing. He is also pursuing the relationships between professional engineering practices and the ecology of high school engineering classrooms.

Student Responses to Challenge-Based Engineering Curricula

Engineering educators are increasingly calling for a challenge-based approach to engineering education at both the pre-collegiate and collegiate levels. This work is simultaneously calling for students to apply and deepen their understandings of fundamental STEM concepts as well as the engineering design practices. The proposed study examines the combination of these goals asking whether and how students perceive STEM concepts and engineering design practices as fundamental to their fulfillment of design challenges.

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[7, 15] and pre-collegiate [13] levels. Engineering modules that emerge out of this work typically employ a version of project-based learning [9] in which students are posed problems or challenges that motivate exploration of the desired engineering science content. In engineering education, this is typically called Challenge-Based instruction (CBI). Across this work we see three different sorts of challenges: Problem, Design, and STEM-Design.

In CBI that focuses on challenging *problems* students are given large complex problems that can be solved by applying the desired content. Many of the modules that came out of VaNTH's research and curriculum development endeavor[3, 7, 12] exemplify this approach. For example, Linsenmeir et al. [11], 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 that learned the content in the context of the challenging problem were better able to apply the concepts to novel situations and more engaged than those students that received more traditional instruction and laboratory activities. More broadly, students in classes that enact VaNTH's engineering modules that contextualize student work within challenging problems have been shown to develop greater adaptive expertise than do students in more traditional engineering classes [3].

CBI that emphasizes *design-challenges*, in contrast, engage students in the design work of engineers, without explicit attention to science and math concepts that may underlie this work. This approach purports to teach "engineering design," to augment typical "engineering science" [15] curricula. Engineering Design and Communication, a freshman/sophomore course at Northwestern University, exemplifies this approach. In this 2-term course, students learn core communication strategies, problem-solving approaches, and engineering processes, through a series of design challenges that are increasingly student-driven[6]. This emphasis on engineering design in either an introductory or capstone courses is seen in numerous engineering programs across the country. In addition, this strategy is seen in pre-collegiate education as well. For example, the popular high school engineering program *Project Lead the Way*[14] begins with a course in which students learn and engage in the engineering design process.

Recently engineering education has gradually shifted away from treating the science of engineering and engineering design as different domains and, instead, to integrate them[15]. In fact, in a synthesis of the state if K-12 engineering education, the National Research Council[13] concluded that students should both engage in engineering design and "incorporate important and developmentally appropriate mathematics, science, and technology knowledge and skills" (p. 5). Possibly as a result of this shift, a third form of challenge has emerged: one we are calling *STEM-design* challenges, because successful design requires the purposeful application of engineering principles and relevant math and science concepts. These challenges differ from the *design*-challenges in emphasis: in design challenges the goal is explicitly for students to engage in engineering practices and more traditional science and math content is not an apparent learning goal. In contrast, STEM-design challenges explicitly support both engineering and math/science learning goals. For example, Wojcik et al. [17] argue for using short "impromptu" design challenges in traditional engineering science courses that can reinforce that content. At the pre-collegiate level we see this sort of integration between design challenges and science/math content goals in science courses[1,5,8,16]. For example, Fortus et al.[5], 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.

As the majority of these pre-collegiate STEM-design challenges are done in the context of science courses, the engineering practices have not been emphasized in research or instruction. *Engineering is Elementary* offers an exception to this trend, demonstrating that their engineering units effectively teach both engineering practices and scientific content[10]. The current study adds to this growing body of research exploring the successes and challenges associated with integrating science, math and engineering learning goals through STEM-design challenges. In particular, the study examines which STEM goals—particular science or math content, and engineering skills—the students found most useful in their work on the design challenges.

Methods

We conducted interviews with 2-5 high-school students (mostly juniors and seniors) in each of 6 classes in a mid-sized city in the southwest. Variation in number of interviewees in each class emerged out of logistical constraints and student preferences. We conducted a total of 19 interviews (2 of which included multiple students[a]) across the 6 classes.

Each class was enacting a pilot engineering curriculum developed in collaboration with a local university. The curriculum was designed around STEM-design challenges such that each 6-weeks (or so) the students were given a new challenge. For example, students were asked to design a model wind turbine using KidWind™ materials, and create a Lego Mindstorms™ robot to accomplish a particular task. Throughout each of these challenges students were learning and applying traditional science and math content. For example, in the wind turbine challenge students explored energy transformations, while the robotics unit was expected to support computational thinking. In addition, the curriculum explicitly taught students to use an engineering design process created by the curriculum development team. This design process included the steps: understand the problem; quantify the need; engineering the concept; embody the concept; implement the design; and finalize the design.

Throughout the units, students generally engaged in student-directed collaborative work on the challenges with occasional direct instruction regarding particular engineering processes,

---

[a] The two group interviews we conducted to accommodate students that were unwilling to be interviewed individually.

mathematical equations or scientific concepts they needed to apply. However, variation in implementation existed across the 6 interviewed classes. Teacher practice ranged from classes in which the teacher led every step of the students' work to more "student discovery" situations. Moreover, within any individual class, the pedagogical practices varied from challenge to challenge; this variation might have been in response to the teacher's familiarity with the content associated with each challenge. Given the within teacher variation and small sample size, we look across students and classes to identify patterns and, as such, we do not work to account for student variation in student responses to the interview in terms of the teacher differences.

The interviews were semi-structured: interviewers were given a set of themes on which to focus and sample questions. The expectation was that interviewers would engage in a conversation with the interviewee in which they worked to elicit student's thoughts about 5 focal themes. As a result, we consider the interviews a "negotiated text"[4] (p. 663) that was co-constructed through the conversation of the interviewer and interviewee(s). For the purpose of this paper, we focus on 2 thematic categories, including:

1. What is the student's understanding of the engineering design process?
2. What STEM concepts did the student perceive as useful for their engineering work?

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. 17 of the interviews were conducted one-on-one, 2 included 1 interviewer and 2-3 interviewees[b]. All interviews lasted 10-30 minutes, depending on how talkative the student(s) was. Interviews were video recorded and transcribed.

The goal of our analysis of these interviews was to describe student perceptions around the 2 themes (i.e., student understanding of the engineering design process; and student perception of the utility of science and math concepts). Thus, we engaged in a grounded theory data analysis[2] of the interviews. The process began with identifying sections of each interview in which the 2 themes were discussed. In doing this, a section was defined as the entire interviewer-interviewee exchange in which the theme was discussed, in addition to any contextualizing discourse that supported the analytical interpretation of that exchange. This process was fluid—a single utterance could speak to both themes and each theme could be addressed multiple times throughout the interview.

Once the broad sections were identified, the researcher summarized the ideas being expressed in each section. All summaries within a single theme were then compared in order to identify codes. Interview sections were then analyzed a third time to apply those emergent codes. These codes were used to identify patterns in the student perceptions of the engineering design process and the utility of science and math content.

---

[b] 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.

Findings

While variation across individual students clearly exists, analyses of the interviews reveal general trends in the students' understandings of the engineering design process, and their perceptions of the relevance and utility of traditional science and math concepts. We report these trends below.

Understandings of Engineering Design Process

The engineering design process (EDP) was discussed in 16 of the 19 interviews. Students in 13 interviews discussed the EDP when describing their work on the wind turbine challenge—a specific STEM-design challenge the students had recently completed—and 8 described it in general terms that abstracted across multiple STEM-design challenges (5 students discussed it in both contexts). Both contexts reveal that the students 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[c] stated

> 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 engineering design process that was taught in the curriculum when asked about their own processes. 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).

Application of Math and Science Concepts

Students discuss the relevance and utility of math and science concepts in all 19 interviews. Across these interviews, we see students consistently portraying the math and science concepts that directly related to their design work as relevant and important. In fact, when discussing the wind turbine challenge, students in 14 of the 19 interviews mentioned topics such as energy, drag, aerodynamics, radius. However, when asked how they made design decisions, students in 16 of the 19 interviews reported relying on information other than the relevant math and science. Instead, they discussed things like their intuition, wanting to reflect the real world, and logic. 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.

---

[c] Student names changed to protect anonymity.

For example, Isabel reports using the 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 she and her partner based their designs on principles of aerodynamics, but the degree to which Isabel and her partner simply copied designs rather than internalizing information to construct their own designs is unclear. Later, 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, while Isabel did not agree with her partner, she followed his lead. As such, we see that Isabel recognized the relevance of the science concepts—or the principles for affecting drag—but did not consistently apply them to her design work.

Jacob provides an additional example of this tension. In Jacob's case, he recognized that it was important 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 8 of these 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 7 of the 19 interviews, students explicitly state 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 he got. 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 states 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.

In this case, it appears that Jason recognized that the science concepts and mathematical calculations were related to the theories of wind turbines but possibly not relevant to his design work.

Even with 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 6 of these 8 interviews in which students reported basing decisions on science and math concepts, they also (in response to other questions) reported basing their decisions on other criteria such as the persuasiveness of a peer, trial-and-error, or logic. As such, these 6 students apparently used the math and science concepts at some point in their design process and not others. We explore the implications of this duplicity in the discussion section.

Discussion and Implications

Looking across these interviews reveals that students recognized the utility of relevant math and science concepts in the abstract (i.e., students in 16 of the 19 interviews identified relevant concepts). Moreover, when discussing their design process, it appears that students based *some* of their decisions on math and science concepts and others on alternative criteria such as trial-and-error, logical constraints, and the persuasiveness of their collaborators.

We see an emphasis on trial-and-error both in the students' discussions of the EDP in which designing, building, and testing emerged as the three most prevalent design steps—leaving out steps that create room for math and science concepts more explicitly such as characterizing the system. In addition, we see this when the students report performing math calculations or learning science concepts but not applying that information to their designs, as well as when they discuss making decisions using trial-and-error.

However in almost half of the interviews, students described situations in which the math and/or science concepts played a prominent role in their decision-making. In addition, in 6 of those interviews (about one-third of all of the interviews), 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 offers an alternative interpretation to the tensions seen throughout these interviews: it isn't that there is a tension between the theoretical relevance of the math and science concepts to their designs—it is that the relevance shifts depending on where they are in the design process. For example, it might be that students used the science and math concepts to construct initial design ideas and to explain results, but trial-and-error when physically building their products.

The possibility that students were basing their decisions on different criteria depending on the particular question and/or phase in the design process suggests a level of sophistication in their decision-making—they are able to shift between various criteria as the context demands it. In addition, it 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. As such, if we expect students to engage in authentic engineering design processes, we must 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—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.

References

1. Burghardt, M. D., & Hacker, M. (2004). Informed design: A contemporary approach to design pedagogy as the core process in technology. *Technology Teacher*, *64*(1), 6-8.
2. Charmaz, K. (2003). Grounded theory: objectivist and constructivist methods. In N. K. Denzin & Y. S. Lincoln (Eds.), *Strategies of qualitative inquiry, 2nd edition* (pp. 249-291). Thousand Oaks, CA: Sage Publications.
3. Cordray, D. S., Harris, T. R., & Klein, S. (2009). A Research Synthesis of the Effectiveness, Replicability, and Generality of the VaNTH Challenge-based Instructional Modules in Bioengineering. *Journal of Engineering Education*, *98*(4), 335-348.
4. Fontana, A., & Frey, J. H. (2003). Interviewing: The art of science. In N. K. Denzin & Y. S. Lincoln (Eds.), *Handbook of Qualitative Research* (pp. 361-376). Thousand Oaks, CA: Sage Publications.

5. Fortus, D., Dershimer, R. C., Krajcik, J., Marx, R. W., & Mamlok-Naaman, R. (2004). Design-Based Science and Student Learning. *Journal of Research in Science Teaching*, *41*(10), 1081-1110.
6. Hirsch, P. L., Shwom, B. L., Yarnoff, C., Anderson, J. C., Kelso, D. M., Olson, G. B., & Colgate, J. E. (2001). Engineering Design and Communication:The Case for InterdisciplinaryCollaboration. *International Journal of Engineering Education*, *17*(4), 342-348.
7. Klein, S. S., & Harris, A. H. (2007). A User's Guide to the Legacy Cycle. *Journal of Education and Human Development*, *1*(1).
8. Kolodner, J. L., Crismond, D., Gray, J., Holbrook, J., & Puntambekar, S. (1998). Learning by design from theory to practice. In A. A. Bruckman, M. Guzdial, J. L. Kolodner, & A. Ram (Eds.), *International Conference of the Learning Sciences 1998* (pp. 16-22). Association for the Advancement of Computing Education.
9. Krajcik, J. S., Czerniak, C. M., & Berger, C. (1999). *Teaching Children Science: A Project-Based Approach*. McGraw Hill College Press.
10. Lachapelle, C. P., & Cunningham, C. M. (2007) *Engineering is Elementary: Children's changing understandings of science and engineering*. Paper presented at ASEE.
11. Linsenmeier, R. A., Harris, T. R., & Olds, S. A. (2002). The VaNTH Bioengineering Curriculum Project, *3*, 2644-2645 vol.3.
12. Martin, T., Rivale, S. D., & Diller, K. R. (2007). Comparison of student learning in challenge-based and traditional instruction in biomedical engineering. *Annals of Biomedical Engineering*, *35*(8), 1312-1323.
13. National Academy of Engineering of, & National Research Council (2009). *Engineering in K-12 Education: Understanding the Status and Improving the Prospects*. (L. Katehi & M. Feder, Eds.). Washington DC: National Academies Press.
14. Project Lead the Way http://www.pltw.org/our-programs/high-school-engineering-program
15. Tate, D., Chandler, J., Fontenot, A. D., & Talkmitt, S. (2010). Matching pedagogical intent with engineering design process models for precollege education. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, *24*, 379-395.
16. TERC. (2000). Construct-A-Glove. Cambridge, MA: NSTA Press.
17. Wojcik, T. G., Clayton, G. M., Radinska, A., & Comolli, N. K. (2011). The Promise of Impromptu Design Exercisesas a Pedagogical Tool in Engineering Design Education. *118th Annual ASEE Annual Conference*. Vancouver, Canada.