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Noticing, Assessing, and Responding to Students' Engineering: Exploring a Responsive Teaching Approach to Engineering Design

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Abstract

This research paper examines formative assessment in engineering design, unpacking the disciplinary substance that instructors must attend to in their teaching. Borrowing the framework of *responsive teaching* from the math and science education literature, we argue for the importance of closely examining the many moment-to-moment assessments and decisions that engineering teachers encounter. Responsive teaching is an instructional approach in which instructors base their pedagogical moves on what their students are saying and doing. Instead of predetermining what will happen in classrooms, teachers elicit students' ideas, interpret and assess disciplinary aspects of students' reasoning, and respond with pedagogical decisions based on their interpretations.

Responsive teaching has the potential to be a particularly useful approach for teaching engineering design: As students adapt to new criteria and constraints when solving ill-defined engineering design problems, teachers need to be responsive to their changing needs. However, most of the work on responsive teaching has occurred in math and science education.

In this paper, we follow in the tradition of math and science education researchers who use their own teaching episodes as the basis for scholarly research on responsive teaching. Using microanalytic analysis, we examined two video-recorded cases from our engineering teaching at both the elementary and university level to explore how different yet equally legitimate disciplinary goals can conflict with each other and produce "instructional tensions" for the teacher. We used purposeful sampling to select cases rich in opportunities to unpack student thinking in engineering. We present in-depth analyses of the tensions that emerged between different disciplinary goals in these STEM learning environments. These results point to the need for increased attention on how teachers manage the different disciplinary practices and goals in STEM activities, particularly when incorporating formative assessment strategies or adopting a responsive teaching approach.

Introduction

There is widespread agreement among educators and researchers that assessment should be an ongoing, integral part of teaching and learning [1,2]. Formative assessment provides feedback to teachers about where students are in their learning so that they can make decisions about what to do next. As opposed to assessments that occur at the end of an activity or unit, formative assessment occurs alongside and within classroom activities. These assessments can be "formal," such as when a teacher poses potential test questions during a unit, or, "informal," in which teachers elicit and examine students' thinking within class discussions and ongoing work [3]. This latter approach emphasizes formative assessment as a *process* [4]: teachers gain insight into how and what their students are thinking, which can inform their instruction. Much of the focus on formative assessment has been on teacher strategies and techniques, such as providing wait time and questioning. These strategies cut across disciplines, providing concrete tools for teachers to use in their classrooms. However, Coffey et al. challenge that formative assessment is not about what teachers do, but what they see [5]: "The point is teachers' *awareness and understanding* of the students' understandings and progress; that's what the strategies are for" (p. 1128). In this view, formative assessment is fundamentally about attention to the disciplinary substance of students' understandings and ways of participating in class.

In this paper, we explore what this "disciplinary substance" is in engineering design and discuss challenges instructors may face assessing and responding to their students' work. First, we review and synthesize the research literature to point out different aspects of students' engineering design that the community has proposed as targets of instruction. Second, to explore these aspects in context, we analyze two cases from our own teaching. We investigate the nature of the multiple, often competing goals that engineering instructors need to balance. We then consider possible moves we could make in response to these assessments, connecting to work on responsive teaching in math and science. One case takes place with fourth graders in an elementary classroom, the other with university students in a graduate-level teacher education program. We conclude by advocating for increased attention to and study of the in-the-moment tensions and decisions engineering instructors face, even in well-designed tasks and learning environments.

Disciplinary substance in engineering design

While formative assessment has not been an explicit focus in engineering education research, there has been extensive work that articulates disciplinary targets of instruction. Most notably, there is extensive literature comparing novices' and experts' designing behaviors [6, 7, 8]. Other work examines students' understandings of the content of engineering [9, 10] or specific concepts in mathematics and science that have high leverage in engineering design and analysis [11, 12]. More recently, ethnographic and case-study based work has emphasized the need for instructors consider students' perspectives in engineering—such as how they are interpreting tasks and course structures [13, 14] or how they develop identities within engineering [15, 16].

In what follows, we draw on this work to sketch three areas of focus for instructors: students' conceptual ideas; students' engagement in design practices, processes, and discourse; and students' perspectives within and about engineering.

Students' ideas within engineering

A small body of literature documents students' conceptions about how things work. For example, Piaget asked children to draw a bicycle and explain their thinking about "what makes it go" [17]. More recently, researchers in pre-college technology and engineering education have explored elementary students' ideas about the properties that make structures strong, stable, and thermally insulated [18, 19, 20], and about the causal relationships in simple mechanical devices [9, 21]. These kinds of conceptions about the functionality of technological artifacts form one important basis for students' ideas in engineering design, and national assessment efforts in technological and engineering literacy [22] suggest these conceptions should be considered for formative assessment.

More extensive recent work, however, examines the scientific and mathematical ideas that students draw on and develop within engineering learning contexts. The Learning by Design (LbD) middle-school curriculum study looked for student reasoning about a wide range of scientific phenomena as they collaboratively solved weeks-long design challenges [23]. An elementary school curriculum development study based on the LbD framework similarly examined elementary students' science ideas as they designed and tested musical instruments, model houses, people-movers, and robotic animal models [24]. Curriculum efficacy studies of the *Engineering Is Elementary* program also look for students to make progress in science content knowledge [25]. Earlier work featured in-depth case studies of scientific sense-making in design contexts, such as Roth's investigation of fourth and fifth graders' reasoning about mechanical advantage as they created lifting machines and Penner et al's study of reasoning about force and motion in an elementary school biomechanics design project [26, 27].

At the college level, engineering education researchers have argued for instructors to pay close attention to students' conceptual knowledge in areas that are fundamental, yet surprisingly challenging for college student reasoning, such as relationships between basic quantities in mechanics (motions, forces) and the thermal sciences (heat, energy, temperature) [10]. Research programs at the college level have also called for greater attention to engineering students' mathematical models of engineering scenarios. Carefully designed "model-eliciting activities" have been recommended as opportunities to assess and strengthen students' capacities for mathematical modeling in the context of engineering design or analysis [28]. Versions of model-eliciting activities have also been explored at the K-12 level as an approach to drawing out mathematical thinking during robotics engineering tasks [29].

Synthesizing these areas of study, we argue that one area of formative assessment involves instructors attending to and assessing their students' *ideas* within engineering.

Design practices, discourses, and processes

By documenting patterns in how novices and experts differ in their approach to engineering design problems, the research literature on design processes and practices promotes productive areas for instructors' attention. Because design is a social process influenced by many cues from the local context, different engineering designers with similar expertise may approach the same design problem in a variety of ways [30]. Yet looking at the design practice literature as a whole, we see that engineers increasingly make well-informed design decisions at all stages of their design processes as they gain more experience [6, 7, 31, 32]. Crismond and Adams' meta-analysis of informed designer practices confirms this conclusion [8].

Research on the discourse practices of engineering designers reveals that there are also discipline-specific ways in which engineers interact and communicate with each other [33]. Engineers on design teams must continuously negotiate uncertainty between team members, competing design criteria and constraints, and alternative analyses of design scenarios [34, 35, 36]. They rely on multiple modes of external representation to instantiate design ideas and analytical results [37, 38, 39]. Furthermore, they must learn strategies for making decision decisions as a team [40]. Engineers in both industry and academia have called for college engineering programs to provide more intentional instruction in teamwork processes [41].

Taken as a whole, this body of literature centers on students' *processes* of engineering design. This represents another important area for instructors' assessment: how are students talking and acting in ways that reflect expert design practice and support their engineering.

Students' perspectives within and about engineering design

A third line of research in engineering education explores students' perspectives within and about learning engineering design. Some of this research examines student perspectives based on evidence gathered *in situ* as students work on engineering design tasks. Researchers draw on the notion of framing [42, 43, 44] and emphasize the importance of examining how students interpret and coordinate different perspectives of the design tasks [13, 14, 45]. For example, McCormick's recent work emphasizes the importance of students' interpreting design tasks in classrooms to consider how the design will be used, how to meet classroom expectations, and how to manufacture a prototype [13]. Other researchers in this area gather evidence from interviews, surveys, and other sources outside of design tasks themselves to characterize what it means for students to see (or not see) themselves or peers as taking on an engineering identity [15, 46, 47]. One recommendation is for engineering educators to adopt a "three-dimensional" view of engineering learning that involves not only "disciplinary knowledge" (of ideas and processes) but also "identification" and "navigation" [16].

We connect these different research strands to highlight the need for teachers' attention to their students' *perspectives* within and about engineering.

Tensions in assessing students' engineering

If formative assessment is fundamentally about attention to the disciplinary substance of students' understandings and ways of participating, then we argue that in teaching engineering design, formative assessment must focus on these three areas - ideas, processes, and perspectives. However, this involves complex and dynamic attention by instructors to what their students are thinking and doing. Instructors may find that what they need to do to support student progress in one area has the potential to interfere with progress in another area. In this way responding to the disciplinary substance of students' engineering design work can be filled with dilemmas. Instructors have to grapple with different objectives that arise, often in-the-moment, and make decisions about what aspects of engineering design they want to support. For instance, when looking to support students' engineering design processes, instructors may notice that their beginning designers are not gathering as much information about a design problem as more experienced designers would [7, 14]. Therefore, when deciding how to respond to students' work, instructors have to balance supporting their students to richly define the problem, while also helping them progress through the design process and not get "stuck" in problem scoping. Similarly, when formatively assessing across the *perspectives* and *ideas* categories, instructors might need to balance supporting their students' feelings of competence and seeing themselves as engineers, while also challenging them to develop new ideas about mechanisms and functionality. This can lead to tension: if instructors lean too much toward supporting productive engineering perspectives they may miss crucial opportunities to develop students' mechanistic reasoning about how technological artifacts function. Likewise, focusing on students' arriving at particular ideas might shut down students' participation and feelings of competence.

These types of challenges that instructors face are not exclusive to engineering design. In fact, in mathematics and science, the growing field of *responsive teaching* centers on the notion that instructors navigate myriad "instructional tensions" as they base their pedagogical moves on the disciplinary substance of what their students are saying and doing. For instance, in a seminal piece of the responsive teaching literature, Ball described dilemmas that emerged when teaching elementary mathematics in ways authentic to disciplinary practices [48]. In one episode a student, Sean, proposed that the number six was both even and odd because it contained "three twos." Ball described how she felt conflicted between respecting Sean's mathematical thinking--he was looking for patterns, developing definitions, and arguing for his ideas--and helping students learn conventional ideas about even and odd numbers. Similarly, Chazan described tensions he faced when leading a discussion his Algebra 1 class [49]. The students had been solving a problem about computing employees' average monetary bonus, when an argument emerged around whether to include the employee that did not get a bonus. Chazan recounted that he was excited to see his students sharing their ideas, listening to one another, and drawing on their own experiences, but was uneasy about how to assist them in resolving their disagreement in a mathematical way that would help them develop confidence in their abilities. In science, Hammer described tensions he experienced when teaching a high school physics course [50]. In one episode, for instance, he described feeling torn between wanting to support students who had been reluctant to participate while also wanting to help students learn what materials do or do not conduct electricity. Lampert described how teaching involves managing multiple, contradictory aims. She presented a view of teaching as managing "pedagogical dilemmas": Teachers are constantly dealing with ambiguity and contradictions [51].

In our research we explore the challenges of assessing and responding to ideas, processes, and perspectives in engineering design. In particular, we analyze dilemmas faced in balancing different objectives that may emerge and then in figuring out how to respond. We draw on the framework of responsive teaching to label these dilemmas as "instructional tensions" [52].

In the study we present here, we follow in the tradition of closely examining our own teaching to explore "instructional tensions" when assessing and responding to students' engineering design. In particular, we ask:

1) During the moment-to-moment trajectory of an engineering design teaching experience, how might we formatively assess what our students are thinking and doing in terms of *ideas*, *processes*, and *perspectives* in engineering design?
2) What dilemmas or tensions emerge in our engineering design teaching?

Methods: Examining episodes of our own teaching

In our teaching, we often videotape our interactions with students, both for our research on teaching and learning engineering design and to allow us to reflect on our teaching practice. For this paper, we selected moments from the first two authors' teaching in which they had noted or experienced dilemmas when figuring out what the students were doing and deciding what to do next. In these episodes, there was a great deal of student thinking on display, which provided opportunities for us to closely examine students' engineering design work and inform our thinking about teaching practice. Notably, we did not select these episodes to be examples of "good" or "bad" teaching: These episodes stood out to us primarily because of their messiness.

We watched each videotaped episode several times, individually, with each other, and with other engineering educators and researchers. These viewings allowed us to refresh our memory of what took place so we could recount what we were thinking in the moment and why we experienced uncertainty. By watching with others, we also noticed new things about what the students were saying and doing, providing new insight into their work and the dilemmas we faced as teachers.

For each episode, we wrote a first-person narrative describing what we were noticing and considering in the moment. Next, we drew on the three areas of formative assessment for engineering design—ideas, processes, and perspectives—to re-examine what the students were doing that was productive for their learning and what could be problematic. From this analysis we highlighted tensions that we see (and may have tacitly experienced) in these moments. We then considered alternative moves or paths we could have taken in our teaching, anticipating how the students may have responded and what trade-offs we may have faced.

Both episodes took place during units designed and facilitated as part of the Novel Engineering research program [53], an instructional approach to teaching engineering design in which design challenges are based on classroom literature, such as stories, novels, and nonfiction texts. The characters in the book become the students' clients, and the students build prototypes to solve problems faced by the characters. The students consider both the constraints and personalities of the characters, and what they can physically build in the own classroom.

Jessica's Episode: Building a structure to keep cool under the hot sun

Introduction

This case describes tensions I (Jessica, the second author) faced when considering learning goals both within engineering design and between engineering and science. This episode came from my interactions with a pair of fifth-grade girls, Caroline and Amelia, who were designing a shelter that could stay cool in the sun. This project was a part of a Novel Engineering unit [53] around *The Swiss Family Robinson*. Their class had read an excerpt from the book about how the stranded family first built a shelter on the beach, which got too hot in the sun. The students then had one day to design, build, and test a prototype of a new and improved shelter, using recycled and everyday materials such as shoeboxes, cotton balls, aluminum foil, tape, paper, and felt.

I was not the primary teacher for this project; I had come in to help for the day and videotape the students' work for our research on elementary students' engineering design. I was familiar with many of the students, as they had participated in Novel Engineering units the prior year. In particular, I remembered Caroline and Amelia, who had been paired together previously. In their earlier project in 4th grade, the girls had engaged in extensive brainstorming and made detailed drawings of their design, but spent too much time planning. When they finally started building, their classmates had taken many of the materials they wanted and they ran out of time to finish their prototype. When they presented their unfinished project to their classmates, they were clearly upset and discouraged.

Narrative

When I came up to the girls during this project, I was curious to see how they were doing—in terms of their attitudes, but also what they had taken away from their earlier experiences.

Jessica: How’s it going girls?
Caroline: Good.
Author: Yeah? Did you get all the materials you wanted this time around?
Amelia: Yeah.
Jessica: Yeah?
Caroline: We haven’t had to go back once!
Jessica: Haven’t had to go back once, well that’s good. So what's your design, can you tell me all about it?
Caroline: [inaudible] So felt [keeps you] very warm, but that reflects up any heat as well. Felt also reflects back cold as well. And I remember that cold air is less thick than heat, warm air.
Jessica: Cold air is less thick than warm air?
Caroline: So we have a little chimney for the cold air to come in, but it'll be clogged up halfway with this stuff that's spread out so that the more cold air would be coming in than the warm air would.

I first noticed that the girls seemed to be in much better spirits than they were during their last project. First, they were working collaboratively and had already started building. Caroline seemed proud that they not only had what they needed, but had gotten enough materials so they didn’t have to go back for more.

When I asked them about their design, Caroline started by talking about the ideas that motivated their design. She quickly outlined several ideas to me, and given the noise in the room I remember having a hard time keeping track of them all. The two ideas I did hear (and the camera caught) were about the reflective properties of felt and the thickness of cold and warm air. Neither idea was very clear to me at the time. When I asked what she meant by cold air being less “thick,” Caroline described how they were using that idea for their design. They were going to spread out cotton balls in the chimney to act as a filter that would only allow in cold air. I remember being confused about how she was thinking of the movement of hot and cold air in her design, so asked for more details:

Author: This is a really cool idea and I want to make sure I understand it. So you have the-
[*camera is moved closer*]
Caroline: And heat ri-
Amelia: And that way, and also it'll go out-
Caroline: And heat rises, so-
Author: Heat rises, so that's why you have the chimney on top? So heat air will go out this way and cold air will come in that way.

Caroline: Cause heat air, I mean, well, cold goes down and heat goes up.

Author: Cold goes down, heat goes up. So this is a way to have a like, little path for them go [hand gestures]. And so, why do you have the cotton stuff on top of here?

Caroline: That's for insulation, just to make sure the air doesn't get through. I know, like, cause that's what you'd have to have, if this was made out of sticks like it's representing.

Author: This is sticks, not-

Caroline: This is supposed to be like tons of sticks and stuff, so.

The girls then introduced another idea underlying their design: Heat rises and cold goes down. Based on the girls' gestures, I connected their idea to the chimney feature of their design. I also noted that they had more of the spread-out cotton on the top of the shoebox. While in the chimney she seemed to claim that the cotton would differentially filter hot and cold air, Caroline now labels it as insulation that will prevent all air from going through the holes in the shoebox. She then refers to another aspect of their design: While they are using a shoebox for their prototype, they modified it so that it would reflect the features of an actual structure to be built in the setting.

Author: OK. Um, and you were saying something about- where's the felt going to go? It's on the bottom?

Caroline: Felt, there's some-

Amelia: There's some on the bottom. We might do it on the side too, so it's hard harder for the heat [unclear]

Caroline: We also put some felt on our door so that the heat wouldn't get through the cracks… We don't want the cold air since it's less dense to get out the cracks. And we want the heat air to go up there.

Author: You said cold air is less dense, so

Caroline: So it can fit through smaller things.

Author: It can fit through smaller things. And so that's, so where do you have, where do you use that idea?

Caroline: Well there's lots of things we've learned since we were a little kids, about how air-

Amelia: [unclear] We are going to put holes, going to stick holes in the roof, holes. But we'll have this here, so it'll be harder for the heat to go through that.

Caroline: Yeah to come in and then the cold air can go down. So cold air sinks, hot air rises.

Author: Gotcha. So you have two ideas that you're using, cold air sinks hot air rises, and cold air is less dense than so it can fit through smaller things.

Author: Awesome. And then you said something about the heat reflecting both? Or the felt reflecting both?

Caroline: Well the felt is supposed to keep the heat down, so heat will be down instead of up, and that's what fe- like felt blankets and stuff that keep the heat down onto you instead of-

Author: Yeah yeah yeah.

Felt played a key role in their design. They had it lining the bottom of their shoebox and Caroline talked about also putting it on the door to keep the heat and cold from going through the cracks.

These two different uses were connected to different scientific ideas. First, the felt on the door covered the cracks, which Caroline claimed will help keep the heat from coming in and the cold air from leaving. At this point, she seemed to pose another scientific idea: cold air is less dense, "so it can fit through smaller things." I remember not understanding what she meant by "dense." Did this idea contradict her earlier idea that hot air rises? Was this connected to her earlier idea that cold air was less thick than hot air?

Caroline also talked about felt reflecting heat and cold. I appreciated that she gave me the example of a blanket to describe how felt can keep the heat down on you when you're wrapped in a blanket. However, I didn't understand why she then had felt on the bottom of their shoebox. They would be testing their design with a heat lamp held on top of their prototype, so it wasn't clear what role the felt would play in their design. Perhaps it was there to represent how their prototype would be used on a beach and the felt would reflect back heat from the hot sand?

Considerations in the moment (and later)

Caroline and Amelia had such a negative experience in their first project that I was thrilled to see them having a more positive experience this time and feeling capable in using their ideas and building an effective design.

Furthermore, the girls seemed to have a better sense of the design process than they did during their first project. They spent some time brainstorming and drawing their design ideas, but they also made sure they had enough time to gather materials and realize their ideas. They also referred to the fact that their project was "representing" a solution, offering evidence that they saw it as a prototype for a structure that could be built and used in the setting of the book.
I was also encouraged by how they were making principled decisions about their design based on their understandings of the world. They talked about each feature of their design in relation to a scientific idea about heat, including how it moves and interacts with other materials.

While there were clearly productive aspects of their engineering, I also had concerns. There seemed to be multiple features to their design functionality: 1) the chimney to channel the heat out the top, 2) materials that could filter between hot and cold air, and 3) felt reflecting heat back. However, some of these features seemed to conflict. For example, if the spread-out cotton was designed to prevent hot air from passing through, then wouldn't the cotton in the chimney prevent hot air from escaping? Furthermore, since they were implementing these different features all together, it didn't seem that they would be able to really identify the features of their design that were successful. They didn't seem to be thinking systematically about testing and refining their solution.

Alongside my considerations of their engineering design, I was also curious about their scientific ideas. I wanted to know more about what they meant by cold air being less thick or dense than hot air. I can imagine that they were drawing on their experiences from hot, humid summers in the Northeast or being in the cold, "thin" air in the mountains. Caroline also claimed that heat rises and cold sinks—how did that mesh with her other idea about cold air being thinner and less dense? Lastly, I appreciated that they were thinking about how heat interacts with objects, such as felt reflecting back heat. These ideas seemed to have some productive seeds for concepts in thermodynamics: heat can flow from one object to another and that objects can prevent this flow. They also show some beginnings of mechanistic reasoning, namely in Caroline's example of how a blanket reflects heat. However, as a scientist, I wanted them to better articulate how they were thinking about heat flow, such as why hot or cold air would slip through the cracks of their design and what happens when an object reflects heat. I also wondered about how to help them refine their ideas to be more in line with science content objectives around heat transfer.

What to do next?

Although I was not the primary teacher, I remember feeling conflicted about what to do next. I could see pursuing multiple avenues to support their design, such as encouraging them to independently test the different features of their design or asking them to draw out how they each worked. I could also imagine supporting their scientific work, perhaps by asking them to write about how heat flows or asking them to draw how heat moves through their design. However, by interrupting their building, I might keep them from finishing their design and experiencing the full design process—something they didn't get to do in their last project. I could also let them continue building and check back after they had finished, but I questioned whether there would be time to return to these issues. In the end, I hoped that letting them continue to build might leave opportunities for them to discuss and refine their ideas—about both engineering design and science—and would better support them in seeing themselves as capable in doing engineering.

Kristen's Episode: Coming to consensus on furniture design

Introduction

This case describes instructional tensions I (Kristen, the first author) felt between supporting a class's stable framing as an engineering design community and pressing for students to try out particular engineering design practices. The episode took place during a science methods course for graduate students in an elementary teacher education program at a large public university. All but one or two of the 27 students had taken minimal science coursework in college, and none had prior engineering coursework or experience.

The course had traditionally focused only on learning to support scientific inquiry in the elementary classroom, but I had added a module on engineering design. It included three design tasks based on works of literature. For the task in this episode, the students had read excerpts from *Tales of a 4th Grade Nothing*, in which the main character finds some of his precious belongings wrecked by his two-year-old brother. The challenge I posed was to design a piece or set of "older sibling's" furniture that would help the older brother protect his belongings from his younger brother while at the same time be appealing to their parents.

In an earlier design task, the students had worked in small groups to identify, scope, and prototype solutions to problems faced by a historical figure featured in a non-fiction biographical text. I wanted this activity to illustrate a different version of literature-based engineering. First, we identified the design problem in a work of fiction rather than in a historical biography. Second, the particular problem statement was initially framed by me, the instructor, instead of by the students. Third, I positioned the whole class as a large team tasked with making a single design recommendation to a (fictitious) furniture company, although I had the students first work in small groups to design draft solutions to pitch to the whole class. I told the students that they should think of themselves as a design company, and by the end of the class period they would need to decide on one solution to offer to the client.

Narrative

After I presented the furniture design problem statement, I assigned the students to four small groups and they got to work preparing to “pitch” a design idea to the whole class. I made a cart of prototyping materials available during this time but did not require three-dimensional models. After 25 minutes of group work, each group pitched their solution proposal to the rest of their peers. In their pitches, they displayed large posters and sticky note configurations, but no physical prototypes. I took notes on the board about the four proposals, which included a wall-mounted “3-in-1 shelf,” a “discovery desk” with compartment for protecting belongings and a chalkboard desktop, a lockable toy chest camouflaged as a room decoration, and a bed with alarmed secret compartments accessible by key code. Students asked clarification questions after each pitch.

In the students’ small-group work and presentations to the class, I noticed they were thinking divergently with ideas ranging from entirely new pieces of furniture to adaptations of traditional pieces. I also saw them communicating their design ideas to each other through speech, text, and drawings. I anticipated a lively whole-class discussion about which proposal best met the criteria and constraints set out for the design problem. This episode picks up at the beginning of our whole-class conversation.

Bethany immediately raised her hand to say that she thought a lock feature should be excluded from the design.

Author: What are people thinking? Anyone want to make an argument for why one of these should be what we pursue? Or why there's some combination of um, proposals that we could pursue? Bethany.
Bethany: This could be wildly unpopular, but I personally, I don't have kids, but I can't imagine wanting to buy my kids something that has any kind of combination lock, or actual lock, because I don't want to be encouraging them to hide things from me, but I also don't want to be demanding that they give me the password and crossing the lines of privacy. So, that's one of the things we talked about, and we threw out the idea of a lock for, of an actual lock, for that reason.
Author: Okay. Okay, cuz you were, right, you suggested -
Bethany: I just don't think that the kind of parents shopping at Pottery Barn or whatever are gonna be encouraging their kids to be locking their stuff up from them.
Author: Okay, so you're thinking about the-
Bethany: So maybe in a sales pitch, kind of-
Author: [Inaudible]
Bethany: Yeah.
Author: Okay, okay. Flor.

Flor: You know, I'm thinking more, a combination to keep the younger siblings out, not necessarily that the parents won't have the combination. So I would keep those ideas in, you know what I mean, like so if the child had like three shapes, let's say he had square, circle, triangle… The parent could always say, you pick a code that you and I know, but your little brother or little sister wouldn't know the code.

Bethany thought the lock would enable the older sibling to hide things from their parents, and that parents wouldn't want them to have that capability. Flor clarified that the lock would be simple and that parents would have the combination. I noticed that Bethany was considering the viewpoint of a specific potential user (a Pottery Barn shopper) and using that insight to argue against a particular design. I saw Flor listening to the critique and addressing Bethany's interpretation of her group's proposal. And I was aware during this exchange that Bethany strained to face Flor so they could talk and gesture to each other rather than to me.

Next, another student from Flor's group, Deanna, turned to Bethany to voice her own response to the critique.

Author: Okay, Deanna.
Deanna: I just, that was such an interesting point, I never thought of that. [Turning towards Bethany] I totally see where you're coming from, but also growing up, like you had diaries that had like little locks with keys, and it is kind of good, little relationsh-, it makes that older sibling like feel like, okay, my mom knows that my things are special to me and wanna, you know, I feel a little bit older, I have my own little lock so [points toward Flor], it's so, yeah. But I didn't [points toward Bethany], it's interesting cuz I didn't -
Bethany: [Turning to look at Deanna] I just think there's a difference between a diary or like, you know, a little box, versus a desk, or something, you know what I mean?
Deanna: Mm-hm.
Flor: Yeah, I think that's why we said that parents should know a reset because -
Bethany: Yeah. Yeah, that's good, yeah.
Flor: We thought about that, the parents can reset it if they wanna get in.
Deanna: Yeah, the parent has like, the button.

Deanna acknowledged Bethany's opinion about the lock but then suggested she consider its potential for making the older sibling feel special for being more responsible than the younger sibling. Bethany pressed her point by saying a piece of furniture was quite different from a diary, and Flor made another clarification – that parents would have the capacity to reset the lock. I noticed a degree of intellectual risk-taking among all three students: they were putting themselves in a vulnerable position by critiquing each other's design proposals and reasoning. This stance seemed to be a productive epistemological framing, with the students enthusiastically playing an "engineering design" game rather than a "classroom" one [44].

At this point, another student asked for confirmation that we were a “company” and then said she was “going with” the hidden compartment design proposed by the yellow group, even though she had been in the blue group. I remember noticing and finding it productive that a student was willing to give up her group’s proposal and take up another group’s, and I could have built upon that by asking her why she found the hidden compartment design compelling. But another student jumped in with another line of thinking, this time about cost.

Cathy: Yellow. I'm going with yellow.
Author: Yellow, the hidden compartments, oh, with the alarm system and the, okay.
Julie: Was the requirement that the whole thing had to cost $100? Or -
Author: No, that any one product that Land of Nod would offer, its cost of materials would be under 100 dollars.
Julie: Okay. Cuz in that case we think ours [the 3-in-1 shelf] would be very cost effective.
Author: Okay, good point.
Julie: Cuz it's not very elaborate. It's simple, and it could be made of high quality materials, and kept under 100 dollars.

I noticed Julie attending to the constraint of budget and could have pressed for her reasoning about why she thought their design would cost less than 100 dollars. However, other students had their hands up, and I gave the floor to the waiting students. The next speaker changed the subject from the budget to the potential downsides of the alarm feature. She saw it as either frightening for the toddler or an annoyance to the parent. The group who proposed the alarm defended it, and then the other student waiting to comment changed the subject to her concern about the safety of the wall-mounted shelf. Again, the proposing team defended the wall-mounted feature. I was pleased with the students’ user-centered design thinking; they were considering both the parents and the children and creating new criteria and constraints based on those user considerations. For example, they suggested that it was important to not annoy parents with false alarms. At the same time I noticed that a pattern of critique-defend-critique-defend was being established in the students’ discourse. I called on Flor, who was admired by everyone in the class, in the hope that her comments would tip the class’s framing back to collaborative engineering decision-making.

Flor: First of all, I love the three in one desk, I would buy it for myself. [laughter] But, because I'm all about space, saving space, I think that's huge on saving space. BUT I'm thinking how does that offer some protection and privacy, too? I'm thinking, yeah, the height, but then I'm like where's the privacy piece, so I'm thinking if we have to follow these guidelines, how does that play a role?
Julie: [Turning to group member Violet] Privacy as far as yourself, right? [to whole class] Privacy as far as your belongings, like, would be protected by -
Flor: The height?
Julie: How high up it is.
Violet: That's what we had discussed.
Student: Chair.
Author: Lisa?
Lisa: Um, for the privacy thing, there is the chair concept, but also if -

Author: What do you mean, the chair concept?

Lisa: Well, like, you could bring a chair over, and, step on it and climb up. But also, um, for a little kid, if the little kid can't put the shelf up and bring it down, they're always depending on the parent, they might not really like always going to mom and dad.

Flor did do something different than critique or defend: she suggested prioritizing certain design criteria and analyzing the design proposals with more weight given to the more important criteria. Pointing out that “we have to follow these guidelines,” she argued that privacy and protection might be more important to consider than saving space. Lisa responded to Flor’s emphasis on privacy by pointing out more weaknesses in the three-in-one desk from the older sibling’s point of view. The younger sibling might be able to access it by climbing on a chair. It it was high enough to be inaccessible by chair, then the older sibling would have to ask the parent for help each time he or she wanted to access it. Either way, there was a problem from the older sibling’s point of view.

Considerations in the moment (and later)

As the students considered and critiqued each other’s design proposals and attempted to clarify what their own small groups had attended, I noticed productive beginnings of engineering design practices. The students were evaluating design ideas from the point of view of multiple users (parents and children), proposing new criteria and constraints based on their analysis of those users’ needs and preferences, attending to multiple criteria and constraints, and presenting careful reasoning to each other as they argued for certain design features to be excluded. I also saw the students adopting productive engineering perspectives. Students from all groups were animated and passionate as they discussed design ideas with each other, and they were not taking personal offense when peers critiqued their ideas. They conveyed confidence in trying out engineering design, a confidence they had explicitly denied earlier in the semester. Yet just as Chazan wanted his students “to develop a greater confidence in their ability to reason their way to mathematical decisions”[49], I wanted my students’ confidence in trying engineering to come from a place of having made a carefully reasoned and well-informed engineering design decision.

Throughout the episode I felt increasingly uneasy that I was not pressing individual students to deepen their design thinking. I wanted as many students as possible to experience contributing to a collaborative design decision, so rather than pressing a student for more, I often gave the floor to one of the other students eagerly signaling they had something to say. In enabling more voices to contribute, I may have been sacrificing opportunities to encourage individual students to reason carefully, refine the design ideas under consideration, and make progress toward a collaborative design decision.

I was also concerned that students, with the exception of Flor, were becoming more focused on what *not* to include in the design. They seemed so far from achieving consensus on what *to* do. What I saw happening was that each time a student proposed a new strand of thinking about the design proposals, it was based on a negative criticism, a flaw they saw in another group’s proposal. Some students seemed to be arguing against their peers’ design proposals for the sake of winning a competition rather than for the sake of making the best design decision. Pointing out weaknesses is an important design practice, but the students seemed to be stuck in this practice. Moreover, each criticism seemed to attend to a different part of the design space - from the budget to problems with particular features to the needs of multiple users. The critiques weren't proceeding systematically, and I hadn't yet heard any thinking about how any of the proposed furniture would be put together to carry out its intended function. Since no physical prototypes had been created, neither could I *see* any evidence of that thinking.

My concerns can be summed up as a tension between supporting the students' stable framing of the activity as student-led design critique (in itself an important design practice) and creating a teacher-led opportunity for students to develop a different design practice – feasibility analysis. The students seemed to be enjoying debating the choice of features (e.g., lock, alarm) to include in the furniture. And making design decisions about features is something that engineers do. However, I wanted students to practice conducting feasibility analysis related to design functionality – that is, to consider the extent to which these proposed designs could actually be put together and work.

What to do next?

In planning this lesson, I had thought it would be easier for a whole-group design consensus to emerge. I had anticipated that at least some groups would build rough prototypes, and that after the pitches, the students would readily would be impressed by one group's idea or would suggest synthesis proposals. These expectations were based on my students' ways of scientific sense-making earlier in the semester. When exploring scientific phenomena together, many students had been willing to abandon their own interpretations of scientific investigations if a classmate presented a persuasive and evidence-based alternative interpretation. That willingness to be persuaded was not apparent in this design task. I found myself in a scenario for which I had not planned any instructional moves. So what would be a productive next step?

One possibility would have been to guide the students in creating a decision matrix. We could have listed all the design requirements, established weighting factors, and scored each design proposal on each requirements. This approach would have exposed students to a systematic strategy for evaluating different design proposals against each other. But the students might have framed the decision matrix as a "classroom game" (since it was introduced by me, the instructor) rather than an authentic next step in the engineering design game that they were so enthusiastically playing at the moment. Students might have learned about an engineering design decision-making strategy at the expense of feeling like they'd made their own engineering design decision.

I could also have paused the large-group conversation and asked groups to go back to their designs and take them a step further via 3D prototyping. The data generated by the prototyping attempt (e.g., was the idea geometrically possible? did it look any different than existing bedroom furniture? was there a way to make it stable?) might have been the substance that students needed to have a more productive conversation about which design to pursue as a large team. On the other hand, a move toward miniature prototypes (without enough time for careful building) could have become a crafting activity with even less attention to feasibility and functionality.

Another potential move would have been to prompt the students to do some independent analysis of the design proposals under consideration. For example, I could have asked each student to sketch each of the four ideas, as they understood them, and list questions they had about each one (e.g., its material composition, its dimensions). However, while this independent work might have helped each student develop more nuanced ideas about the furniture design task, it may not have supported them in making progress toward the goal of a large-group decision. There was no guarantee that independent thinking about the design proposals would help the students see ways to synthesize across proposals or to generate a convincing argument in favor of one single existing proposal.

Discussion

This close study of two episodes from our own teaching highlights the need to examine what teachers notice and assess moment-by-moment in their students' engineering design work. In this paper we argue that the literature on responsive teaching in math and science can contribute to the study of engineering design teaching and learning [54]. We view our analyses as a new kind of investigation into engineering design education, distinct from the large body of K-16 engineering education research that has focused on how to design learning tasks, tools, or environments that support students' engagement in aspects of engineering design. In addition to this work, we argue for the need to examine the teaching and the "instructional tensions," that happen with these tasks and tools and within these environments [52]. By drawing on our experiences in the classroom, we were able to use our own perceptions and feelings from teaching to inform our analysis of the dilemmas that emerge. Furthermore, by reflecting on our own teaching, we hoped to represent teaching engineering as a reflective practice [55].

We did not analyze the focal episodes in this research study as "exemplars" of engineering design pedagogy. Instead, we wanted to examine the complexities that are involved in the moment-to-moment decisions of teaching engineering design. Ball and Chazan explicitly challenge the discourse of evaluating teaching in terms of good or bad: "The common syntax of 'should' and 'should haves' distorts practice with a stance of implied clarity" (p. 9) [49]. In our work with teachers, we have to fight the tendency to represent the teaching of engineering in ways that suggest there is one right way to organize an engineering lesson or respond to students. Instead, we propose representing teaching as an endeavor that is in many ways analogous with engineering design; that is, that there are multiple paths for solving the pedagogical problems that emerge, each with different affordances and trade-offs.

As mentioned above, this representation of teaching connects to work emerging in math and science around responsive teaching [54]. Responsive teaching is a pedagogical approach in which teachers base their instructional moves on what the students are saying and doing. In responsive teaching, teachers elicit students' ideas, interpret and recognize disciplinary aspects of their activities, and make pedagogical decisions based on their interpretations [54]. This approach is continuous with practices of formative assessment, such that teachers are continually noticing, interpreting, and assessing their students' learning as they decide what to do next.

This perspective has meaningful implications for how we think about preparing instructors for engineering. Particularly at the elementary level, most professional development efforts focus on teachers' understanding of engineering design, such as what they know about the design process and technologies, what they recognize as engineering in the world, and what connections exist between engineering and other domains [56]. While this focus supports teachers' development of disciplinary knowledge, we argue that it is not sufficient to support their students' engineering design. Teachers need to learn how to examine their students' work for productive aspects of engineering *ideas*, *processes*, and *perspectives*, and how to balance the tensions that may emerge within and across different disciplinary objectives. Furthermore, to inform professional development efforts, there is a need for research on how teachers notice and interpret their students' disciplinary work. We are beginning this work in our research with elementary teachers as we examine how they develop disciplinary "lenses" with which to see their students' activities[57, 58, 59].

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