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Keywords

problem scoping, design, methodology

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Abstract

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Introduction

With the increased focus on engineering in national and local science education frameworks, engineering design is becoming a more integral part of K-12 education (Massachusetts Department of Education, 2001; National Academy of Engineering & National Research Council, 2009; National Research Council, 2011). Most prominently, the Next Generation Science Standards articulate that students should learn how to define engineering problems, develop multiple solutions, and evaluate these solutions. While this emphasis on engineering design in schools marks an exciting frontier for engineering education, it also warrants increased attention on how educators characterize beginning students' designing in the classroom. The ways in which educators describe and interpret the nature of students' design activities will not only impact research claims about students' designing, but also what gets assessed and promoted in emerging curricula and policies in engineering education. However, current research methodologies generally rely on simple measures to capture

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students' designing, measures which do not reflect the nuance and richness found in accounts of experts. With the prevailing measures, the engineering education community risks missing important aspects of students' design activities, promoting superficial performances, and developing misguided claims about what students can and should do in engineering classrooms.

In this paper, we focus on measures used to characterize the beginning of the engineering design process, when student designers are figuring out the problems they have to solve. Because engineering design problems are inherently complex and ill defined with unknown constraints and criteria (Jonassen, Strobel, & Lee, 2006), determining the nature and boundaries of the problem space is a critical aspect of design. We refer to that determination as problem scoping, which we define as the process of discovering and understanding aspects of the problem that need consideration. More specifically, problem scoping involves both naming the things to attend to in a problem and framing the context in which to attend to them (Schön, 1983, p. 40). While problem scoping is particularly important at the outset, the problem space and the solution space can co-evolve (Dorst & Cross, 2001). That is, designers not only use information about the problem to develop solutions, they also use solution ideas to help them refine their initial problem scoping. Therefore, problem scoping occurs both at the start of the design process, when designers do not have specific solutions in mind, *and* when they are redefining the problem as they are developing solutions.

We focus on problem scoping first because it is widely understood as an important feature of expertise and because the literature to date, which we review in the next section, has generally characterized it as an area of particular weakness for students. Our core purpose is to argue that this characterization stems largely from methodology and that expanded approaches to research can show more of students' nascent abilities for problem scoping, even in elementary school.

To be sure, little is known about young learners' designing; most research on problem scoping has focused on adult learners. Prior work on beginning designers has focused on simple measurable aspects of their behavior, such as the time they spend problem scoping and the number of criteria they consider. This contrasts with the significantly more nuanced, complex, and contextual accounts of expert design.

In this article, we argue for the importance of describing and interpreting beginning problem scoping in ways that draw from accounts of expert practice. In doing so, educators can better characterize not just the differences between experts and novices, but also more richly document the productive resources for problem scoping that students display. These beginning resources for design practice are particularly important in constructivist theories of learning which focus on the ways that students use their existing understandings to build new knowledge of the discipline (Brown & Cocking, 2000; Smith, diSessa, & Roschelle, 1994).

We begin with a brief review of the literature on novices' problem scoping. In it we identify problems with the measures that are predominantly used to characterize their behaviors. We then review expert and theoretical design literature to highlight themes of problem scoping practice found across these accounts. Drawing on these themes, we analyze three episodes of elementary students' problem scoping, detailing (1) the complexity that can be seen in these students' design behaviors and (2) how their actions are in service of their pursuit of a design solution for clients. In contrast to more typical methods of characterizing problem scoping, which often rely on simple codes and counts, our analyses show more richness and promising beginnings in children's designing. Finally, we discuss the implications of this work for engineering education research, policy recommendations, and curriculum development and implementation.

Engineering Design Problems and Problem Scoping

Engineering design problems are often characterized as complicated and ill-defined, standing in contrast to traditional textbook end-of-chapter problems. In their analysis of problems faced by practicing engineers, Jonassen, Strobel, and Lee (2006) documented how design problems often have multiple nested sub-problems that can conflict with each other and how criteria for success were often unclear or unstated and that constraints arose throughout the design process. For example, working engineers recounted tensions between addressing unexpected environmental issues and keeping a project within budget; they described how sub-problems related to weather, changing client preferences, and structural difficulties often arise while projects are underway (p. 146). To design effective solutions to problems, designers must define the goals, criteria, and constraints, while responding to the dynamic nature of the problem's boundaries.

The complexity of a design problem depends not just on the features of a problem, but how a designer interprets and interacts with it. Thomas and Carroll (1979) argued that design is not about a "type of problem" but a "way of looking at a problem." They claim that designers can take seemingly well-defined problems and treat them as ill-defined with underspecified rules or conventions. Even working from a seemingly straightforward textbook problem, which may contain all the information needed to obtain the answer in the back of the book, a problem-solver may bring in other considerations or challenge the given information to rethink the problem and take a novel approach to solving it. Similarly, design problems with underspecified criteria and constraints can be misinterpreted as well-defined (Rowland, 1992). Thomas and

Carroll (1979) give a problematic example of an architect handing a questionnaire to a home buyer and then using their answers to determine preset features for a home. They concluded that design "is a type of problem solving in which the problem solver views the problem or acts as though there is some ill-definedness in the goals, initial conditions or allowable transformations." (p.5) In this sense, the ill-defined nature of design problems can be attributed not just to the features of a given task, but how a designer interprets the task.

Research on Problem Scoping

Much of the research examining students' problem scoping has been conducted at the undergraduate level. In particular, Atman and colleagues have extensively documented and compared the design processes of undergraduate engineering students and practicing expert engineers (Atman, Adams, & Cardella, 2007; Atman, Chimka, Bursic, & Nachtmann, 1999; Atman, Turns, Cardella, & Adams, 2003; Atman & Bursic, 1998). They asked participants in think-aloud interviews to design a playground for a fictitious neighborhood, encouraging them to ask for any information they thought they needed (for more information about the protocol, see Atman and Bursic, 1998). The authors then recorded the amount of time that interviewees spent defining the problem and gathering information, as well as time spent on other design activities. They developed individual timelines to show how interviewees navigated among problem definition, information gathering, and other design activities. In addition, they counted the number of information requests that interviewees made and the number of categories these requests spanned. These quantities, the amount of time spent scoping the problem and the number and diversity of information considered, served as data the authors used to determine students' problem-scoping abilities in designing a system, process, or component (Atman & Bursic, 1998). Similarly, Jain and Sobek (2006) assessed students' design processes by considering the amount of time they spent defining the problem. Other examinations of students' problem scoping have focused on who they identify as the client and what they state as the client's needs (Diefes-Dux & Salim, 2009).

These different studies found correlations between problem scoping and solution quality and documented significant differences between beginning students and expert engineers. In doing so, they further highlight the importance of attending to this aspect of the design process for beginning students. The measures used in these studies offer a first pass at unpacking beginning problem scoping. There are, however, important reasons to move beyond them.

First, the amount of time spent formulating a problem is challenging to interpret because experts themselves may spend varying amounts of time problem scoping depending on the problem context. For example, while Atman's work documented that expert engineers spent longer times problem scoping than students in the playground prompt, when they work in familiar domains the experts may spend less time, having encountered similar situations in the past (Cross, 2007). Furthermore, other studies suggest that beginning designers can spend too much time problem scoping and never get to developing solutions (Christiaans & Dorst, 1991). Therefore, the relationship between progress in design and the amount of time spent problem scoping is complicated and likely depends on the problem at hand. Similar concerns apply to the number of information requests or criteria named. Students may not use information they gather or constraints they mention as a substantive part of their designing (Bursic & Atman, 1997). Counting the number of criteria mentioned does not capture how students connect the information mentioned with the overall problem space for which they are designing. We argue there is a need to build on this work to better document progress in this aspect of design. In particular, we propose that accounts of beginning designers may benefit from the similar levels of contextuality and complexity found in accounts of experts.

The first part of Schön's definition centered on naming the different things to attend to in a given problem, which could be constraints on the problem (Lawson, 2006), information about the task and system in which it is situated (Ennis & Gyeszly, 1991), or criteria by which the solution will be evaluated (Portillo & Dohr, 1994). Atman, et al.'s framework addresses this aspect of problem scoping by counting the pieces of information and the number of categories this information spanned. Their measures therefore offer a first-order approximation of students' problem scoping. We build on their work by considering more of what is involved in naming the different considerations of a design problem. In particular, we note that naming different criteria often entails considering the problem from multiple perspectives, as Cross (2007) documented in his account of experts' designing. He observed that when considering the different criteria and constraints, designers thought about the problem from the different perspectives of the players involved, such as the clients, users, manufacturers, and designers themselves. Cross and Cross (1998) showed how an experienced designer, tasked in a design interview with developing a device to carry a backpack on a mountain bicycle, shifted from thinking of a problem solely from the perspective of the user to thinking about the client—the manufacturer of the device. This shift led the designer to consider the need for a 'proprietary feature' that would set the product apart from others on the market. While perspective taking is important for unpacking the different layers of a problem, it cannot be observed with the simple measures of problem scoping currently used in engineering education.

Accounts of expert design also highlight the complexity of interactions among the different constraints, criteria, and information in a design problem. For example, keeping costs down is likely to be in tension with using high-quality materials. This was evident in Cross's (2007) analysis as well: A designer had high-level goals for their design, such as improving a user's experience or increasing the speed of a racecar, but these goals did not always align with those of the client, who was more concerned with cost, branding, and industry regulations. Lawson (2006) discusses how scoping a problem requires combining and integrating different requirements: "Design problems are often both multi-dimensional and highly interactive… [The designer of] a chair is unlikely to succeed by thinking separately about the problems of stability, support, stacking, and visual line since all must be satisfied by the same element of a solution" (p. 58). In this sense, problem scoping involves thinking about the relationships between factors, rather than just thinking of them each in isolation.

Another issue with simply considering the number of constraints and categories mentioned is that they are not all of equal value. Some requirements and interactions are of greater importance for and may have a greater impact on the problem and solution than others. For example, in Cross and Cross's (1998) study of an expert engineer's design of a bicycle rack, they observed that the designer first established the essential criterion to address: maintaining stability for the rider. The designer considered other criteria as well, such as marketability, but prioritized stability as the critical issue for success.

Relatedly, Schön's definition highlights how a designer must establish the broader context of a design problem. In the bicycle carrier example, the designer did not just focus on the carrier alone, but considered the dynamic situation of the rider, bicycle, and carrier. Several design researchers describe this aspect of problem-scoping practice as thinking holistically about the problem space. For example, in Candy and Edmond's (1996) case study of an engineer redesigning a racing bike, they noted that he first identified and emphasized the higher-level concern of aerodynamics, rather than focusing narrowly on weight or angles. "Taking a higher level view of the problem space proved to be a critical change that enabled him to step outside existing constraints and dare to be radically different" (p. 78).

Lastly, Schön highlights the importance of reflection in problem scoping. By reflecting on the problem space, designers note the criteria, values, norms, and information they have prioritized, moved to the background, included or left out. Designers are also then aware of the alternative ways of scoping the problem, which allows for them to notice dilemmas inherent in their problem and solution space. Valkenburg and Dorst (1998) focused on this aspect of Schön's theory of reflective practice in their analysis of a competition to design and build a robot that can transport balls from a table to a basket 1 meter away. They compared two teams: one was successful in completing the task and winning the competition while the other was unsuccessful in completing the task. The successful design team spent time scoping the problem early in their design activities and reflected on their problem space throughout the design process. For example, they started by breaking the task into three sub-problems: shooting the balls, collecting the balls, and driving the design. They then decided that "shooting" was the aspect of the task to focus on first. After brainstorming solution ideas, the winning group reflected on their conceptualization of the problem and decided that shooting was not the only way to accomplish this part of the task. They then reframed the problem as "getting the balls in the basket." In contrast, the unsuccessful team spent the majority of their time "naming" (generating ideas, discussing different items, making an inventory of sub-solutions, choosing materials and drawing the chassis and the product), without developing a coherent problem space or reflecting on their problem and design decisions. Unlike the winning team, they do not develop multiple conceptualizations of the problem or reflect on their designing; they only developed a coherent problem space towards the end of the project, when being questioned by expert advisors.

Schön's theory and the results of Valkenburg and Dorst cut across the different themes described expert accounts. As we discussed above, problem scoping involves more than listing criteria or information; it involves prioritizing and integrating different aspects of the problem space. In addition, these authors noted the importance of reflection alongside these practices. By being aware of different ways of conceptualizing a problem, designers are more likely to "experience the need to choose among them." (Schön, 1983; p. 310).

Using these different accounts from theoretical and empirical studies of expert design, we can expand on the work from engineering education to broaden our conceptualizations of beginning problem scoping. Specifically, based on this brief review of expert design literature, we argue for the importance of attending to the following features in students' problem scoping:

- **naming**: *identifying* the different constraints, criteria, and pieces of information in a problem that span across different categories and arise from *navigating the different perspectives* of the players involved in the problem;
- **setting the context**: *considering interactions* among problem requirements, *balancing* and *prioritizing* the different components and interactions in a problem, and *developing a coherent sense* of the problem context; and
- **reflecting**: explicitly *acknowledging* and *evaluating the problem space* and the decisions made about what to consider and prioritize.

Recognizing the Beginnings of Problem Scoping in Students

Most results from studies of beginning students' problem scoping highlight differences between experts' and novices' design abilities. For example, Crismond and Adams (2012) claim,

> Beginning designers *feel that understanding the design challenge is straightforward, and a matter of comprehending the basic task and its requirements. By perceiving the design task as a well-structured problem and believing there is a single correct answer, they can act prematurely and attempt to solve it immediately*. (Italics in original, p 747)

However, research on beginning designers is constrained by what researchers attend to in students' designing. In the following analysis, we show that by broadening our characterizations of beginning problem scoping to include more features from expert accounts we can capture and call attention to more richness and complexity in students' designing. We show that these beginning designers did not treat design problems as well-defined, straightforward tasks. Rather, they demonstrated promising beginnings of expert practice that could not be captured by the extant measures used to characterize students' designing.

We present data from our NSF-funded project integrating engineering and literacy (IEL). In this project, students read narrative texts and use them as a basis for identifying, scoping, and designing solutions for an engineering problem that the characters face. Prior work from this project has shown how the rich development of characters, plot, and context in the book can support students' engagement in engineering design (McCormick & Hynes, 2012), and, in return, how students' purposeful use of the text to develop design solutions can support students' reading comprehension (Spencer, Watkins, & Hammer, submitted).

We present transcriptions from video clips from two suburban fourth-grade classrooms taught by the same teacher in consecutive years. In this particular unit, the teacher read aloud The Mixed-up Files of Mrs. Basil E. Frankweiler by E. L. Konigsburg (1967). The book centers on siblings Claudia and Jamie, who run away from home and hide in the Metropolitan Museum of Art in New York. During their adventure, they face several challenges, such as hiding from guards, waking up before the cleaning crews arrive in the morning, getting and storing money, and seeing some of the art exhibits. The students were tasked with choosing one of these problems and devising a solution that they could build and test in the classroom. They were encouraged by the teacher to consider the characters as their clients and to think about how to design something that would help them. In the first year of the project, the teacher assigned this unit as the students' first engineering design experience in the classroom; in the second year, the teacher had assigned another engineering project several months prior to this unit.

Students worked in groups of 2–3 first to plan their solution. A worksheet prompted them to sketch their design. In the second year, we added a prompt for students to write about how they would test their design to see if it works. Students then built their solutions – or functional prototypes – using found materials such as egg cartons, cardboard boxes, and ping pong balls. They shared their solution with their classmates at a few points throughout the design process, including a final presentation and test of functionality. The entire engineering project took place over the course of two weeks, with students working for 1–2 hours several days each week. We examine clips from three student groups here. We selected these clips because they exemplify some of the rich problem scoping we observed. In this way, they allow us to show how a more expansive methodology can reveal productive beginnings in learners' problem scoping.

Jen and Alice Brainstorm How to Help Claudia and Jamie

In this class in the second year of the project, the teacher and students first brainstormed all the problems that the characters faced in the book as a large group, writing a class list on a large piece of butcher paper at the front of the classroom. Students then broke off into pairs to decide which problem they would like to solve for their engineering project. One problem was that Claudia and Jamie needed to wake up before the guards in the museum made their rounds. We present a short clip of two students, Jen and Alice, at they started to brainstorm possible problems and solutions:

(Parentheses indicate uncertainty in transcription)

> *Jen: I know what we can do, like, (see), make something somehow to wake them up (…)*
> *Alice: Yeah, but it shouldn't be too noisy cause there might be night guards or something.*
> *Jen: Yeah, so, what-they couldn't buy an alarm clock cause they wouldn't have enough money to do that. So what should they do?*
> *Alice: Uh, um, what do you think they should do?*
> *Jen: Well I really like (things like) a machine,*
> *Alice: What about something that vibrates or some thing?*
> *Jen: I've got an idea. Maybe we could, um, see if they could find something that's laying around, like everyday things, like a pencil, to wake them up. Because they can't pay. What you might find on the street.*
> *Alice: Yeah, you don't just find like things like batteries just laying around.*
> *Jen: Maybe, like in the park, people always leave around things like frisbees.*
> *Alice: Yeah.*
> *Jen: Use something like that. We could like, um, so like (…) I like your idea about the vibrating. But how would they make it vibrate?*

Alice: Yeah, they should, they could find like a row of rocks and put it in something, to make noise, but we need something to make-
Jen: Yeah, but how-
Alice: um, it move. Back and forth.
Jen: Well the thing is they could put rocks, onto- [giggles] (their back), but that wouldn't
Alice: That wouldn't be useful, but
Jen: That wouldn't be, how would they get it on (them).
Jen: Here we go. Sometimes people do this. Everybody has watches, right?
Alice: Yes.
Jen: Most people have watches. And I usually- sometimes they leave them around, you know how if they find a watch in the park.
Alice: Yeah, but you have to remember that it's not like present, it's in the past.

In this exchange, Jen and Alice explored different problem and solution possibilities as they discussed whether to solve the problem of waking Claudia and Jamie up. As with many students in these classes, one of their considerations for choosing a problem was whether it could be solved — by the characters in the book and the students themselves. Therefore, as they were defining the boundaries of the problem space, they were also thinking of ways to solve the problem. Likewise, as they were discussing possible solutions, they were also negotiating the problem space. In this sense, we can see the beginnings of what Dorst and Cross (2001) described as the co-evolution of the problem and solution in the girls' discussion.

When Jen opened the discussion by suggesting that they make something to help Claudia and Jamie wake up, Alice's first response was to bring up a relevant criterion: "but it shouldn't be too noisy." Jen then introduced another consideration: Claudia and Jamie's lack of money. In these first three turns, the girls *named* three different problem considerations: the need to be woken up, not make too much noise, and limited money. After introducing these few criteria, they started brainstorming possible solutions, coming up with ways to make something vibrate and thinking about where Claudia and Jamie might find materials to make their design. As they narrowed down a possible solution, they *identified* sub-problems they would need to solve to make it work: how to make a box move, set up the device, and gather materials. That is, as the girls were trying to decide which solution path to follow, they considered sub-problems nested within one of the possibilities.

Jen and Alice's problem considerations spanned multiple categories, such as cost, feasibility, and usability. Moreover, they examined these problems by *navigating multiple perspectives*. Given that an engineering problem involves multiple players, such as the client, user, manufacturer, and salesman, thinking about problem constraints and criteria through these different lenses is a particularly productive beginning of Jen and Alice's engineering. They first considered their own perspective as designers and manufacturers in the classroom, deliberating about what they can make and how they can make it in the classroom: "I know what we can do," "we need something to make it move." Woven into their discourse, however, were considerations from the book, where their "clients" would be using their design. They considered the setting of the museum: "there might be night guards" and the characters' situation: "they wouldn't have enough money."

Interestingly, they also seemed to orient to another perspective that allowed them to use their personal experiences to project beyond the text and fill out the world of Claudia and Jamie. For example, they decided to make their design out of "everyday things" that Claudia and Jamie could find lying around. To then hypothesize what everyday things they might find, they relied on their own experiences: "You don't just find like things like batteries just laying around" and "like in the park, people always leave around things like Frisbees." Tapping into personal experiences is a technique that expert designers have been found to rely on as well. For example, in their case study of an experienced designer developing a carrier on a mountain bike, Cross and Cross (1998) documented how the designer considered his own experiences riding bikes over rough terrain and while carrying a backpack. Cross and Cross highlighted how these personal experiences allowed the designer to better scope the problem and identify stability issues for adding weight to the bicycle.

While Jen and Alice considered each of these perspectives in their exploration of the problem space, Alice explicitly argued for the importance of considering the book: "but you have to remember that it's not like present, it's in the past." In this move, she *evaluated* their problem space by arguing for the need to remember that the problem they were solving took place in the past. This meta-comment can be seen as the beginning of another aspect of problem scoping: *reflecting*, a practice Schön (1983) highlights in his analysis of design thinking.

Mike and Thomas Plan their Periscope

In the first year of the project, Mike and Thomas worked on a different problem: how to help Claudia and Jamie see a statue in the museum that was always surrounded by crowds of adults. The boys decided to build a periscope, perhaps in part because Mike had a periscope at home. While their quickness to make that decision fits accounts of novices (Crismond & Adams, 2012), they later spent more time scoping sub-problems nested within their main problem of how to make this periscope. During their conversation, we argue, they simultaneously engaged in planning their periscope and negotiating the problem space in which they were designing.

1 Mike: And do you wanna make this out of wood?
2 Thomas: Mmm, wood would be more artificial but it would take longer.
3 Mike: It would take longer, but it would be stronger, and um,
4 Thomas: But how would um they, how would they get the wood?
5 Mike: Do they have to?
6 Thomas: Yeah, but if they get if- when like- but- you know how Jamie is really cheap?
7 Mike: Yeah he is.
8 Thomas: So if, they wouldn't probably get the wood. They would probably get the cardboard, cause,
9 Mike: (softly) Yeah, I see what you're saying, I see what you're saying.
10 Thomas: Cause Jamie's cheap and he, and that would probably cost a lot more than cardboard.
11 Mike: (louder) But then cardboard wouldn't be as sturdy and um, you, you know how flimsy card board is. Yeah, I mean,
12 Thomas: But then they, once they get the wood they'd have to get the cardbo- Like they'd have to get glue. They'd have to get all this other stuff.
13 Mike: Why not just nails?
14 Thomas: Yeah, but nails cost money also. But we could still use wood and just pretend it's card board.
15 Mike: I don't- I don't think it has to be something that they would buy. I think that's, I don't think it would be like, they have to pay for it.
16 Thomas: OK.

This exchange began with Mike asking about the primary material with which they would build their periscope. This question opened up a negotiation between the boys, in which they discussed not only different materials, but by arguing about the importance of different problem considerations, they also negotiated the content and boundaries of the problem space for which they were choosing these materials.

We first notice that Mike and Thomas both *named* several aspects of the problem space that they thought they needed to consider. Thomas initiated this pattern by making explicit two criteria he was using to evaluate the material choice: whether a material is "artificial" and how long it will take to build. Mike responded by stating his own considerations, namely the time it will take to build and the sturdiness of the final product. Like Jen and Alice, they considered criteria across various categories: structural considerations, manufacturing feasibility, and cost. Mike emphasized the structural considerations, noting the strength of wood as a material and citing how flimsy cardboard is. Both Mike and Thomas considered feasibility by noting that the length of time it would take to build the periscope was a consideration for deciding which material to use. Thomas also raised a concern with how their "clients" might be able to get the wood. Similarly, he also introduced cost as a consideration, explicitly referring to the characteristics of the characters in the book to motivate this criterion (i.e., "you know how Jamie is really cheap?").

As with expert designers, Mike and Thomas were doing more than just listing different criteria across categories. They were actively involved in *balancing* and *prioritizing* these different considerations. For example, at the opening of this clip, Thomas did not simply list two criteria, he explicitly positioned them opposite each other to evaluate the material choice: "wood would be more artificial but it would take longer." Mike used similar language, acknowledging Thomas's point that wood would take longer to build with, but countering that it would contribute to the structural integrity of the device. In addition to balancing criteria within a speaking turn, they countered each other's points about how a material choice might meet a given criterion (for example, exchanges 11 and 12 each start with "but then"). In both ways, the boys were working to consider multiple criteria at once, weighing different considerations against each other in their choice of material.

In addition to balancing individual criteria, Mike and Thomas were explicitly *negotiating the different perspectives* involved in their problem. Like Jen and Alice, Thomas brought in the perspectives of the characters to consider the logistics of building, acquiring, and paying for the materials, particularly when he considered the stingy nature of one of their "clients," Jamie. Mike pushed against the role of this fictional world in their design, responding, "do they have to?" when Thomas asked how the characters would get the wood. Thomas eventually introduced a compromise — they could use wood in the classroom world, but pretend it is cardboard to satisfy the constraints of the fictional world. While they were considering individual criteria in this exchange, they were also *setting the context* of the problem space by considering how to incorporate and balance the different perspectives involved from both the classroom and book.

Finally, we note that Mike and Thomas were *reflecting* on their problem space, making this aspect of their designing even more explicit than Jen and Alice. For example, Mike's last comment in this episode, "I don't think it would be like, *they* have to pay for it," was a meta-comment about what they needed to consider in their design problem. While they chose at this point to not incorporate this aspect of the fictional world, they explicitly reflected on and discussed this decision. Thus Mike and Thomas were aware of other ways of scoping the problem with different considerations and constraints and made conscious choices about the problem space they were addressing. This exchange demonstrated productive seeds of reflective design practice for these students.

Zane and Sean Build their Money Scooper

Our third episode looks at the problem scoping that Zane and Sean engaged in while they were building a prototype of their design during year 2 of the project. Zane and Sean chose to design a device that would help the novel's protagonists collect change from the museum's fountain more efficiently than picking up individual coins by hand. The boys had spent time in previous days choosing this problem and planning their money scooper.

In the following clip, a classroom volunteer asked the boys to talk about their problem and the prototype they were building. Zane started by describing their problem: they need to make something that allows the novel's protagonists to "collect money" from the museum's fountain, "hold more money," and keep the money "somewhat quieter." Sean interjected with the phrase "in due time," referring either to the speed at which Claudia and Jamie would collect the change or the speed at which the boys would complete the design. Zane then explained their design. First, they planned to attach a perforated plastic bag to a dustpan, allowing the user to collect the change and drain off the water. The dustpan and plastic bag would be connected by a cardboard tube, which would be wrapped in duct tape so the cardboard would not get wet and "fall apart." He also pointed out that the plastic bag would contain soft materials to soften the noise of the collected money.

During Zane's explanation to the volunteer, Sean interrupted twice to voice his concern about the cotton balls and foam packing peanuts that Zane had put in the perforated bag. Sean first argued that the packing peanuts could make the bag float while they are trying to collect coins. His next concern was that the cotton balls would absorb water. Zane responded that they could squeeze the water out. As the volunteer prepares to leave, the boys continued to argue about the presence of cotton balls and other padding inside the bag.

> *Sean: Let's just not have all this stuff in there.*
> *Zane: And then we'll also squeeze the, that, so all the cotton balls, the water inside the cotton balls will [makes motion down with hands] leave.*
> *Volunteer: Awesome. Good job. You got a nice little money filter there. [Leaves.]*
> *Sean: We don't really need the [unclear]*
> *Zane: Come on, let's keep that there, just to keep it quiet.*
> *Sean: No, we don't really need to keep it quiet. We don't need to keep the money quiet though.*
> *Zane: Yeah, we do. Remember it was loud.*
> *Sean: That's probably someone else's.*
> *Zane: What?*
> *Sean: Keep Jamie's money quiet, that's a whole 'nother thing. [points to butcher paper across the room] That's a whole entire other problem.*
> *Zane: So? We can still do it, it'll be fine.*
> *Sean: But I don't want the stuff in there.*
> *Zane: Why not?*
> *Sean: It's going to be so hard to get the money out.*
> *Zane: How will it be hard?*
> *Sean: Because [reaches for bag]*
> *Zane: [Digging in bag] All they have to do is reach in, do that, look for the money, take it out.*
> *Sean: No, but then when you-*
> *Zane: It's not much.*
> *Sean: when you pour the water out and then eventually when they're done taking the bath [makes air quotes], then you're going to have to, then all that stuff is going to come with the money. And we're going to have to keep changing it over and over and over. That stuff isn't going to dry overnight.*
> *Zane: No, you just squeeze it out over the, um-*
> *Sean: Still, it's not going to dry. Overnight.*

In this exchange, Zane and Sean argued about a particular feature of their design – the inclusion of foam peanuts and cotton balls in their bag. As they evaluated this feature, they negotiated how to *prioritize* the different problems of collecting money and keeping the coins quiet. They also *identified* the sub-problems that arose from their solutions, such as how to retrieve the money easily from their waterlogged bag. This exchange therefore reflected problem scoping at multiple levels of problems in their design (Roth, 1995).

Zane introduced their main problems by explaining (1) that the money scooper needed to be able to collect and hold money and (2) that it should keep the money "quieter." During their presentation to the researcher, both Sean and Zane *named* several criteria related to these problems, considering client needs, usability, and structural considerations. For example, Sean seemingly voiced concern about efficiency – stating that they needed to collect the money "in due time." Zane highlighted structural considerations of their design when he described how they would cover the cardboard tube with duct tape to protect it from water. Like the other student pairs, they *navigated different perspectives* to scope these problems, considering themselves as manufacturers and the characters in the book as clients.

While presenting the specifics of their design, Sean *considered interactions* among their problem considerations. He realized that their solution to keeping the money quiet might be in tension with the problem of collecting money. In particular, he pointed to several sub-problems that arose as a result of keeping the filler materials in the bag. He brought up a possible sub-problem related to usability when he argued that the soft materials would make it difficult to get the money out of the bag. He also expressed concern about how the water would affect the filler materials, by either making the bag float or keeping the design wet for long periods of time.

After realizing this potential conflict in their design, Sean argued that they should not keep the filler materials in the bag, leading to a negotiation between the boys over how to *prioritize* the problem consideration of keeping money quiet. Zane considered this problem alongside the problem of gathering money from the fountain. He acknowledged Sean's concerns about the functionality of the filler materials in the bag, but volunteered solutions that allowed the cotton balls and their sound-muffling capacity to remain a part of the design. When Sean argued that they did not need to keep the money quiet, Zane reminded Sean that the noise the loose change made was a noticeable problem: "Remember, it was loud." In contrast, Sean placed more weight on their first problem: collecting and retrieving money. He argued that muffling the sound of the money was not needed, as other student designers were considering this problem: "Keep Jamie's money quiet, that's a whole 'nother thing. That's a whole entire other problem." In this disagreement, Zane and Sean were exploring criteria and constraints at multiple problem levels, examining how problems interact with each other, and negotiating the importance of different problem considerations.

Problem Scoping Nested Within a Disciplinary Pursuit

In the above analyses, we document how these students' design behaviors reflect aspects of the complexity and nuance in expert practice. We argue that simple measures—counting the number of criteria, recording the time spent—would miss how Jen and Alice explored different players' perspectives on the problem, how Mike and Thomas reflected on their design decisions, and how Zane and Dean negotiated over how to prioritize their different problems. These clips, while chosen because they were exemplars, highlight these students' promising abilities to engage in problem-scoping practices of expert designers.

While these individual problem-scoping behaviors are important, we also argue that researchers need to consider how they are embedded for students within a larger purpose or activity. For example, we need to consider not just whether students are naming a particular criterion or balancing different considerations, but also whether students are doing those things as part of their pursuit of a design solution.

This argument is motivated by findings that students' individual behaviors can be disconnected from their designs. For example, Bursic and Atman (1997) found in their analyses that students may list particular criteria but not tie them to their development of the problem or solution. Similarly, we could find that students demonstrate other design behaviors, such as weighing criteria, without making connections to a larger endeavor of designing and building a solution. The danger in focusing solely on individual actions of problem scoping (or testing, building, planning, etc.) is that these actions may in actuality be a part of a different activity from design, particularly in school or interview settings. Phenomena of students carrying out steps in the service of making their way through a worksheet or an instructed procedure are familiar in other areas, from science investigations (Tang, Coffey, Elby, & Levin, 2010) to math class (Schoenfeld, 1988). As a result, science education researchers have argued that practices such as experimentation and argumentation need to be embedded in a larger endeavor of building and evaluating models of the natural world (Berland & Hammer, 2012; Ford & Forman, 2006; Hammer, 1995; Lehrer, Schauble, & Petrosino, 2001). Otherwise, these actions are at risk of being disconnected from the actual doing of science or being solely in service of a school-ish activity, such as "answer-making" for the teacher or interviewer (Hutchison & Hammer, 2009). Therefore, we argue that analyses of students' designing needs to attend to how their problem-scoping (or other design) actions are connected to a larger disciplinary activity, namely the pursuit of developing solutions to ill-defined engineering problems.

Simple methods of characterizing students' designing cannot capture the nuances of this aspect of their engagement. Therefore, we again suggest the need for more detailed, qualitative accounts to unpack some of the complex dynamics relating students' design actions to broader purposes. In particular we show here how looking closely at students' talk can reveal how students make explicit to each other the purpose of the activity and its connection to their problem scoping. For example, in the first episode, Jen and Alice were just starting out in their collaboration and therefore made several comments to communicate purpose: "I know what we can do, see, like, make something…", "what should they do?", "We need something to make…" These comments reveal an orientation to finding a problem and a solution. Furthermore, the first and last quotes suggest an expectation that they (or the characters) would "make" or build a solution and the resulting conversation about criteria is then linked to what they need to make.

Further along in the design process, Mike and Thomas's problem negotiations emerged from deciding on a key material choice: whether to make the device out of wood or not. Throughout their discussion, we noted that their introductions of new constraints or criteria were connected to this material selection. For example, in discussing the importance of cost for the problem because of the client's preferences, Thomas explicitly referred to the consequence of this criterion for their material choice: "Cause Jamie's cheap and he, and that [wood] would probably cost a lot more than cardboard." In this quote, he articulates how the criterion of cost has concrete implications for the solution, thereby reinforcing that this discussion was nested within their pursuit of a design (that either they or their clients could build) to solve a complex problem.

Lastly, Zane and Sean's argument focused on the inclusion of soft materials in their money scooper bag, a design element of their solution. Their comments about prioritizing different aspects of the problem were often in response to the need to justify whether to include or exclude these materials. For example, Sean's concern about the difficulty to get the money out of the bag arose from Zane's questioning about why he didn't want the "stuff in there." Similarly, Zane's emphasis on the importance of keeping the money quiet was used as justification for keeping the materials there. In these ways, Zane and Sean tightly connected their exploration of the problem to the design and evaluation of their solution.

Discussion

A major focus of engineering education research has been examining and comparing students' and experts' design processes. We argue here that by broadening our ways of identifying and evaluating students' problem scoping, we notice more of the richness of beginning students' starting endeavors than we would by counting the number of pieces of information they mention or relying on timing. The need for expanding research methodologies in engineering education has been previously discussed in the literature (Borrego, Douglas, & Amelink, 2009; Case & Light, 2011). Most recently, Case and Light (2011) argued the need to consider more diverse methodologies to broaden the research questions the community addresses. In this paper, we add to this call by showing how narrow characterizations of students' designing can impact not only the questions researchers address, but also the claims about what students do.

The richness we documented in our analyses highlights the implications of simple methodologies for research claims. In particular, we contend that the students in these three episodes demonstrate greater abilities for problem scoping than suggested by previous research (Crismond & Adams, 2012). Similarly, Roth (1995) developed a case study of elementary students building an "earthquake-proof" tower, examining how the students interacted with and constructed different problems during their construction of the tower. Roth found that students displayed "uncanny competence" for responding to and negotiating the dynamic problems and solutions. While we focus on problem scoping in this paper, it is likely that richer conceptualizations of other aspects of the design process will help provide a more developed picture of what beginning students are able to do in design more broadly.

In addition to expanding our notions of what students can do, a more complex approach to studying problem scoping has implications for what is supported in the teaching and learning of engineering design. Prior methods, used as the bases for assessment rubrics, could send the message that educators should focus on simply increasing the number of criteria that students mention and encouraging students to spend more time problem scoping. Furthermore, even strategies as straightforward as helping students search for background information or prior art (Crismond & Adams, 2012) can backfire for students if, for them, conducting the search is a *pro forma* obligation to the teacher rather than a meaningful part of their designing. Instead, we advocate that teachers need to attend and respond to the rich beginnings of problem scoping, rather than simplistic measures of their students' engineering. By providing complex images of what engineering design can look like in the classroom, research can help teachers better recognize productive aspects of their own students' engineering.

Furthermore, this type of in-depth qualitative research is particularly needed as engineering educators develop policies and goals for K-12 design education (Rogers, Wendell, & Foster, 2010). As the community develops a vision for K-12 engineering education (Marshall & Berland, 2012), providing this type of thick description of students' designing will help develop productive goals for what engineering can look like in the classroom. Having a more complete and developed picture of what even young students can do will impact recommendations and expectations for engineering design education at all ages. Districts and states are currently preparing standards and assessment measures of students' engineering design (e.g. Massachusetts). Therefore, engineering education researchers need to provide accounts of the depth and complexity involved in classroom design projects to inform perspectives on what and how to measure learning in engineering design.

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