AC 2012-3906: NEGOTIATING STEM EPISTEMIC COMMITMENTS FOR ENGINEERING DESIGN CHALLENGES

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Negotiating STEM epistemic commitments for engineering design challenges

There exists an increasing emphasis on engineering students collaborating on engineering design challenges throughout their educational experiences. Collaboration includes the expectation that students will negotiate across their different ideas in order to converge on a single understanding and, in the case of engineering, a single design. This convergence requires that individuals compare and evaluate their disparate ideas as they move towards consensus. Solving engineering challenges requires that individuals apply knowledge from numerous domains (i.e., traditional science and math content), each of which has unique epistemic commitments for guiding decision making and negotiation processes. The inter-disciplinary nature of engineering work raises questions about which epistemic commitments individuals will use to guide their collaborative decision-making. As such, this paper explores the question: how do novice engineering students negotiate and apply their various epistemic commitments to their collaborative decision making?

Background

Engineering is often characterized as the application of math and science to solve society’s problems. As such, engaging in engineering design challenges requires that individuals consider and use relevant engineering, math, and science concepts and processes—that is, it requires that individuals work across numerous domains. In this paper, we posit that the cross-disciplinary nature of engineering design work is potentially challenging for students as they learn to not only engage in engineering design practices but to do so while negotiating the epistemic commitments of these disparate domains.

Synthesizing the literature comparing these disparate fields, we see that math, science, and engineering have much in common but differ on a few key features. In all cases, individuals are: constructing and testing models of the object of study and engaging in systems thinking. In addition, in all three fields, knowledge is built through a social process in which ideas and solutions are argued for, challenged and revised. As such, many of the activities in which one participates as they engage in scientific, mathematics, and engineering problem solving are similar.

However, the goal of this problem solving and the epistemic commitments to which individuals attend as they do so differs across the domains. For example, the goal of science is to construct explanations and generalizations that explain numerous phenomena while the goal of engineering it is to design a specific solution to a problem. As such, the decisions that are made differ:

In engineering the goal of argumentation is to evaluate prospective designs and then produce the most effective design for meeting the specifications and constraints. This optimization process typically involves trade-offs between competing goals, with the consequence that there is never just one ‘correct’ solution...In contrast, theories in science must meet a very different set of criteria such as parsimony...and explanatory coherence...Moreover, the aim of science is to find a single coherent and comprehensive theory for a range of related phenomena.
While we make no pretense of resolving the many disputes regarding the philosophies of each of these fields, we submit that there is agreement on fundamental goals and epistemic commitments that drive the work within each of them. Table 1 summarizes this agreement.

Table 1: Comparison of epistemic commitments and practices in mathematics, science and engineering

<table>
<thead>
<tr>
<th></th>
<th>Science</th>
<th>Engineering Design</th>
<th>Mathematics</th>
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<tbody>
<tr>
<td><strong>Goal</strong></td>
<td>Explain natural phenomenon by building general principles, understanding the world</td>
<td>Solve a problem through design, changing the world</td>
<td>Identify patterns and structures on which to base conjectures regarding future patterns and structures.</td>
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</table>
| **Common Processes**| • Ask and refine questions  
• Construct and use models  
• Plan investigations  
• Predict and construct explanations  
• Construct arguments from evidence  
• Test and evaluate explanations | • Define problems  
• Research and brainstorm possible solutions  
• Construct and test prototypes  
• Construct arguments from evidence  
• Evaluate solution  
• Iterate and revise solution | • Make sense of problems  
• Reason abstractly and quantitatively  
• Construct viable arguments  
• Construct and use mathematical models  
• Evaluate solution |
| **Epistemic commitments that Guide Decision Making** | • Alignment with existing scientific knowledge  
• Appreciation for parsimony  
• Expectation that explanation/model/argument will account for all known evidence with theory | • Solution must fulfill requirements within constraints  
• Need to make trade-offs  
• Failure must be obviated  
• Design is done with attention to user-needs  
• Solution must be practical | • Alignment with known/agreed upon mathematical principles and axioms  
• Expectation of precision  
• Use of patterns and structure to guide solution-finding |

Given the differences and similarities in the questions that each of these fields addresses and the ways in which they do so, it stands to reason that, as individuals shift between the domains—as they apply mathematical processes such as reasoning about geometric axioms and scientific knowledge such as the way that light travels to solve an engineering challenge such as constructing a pinhole camera—epistemic commitments from each of the utilized fields may
emerge as relevant to the decision making process. Not only is this a reasonable expectation, but a hoped for result.

That is, engineering education in pre-collegiate and collegiate settings is increasingly expected to teach students both how to engage in engineering design and to work with the epistemic commitments that guide the engineering design processes, as well as particular science and mathematics content goals. Doing so requires that one potentially apply each of these criterions, from each of these relevant domains, as they move through their engineering design projects. This study explores this conjecture, examining the types of information novice engineering students apply to their decision making processes as they engage in an engineering design challenge. As such, this study answers the question: How do novice engineering students negotiate and apply their various epistemic commitments to their collaborative decision making?

Study Context

The professional development program studied, a collaboration between the colleges of science and engineering and a teaching preparation program at our university, offers several programs for pre-service and in-service teachers to support their use of innovative engineering curriculum. The specific course examined in this paper provides an in-depth, hands-on six-week summer workshop for in-service teachers. Fifteen in-service teachers participated in this course; 9 females and 6 males. The participants ranged in experience from 1 year to over 20 years of teaching, came from a variety of middle and high schools from the area, and taught several subjects ranging from mathematics to engineering. A few of the teachers had a bachelor of science in engineering, but for most, engineering design was a new topic. They were participating in the focal course as well as the professional development program writ large to develop expertise in engineering teaching. This context was chosen because the participants had limited engineering background but expertise in related math and science content. It was expected that this combination of background knowledge would be ideal for an exploratory study examining how novice engineers use math and science concepts, processes and epistemic commitments in their engineering decision-making.

The focal course includes instruction on engineering design methods through a design challenge taken from a yearlong engineering course designed by professors and clinical faculty working on this project as well as on engineering education issues including pedagogy and equity. The design challenge enacted during the 2011 institute, “From Pinholes to Pixels”, challenged the participants to create a pinhole camera as a means to understand the how and why of the engineering design process as well as providing an authentic context in which to apply prior knowledge from mathematics and physics. It is assumed that students entering the course have: 1) algebraic skills to be able to find slope and use equations for lines, 2) geometry skills to be able to use a coordinate grid, understand the concept of similar figures and the area-diameter relationship of circles, and 3) physics knowledge of light reflection and how light travels in straight lines. While these concepts are considered pre-requisite knowledge, the concepts are reviewed within the first few lessons of the unit. The unit consists of 11 lessons and was taught over the course of 9 3-hour workshops. The lessons were organized into lesson sets grouping together broader learning episodes; these lesson sets are described in greater detail in table 2.
Table 2. Unit Plan for “From Pinholes to Pixels”

<table>
<thead>
<tr>
<th>Lesson Set 1: Understanding and Characterizing (3-5 days)</th>
<th>Description</th>
<th>Lessons</th>
</tr>
</thead>
</table>
| The students are introduced to the topic from the scientific viewpoint to understand how science and technology exist in parallel with the evolution of societal needs and that engineers are the people who apply scientific knowledge to solve societal needs. | 1. We need Engineers and Engineers Need Us  
2. Describing the Need  
3. Characterize and Analyze the System | |

<table>
<thead>
<tr>
<th>Lesson Set 2: Creating and Selecting a Concept (3 days)</th>
<th>Description</th>
<th>Lessons</th>
</tr>
</thead>
</table>
| The students use design requirements and customer needs information to create and select a design. The goal is to model the decision making process as a structured, purposeful process rather than choices due to personal preferences. | 1. Generating Concepts  
2. Selecting the Concept | |

<table>
<thead>
<tr>
<th>Lesson Set 3: Building, Verifying and Refining (6-10 days)</th>
<th>Description</th>
<th>Lessons</th>
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</table>
| Students build and use their cameras, evaluating the success based upon how they met the design requirements. The emphasis of this set of activities is the plan to measure and test for those requirements. | 1. Embody the Concept  
2. Test, Evaluate and Refine  
3. Finalize and Share the Design | |

<table>
<thead>
<tr>
<th>Lesson Set 4: Evolving Over Time (2 days)</th>
<th>Description</th>
<th>Lessons</th>
</tr>
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</table>
| Students set their work in the larger context of current technology by completing a parallel activity involving research on the grand achievement of imagery. Students also reflect on their learning. | 1. Historical Timeline Presentations  
2. Reflect on the Engineering Design Process | |

Data Sources

Two teacher groups were videotaped as they navigated through the pinhole camera unit. The first group comprised 2 females, and the second group comprised 3 females and 3 males. Initially, the second group was only 2 females and 1 male, but early within the unit, another group merged with them. The first group will be referred to as the “pair” and the second group will be referred to as the “group” throughout this paper. The groups were chosen because preliminary observations suggested that these participants would be talkative and articulate their thinking, essential elements to the discourse analysis methods that we employed.

All discussions the participants had throughout the design unit were video-recorded. To focus our analysis, video segments from two of the design phases – generate and embody – were chosen based on high levels of negotiation and discourse.
Analytical Methods

These video recordings were transcribed for analysis. The analysis process took multiple steps:

1. The second author read through the transcripts, identifying the places that participants made their decision-making criteria explicit and identifying types of criteria participants were using. This provided a data-driven taxonomy of criteria used by the participants in their discussions.
2. Both authors performed a literature review, identifying key epistemic commitments that align with each of the focal domains (math, science and engineering). The theory-based list was aligned with the data-driven list, to identify possible criteria that had been missed in the data-driven process. Table 3 reveals the results of this process.
3. Both authors coded the data independently using the data-driven and theory-driven categories.
4. Results were compared and disagreements were resolved through discussion.
5. The second author made a final pass through the data ensuring that codes were applied consistently throughout.

This process of using existing literature to interpret and refine coding schemes and then coding the data with the result of that process aligns with constant-comparative methods in which researchers work to ensure that data is analyzed iteratively as new possible patterns are identified. In addition, this process worked well for our research question as we hoped to find where student discourse did and did not align with the epistemic commitments of the focal disciplines.

Table 3. Comparison of theory-driven and data-driven epistemic commitments

<table>
<thead>
<tr>
<th>Engineering Commitments</th>
<th>Theory Driven</th>
<th>Data Driven</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Need to fulfill requirements within constraints</td>
<td>Various design requirements</td>
</tr>
<tr>
<td></td>
<td>Need to make trade-offs</td>
<td>None seen</td>
</tr>
<tr>
<td></td>
<td>Failure must be obviated</td>
<td>Redundancy</td>
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<tr>
<td></td>
<td>Design is done with attention to user-needs</td>
<td>User needs</td>
</tr>
<tr>
<td></td>
<td>Solution must be practical to build/scale</td>
<td>Student needs</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Aesthetics</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Feasibility of build</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Availability of materials</td>
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<tr>
<td></td>
<td></td>
<td>Capabilities of materials</td>
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<tr>
<td></td>
<td></td>
<td>Classroom logistics</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Classroom budget</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Time</td>
</tr>
<tr>
<td>Science Commitments</td>
<td>Alignment with scientific principles</td>
<td>How light travels</td>
</tr>
<tr>
<td></td>
<td>Appreciation for parsimony</td>
<td>None seen</td>
</tr>
<tr>
<td></td>
<td>Account for all known evidence with theory</td>
<td>None seen</td>
</tr>
<tr>
<td>Mathematics Commitments</td>
<td>Alignment with mathematical axioms</td>
<td>Similar triangles</td>
</tr>
<tr>
<td></td>
<td>Looking for patterns and structures</td>
<td>None seen</td>
</tr>
<tr>
<td></td>
<td>Measurement</td>
<td>Measurement</td>
</tr>
<tr>
<td>Common Ways of</td>
<td>Consensus building through argumentation</td>
<td>Consensus</td>
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<tr>
<td></td>
<td>Test / Model / Appeal to Evidence</td>
<td>Request to test</td>
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</table>
We organize our discussion of the criteria that students apply to their decision making around the 3 focal fields: engineering, science, and mathematics. We conclude by examining whether and how participant decision-making exhibits ways of thinking that are common across these three domains.

**Engineering Commitments**

Because the lessons observed were a part of an engineering design curriculum, it is not surprising that engineering commitments were used the most often in the participants’ work. In particular, three of the common engineering commitments emerged as most relevant and useful for these participants: attention to design requirements and constraints; attention to user needs; and developing a practical solution. We saw little evidence of the remaining key engineering commitments: obviating failure and making trade-offs. In this section, we describe and exemplify the three emphasized commitments.

**Design Requirements**

Across the groups and phases, 26% (ranging from 17 – 33% within each group and phase) of the criteria discussed by the participants were focused on design requirements—on finding ways to fulfill the requirements of the design challenge. These discussions emphasized a range of requirements—some of which were provided by the course instructor and others of which were identified within participant groups. Requirements that participants emphasized through their discussions include user activities such as: accurately aiming the camera; loading the film reliably; holding the camera steady; measuring the distance from the camera to the pictured object; loading multiple pieces of film at once; and changing the focal length of the camera. In addition, participants discussed key requirements for how the camera would function including: preventing unintended light from entering the camera and holding film that was the specified size.

For example, when building their camera—embodying their concept—Tina and Sara struggled with creating a way that the user could adjust the focal length of the camera. During their discussion of this, Tina suggested using a slider that would stick out of the camera through a slit. Sara questioned the veracity of that approach because light would enter through the slit. In other words, she was concerned that this approach would not meet the design requirement that no unintended light enter the camera. This concern is italicized in the transcript below.

| Tina | … Cut a slit at the top and just do it like that. |
| Sara | Mm-hmm. *But if we do that, doesn't light come in?* |
| Tina | Yeah, we'd have to...[inaudible]...and block it. So maybe....We could just do something, like, if we're looking at it, not pull it through here, right? |
As seen in this excerpt, Tina responded to Sara’s concern about meeting the design requirement by altering her design—thereby basing her decisions on their ability to fulfill this requirement.

We use an example from the group’s generating a concept discussion to further illustrate the ways in which participants attended to the design requirements during their discussions. In this case, the participants are figuring out a way to allow the user to aim the camera. Two competing suggestions are to: 1) use a paper towel or toilet paper roll glued to the top of the camera and to or 2) put a straw through the camera.

Jen …maybe having a slight external viewfinder by essentially gluing on, like, a toilet paper or a paper towel roll on top and doing it dead center.
Lisa I like the straw idea. I thought the straw was very good, because it helps prevent a lot of light.
Jen But if you're – but if it's glued to the top, it wouldn’t matter, right?
Lisa But as far as what is actually being seen, like, what the photo is actually going to be of, you know, a paper towel is going to indicate that I can see a lot more of <inaudible>.

In this exchange, Lisa indicated concern with meeting the design requirement of preventing light when she positively evaluated the suggestion of using a straw that goes through the camera based on its ability to fulfill that requirement. Jen reinforced the importance of this requirement when she argues that her own plan—gluing a paper towel roll to the top of the camera—would also prevent light: since it was outside the camera “it wouldn’t matter.” Lisa then raised the requirement that users be able to accurately aim the camera by questioning whether the paper towel would allow users to see what they were photographing. Thus, we see that, in this discussion, participants are basing their decision about how to aim the camera on 2 design requirements: the need for the user to accurately aim the camera and the importance of preventing unintended light from entering the camera.

Practicality

Practicality, defined as whether and how easily they could build the designs, also emerged as a key decision making criterion for these groups. In fact, across the groups and phases 25% (ranging from 15-32%) of the criteria discussed were focused on this issue. When discussing practicality, participants were focused on issues such as the: feasibility of a building step; time available to build; availability of materials; and capabilities of materials. For example (key utterances are italicized):

- Feasibility – “Cubes are easy to stack. They're easy to work with. We could do that.”
- Time – “I just, I mean, if we could find a way to do it easily with the time constraints.”
- Materials Availability – “It’s going to be like this or this…whatever we can get a hold of.”
- Materials Capabilities – “Okay. I hope it's strong enough to go through this.”

User needs
Both groups often considered the user when making decisions. This manifested as attending to actions the user would have to perform to use the camera as well as aesthetics. User needs were made explicit in 23% (12–35%) of the criteria across design phases and the groups, with greater importance during the generating concepts phase (35% for pair and 22% for group). In the example below, the pair is questioning the ability of the user to easily aim the camera:

Sara  But then if you’re trying to make it people friendly, how are people going to be -- are they going to be making calculations with this? Are they going to be guessing how much height lower or higher they’re going to go?

In this case, her concern with aiming the camera isn’t simply that it needs to be possible (i.e., that they need to fulfill the requirement). Instead, she is explicitly concerned with the user’s ability to aim the camera easily. As such, this is an example of the participant attending to user needs as a decision-making criterion.

Since this class was learning how to teach this unit to their own students, the large group considered their end user to be their students. As such, when considering the user needs, they frequently questioned whether and how they would use the camera in their classroom. For example, in the excerpt below, Mary argues that she would not want to have more than 2 pieces of film in the camera at a time because the film is too expensive to allow students to make the same mistake twice (i.e., to take two pictures without looking to see if the first one was acceptable). In this case, Mary is considering herself and her students as the users of the camera.

Mary  The amount of time it will take to get ready to set up a picture, to take it, and to get back in and manage that is going to be one class period, hopefully. Okay? So, and if I have expensive photo paper in those boxes, and I'll have more than one, the kids will mess it up, and we're only going to get one good picture out of it anyway. So, I would not want to have more than two in there, if more than one, just because you have to take the shot for so long, and organizing a classroom of 30 kids.

Across these disparate examples we see that, regardless of who the teachers identified as the end user of their cameras—unknown photographers, themselves, or their own students—they were invested in designing and building a camera that would be ultimately usable.

As should be expected with an engineering design challenge, the most common criteria these participants used when making design decisions were those associated with the engineering domain. The work of real engineers involves the use of the same types of criteria – design constraints, user needs, and practicality – so it stands to reason that a well-planned design challenge would offer those same opportunities in the decision-making process.9

Science and Mathematics Commitments

Although this design challenge was created to have a strong connection to mathematics and science, science and mathematics commitments were used very little. In fact, in the science domain, the only scientific decision making criteria to which these participants appealed was
alignment with existing principles. Similarly, in the math domain students exhibited only one mathematical criterion: measurement. Moreover, even in these instances, scientific concepts and measurement were only touched upon and never explored in-depth. Science was used more often than mathematics, but, in the end, both were used as “sound bytes” without developing or discussing the content. Possibly as a result of this superficial treatment, the participants were able to maintain incorrect understandings of the underlying science concepts throughout their design work. We exemplify use of scientific concepts and mathematical measurement in the following sections.

Science Concepts

The scientific principles related to how light travels were the most relevant concepts to this particular challenge and it was hoped that the participants would use the challenge as an opportunity to explore and deepen their understandings of these ideas. However, only 2% of the teachers’ explicit criteria exhibited a reliance on these science concepts.

The transcript below is one of the most in-depth discussions observed regarding how light travels. It illustrates the ways in which participants could have explored these concepts. In this particular discussion, teachers in the large group are discussing how light moves—once the light rays enter the pinhole camera, where will they go?

Matt  The film necessarily, like, if you had something in behind it, like this, then you had four behind it, and the light's coming in at an angle like this, and it's projecting out like that, so you have like…[drawing]…things in a row like that. And the light was coming in at an angle. When it hits this edge, is it going to go down and up? Does that make any sense?

Jen  Both down, that it's going to spread out?

Matt  Yeah, so like, from the side, you have things like –

Jen  Like disperse?

Matt  Yeah – like this, right? And if the light's coming in at an angle like this.

As seen in the above exchange, the project context created opportunities for participants to explore principles related to how light travels. However, they rarely did so and, instead, they stated scientific concepts quickly and worked with them as constraints they had to accommodate but did not need to explore further. For example, in the following excerpt, Sara and Tina are discussing how they can have a viewfinder while simultaneously preventing light leaks.

Sara  Why don't you put something small like a straw and tunnel it all the way back? So, that way, when you look through the straw, that one's not going to be exposing any light. You know what I mean?

Tina  You would have to wrap it in something, because it would be exposing light.

In this case, Sara and Tina determined that they could use a straw as a viewfinder if they wrapped it in something to prevent unintended light from entering the camera. This discussion is an opportunity for the them to explore how light travels—similar to the example from Matt and
Jen, Sara and Tina could have asked how the light would travel through the straw. For example, they could have wondered whether a bent straw works as a viewfinder and, whether light would leak out of the straw and onto the photo paper. Instead, they emphasized the need to limit light leaks without further exploration.

In fact, these teachers had ample opportunities to explore the scientific principles related to how light travels: across groups and project phases, 60% of the instances in which participants were discussing design requirements, they were focused on requirements that touched on these principles (in particular, they were discussing aiming the camera and preventing light leaks). However, more often than not, they stated the requirement as a given without delving into the underlying science (i.e., they stated that the user needs to be able to aim the camera rather than discussing how light travels to determine how users can aim the camera). We do not mean to suggest that they should have always treated the science in-depth: their goal was to fulfill the design requirements and, as such, they only needed to understand the science well enough to build the camera. However, these participants did exhibit some misconceptions that could have been resolved through more thoughtful discussions of the science. For example, Tina thought a bent straw would work as a viewfinder (we believe she was picturing a periscope but not considering the requisite mirrors) and participants in the large group were unclear about how light would reflect off of the surfaces inside their camera. As such, we suggest that these participants would have benefitted from a more careful exploration of these underlying principles.

Mathematical Axioms and Measurement

This particular design challenge creates opportunities for students to engage with the mathematic process of measurement (i.e., students measured: distance from the focal object, focal length, film size, etc.), as well as the axioms related to similar triangles (as seen in Figure 1, similar triangles explains how these distances are related to one another). However, we saw little evidence of participants addressing these concepts. In fact, across the groups and phases, only 3% (ranging from 0-6%) of the criteria discussed aligned with these mathematical commitments.

\[
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\frac{F}{f} = \frac{D}{d}
\]

**Figure 1:** Depicting the relationship between object distance, size, focal length and film size.
In addition, when these criteria were addressed, they were only discussed lightly—similar to the treatment of scientific concepts. The excerpt below exemplifies this lack of depth. This example occurred in the large group as they were considering the relationship between the photographed object’s size and distance from the camera.

Jen: This is just for our picture, it's going to be two. But for other pictures, we looked at distance. *Like with the tree out there, if you have a 15-foot-tall tree, your distance away is going to be 25 feet.*

As seen in this example, Jen has touched upon issues of measurement and the relationship between object distance and height, but did not discuss them. In fact, she provides no explanation (or accompanying drawing/representation) as to why a 15-foot tall focal object would require that the camera be 25-feet away (this claim is only true if the height of the film is 2/3s the length of the camera).

Even with this paucity of exploring these mathematical concepts, we suggest that the challenge offered opportunities to consider them, particularly when addressing the design requirements related to focal length and the distance from the focal object. This hypothesis is analogous to drawing on scientific concepts to understand how and why to prevent unintended light from entering their cameras. However, across the groups and phases, only 7% of the design requirements discussed related to these mathematical commitments. Students were able to largely ignore these mathematical axioms because they did not hold the film size or distance to the focal object as stable constraints. Instead, they seemed to revise those criteria as needed.

Through this we see that, on the whole, the epistemic commitments of science and mathematics was not driving decision making nor was, more specifically, the related math and science concepts; the concepts were either treated as constraints on requirements or mentioned in isolation. Connecting science and mathematics concepts to design activities has been shown to be difficult and only occurs if the activity or instructional leader scaffolds and encourages “science talk”.

In this particular design activity, the students were able to make a working camera despite not attending to scientific and mathematics principles, so it seems as if conceptual understanding was not essential. Leonard suggests that because it is possible to construct a working product without exploring the underlying math and science, even more scaffolding is needed to focus student attention on “how does it work?” instead of “does it work?”

**Common Ways of Thinking**

In addition to looking for specific instances in which participants were clearly using epistemic commitments that aligned with the different disciplines of engineering, mathematics, and science, we looked for instances in which the participants’ thinking exhibited traits shared across these disparate domains. In particular, we looked for instances in which the participants were engaged in systems thinking, testing/modeling, and reaching consensus. We expected that this alignment would create a situation in which the participants were engaged in engineering practices in a way that could support their work in science and mathematics—another possible
path to integrating the engineering, math and science. However, the participants rarely exhibited these particular ways of thinking.

Of the three ways of thinking examined, systems thinking—such as considering how the individual components of the camera would work together—was the considered the most often. Testing, including actual testing of ideas as well as statements identifying the need to test, was more common later within the embodiment phase. The participants rarely indicated that they were using consensus—group agreement—as a criterion for reaching a decision.

*Systems thinking*

When engaging in systems thinking, one is considering both the components of the system and the relationships between those components within the system. For example, in a scientific context, systems thinking is evident when students explain how changes in one population (a component of the system) will affect other populations in the ecosystem (other components within the system). This is a commonly considered an overarching theme in science education as it appears across the scientific domains,¹ and is highlighted as a key aspect of problem solving in engineering design work.¹⁶,¹⁷ In addition, mathematical modeling requires systems thinking as individuals work to best represent the quantifiable relationships between parts of the system.

On average, 8% of the criteria discussed revealed participants engaged in systems thinking, however its use was uneven; the pair exhibited systems thinking more than group. The pair used systems thinking in 7% of their decision-making criteria during the generation phase and in 26% during the embodiment phase, whereas the group used systems thinking in only 1% of their criteria during the generation phase and in 3% during the embodiment phase. In the example below, the pair is building separate components of the camera and realizing that the pieces that they have made—the channels/frame to hold the film and the viewfinder—do not fit inside of the box.

Sara: So, the reality...[tries to place the viewfinder in the box, finds that it doesn't fit]
Tina: It [viewfinder] is exactly the size of the box, so I probably need to cut it down a little bit.
Sara: Right, but if you do that, then there's no space for the channels. The channels would have to be really, really, really thin. You know what I mean?
Tina: [cutting] Mm-hmm.
Sara: Because it has to be fitted right there. And, okay, the viewer.
Tina: But we have to set it down in there.
Sara: I know.

In this exchange, Sara and Tina began by focusing on inserting one of their camera components into their box (their selected camera container)—the viewfinder. Upon realizing it does not fit, Tina suggested cutting it slightly. Sara responded to this by expanding the problem: rather than focusing solely on whether and how the viewfinder fits in the box, they needed to consider all of the components in their camera. In other words, Sara responded to the current challenge about a
single component by asking how it will affect their camera-system. As mentioned above, we saw a few instances of this across the groups and phases, however it was emphasized (about a quarter of the criteria they discussed revealed systems thinking) when the pair was building their camera. We discuss the implications of this variation in the discussion section.

*Testing/Modeling*

In this context, we use the term “testing” to refer loosely to the gathering of empirical data. As such, it refers to collecting observations that demonstrate the veracity of a claim or design idea. This often requires modeling all or a portion of the phenomenon or design under study. For example, in the engineering context, one might construct a model or prototype of their design to test the viability of a particular design approach.

In this data set we saw evidence that the participants were valuing this testing/modeling process when they either physically tested whether a design component worked or requested to do so. On average 9% of the criteria used to justify claims was testing/modeling. The vast majority of this occurred during the embodiment phase of their work (20 and 13% in the pair and group, respectively). Given that these participants did not have physical materials that they could test during the generating concepts phase, it is unsurprising and appropriate that testing was more apparent when they engaged in embodying their concepts.

The excerpt below illustrates participants building a model to test the efficacy of their designs. In this case, members of the large group are discussing the need to build one camera—a model—to see if it would work.

```
Matt  I don't know. I was kind of thinking, and I was talking to Jessica out there. We were kind of thinking that maybe we should build this one *just to make sure that we can build it and, like, how everything is going to work.*
Megan Yeah, I think we should build....
Matt  And then that way, *when everybody builds their own, it'll be a lot easier.*
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In this instance, the participants decided to use the first camera they built as a prototype to ensure that all the components fit together and worked as expected. They would then use it to guide their individual camera construction.

The concept of testing efficacy of various design ideas also emerged on a smaller scale such as when participants were putting together the different components and testing the functionality of each one as they added it. We see this in the following excerpt in which Tina and Sara are inserting the frame that will hold their film into their camera and testing to see whether it drops into location correctly.

```
Tina  We're going to put it in here. Okay, let me slide it. Slide it in. Dang it.
Sara  Oops.
Tina  Slide it in. Okay.
Sara  It dropped!
Tina  Yay! [students high five each other]
```
In this case, we see evidence of testing when Tina let go of the frame and they celebrated the fact that it behaved as expected/hoped.

It is important to recognize that the testing these participants were doing falls well short of the scientific ideal of controlled experimentation in which one variable is manipulated in order to identify causal relationships. Even so, that participants looked to tests—that they wanted to make observations in order to make design decisions—suggests an understanding of the value of the empirical observations over assertions or other information sources.

Consensus-Building Through Argumentation

Consensus building is a fundamental knowledge building activity. In science education, researchers and educators support students in engaging in scientific argumentation—a discourse practice in which differences are reconciled through careful examination of the available evidence and scientific principles. This reconciliation can create opportunities for students to develop deeper understandings of the concepts under study. Mathematics standards reveal a similar emphasis on reaching consensus through reasoned argumentation. In addition, the need for effective communication has been well documented among working engineers, as studies have sought means to increase the effectiveness of collaborative design through protocols and processes. Increasing a focus on communication has been shown to deter the tendency to find a quick solution.

In this study, consensus was apparent when participants appealed to a larger group understanding (either something they had decided earlier in their group discussions or something the majority of participants in the class were doing) to validate and make design decisions. For example, in the two examples below we see participants in the large group appealing to a previously stated consensus and asking the group to reach consensus.

Example 1:  *We have consensus.* We're going to stick with that. And that he's just thinking about something that he'll do for, like, we have a group camera and then individual ones individually.

Example 2:  *Well, are we still going to do that, I guess is what I'm asking,* because nobody else included it. So, I don't know if you still want to….

This version of consensus—using it to justify a decision—is a weaker form of the consensus building through argumentation discussed in science and mathematics education research. Moreover, it could be considered an epistemologically weaker criterion than some of the others seen in this study. That is, appealing to consensus is a common decision making process in classroom settings and unless it is part of a larger argumentative discussion, it does not necessitate that students examine the fundamental disagreements and different understandings. As such, appealing to consensus does not require that students develop new or deeper understandings. We were therefore happy to find that this form of appealing to consensus rarely emerged as a criterion for these participants. In fact, only 2% of the criteria across phases and groups emphasized consensus. The richer form of consensus building through argumentation
was in evidence throughout this discourse—whenever students justified their ideas, questioned alternatives, and negotiated their differences.

Discussion

We entered this study expecting to see that participants struggled with merging and applying the domains of mathematics and science to solve engineering design challenges because the epistemological differences in the fields would result in conflict. Instead, we found that these participants relied almost solely on the epistemological commitments of engineering. In addition, we found that participants rarely explored the relevant math and science concepts in-depth. These are sensible findings: the participants were solving an engineering challenge. As such, they were using engineering commitments to accomplish an engineering goal and that goal did not require understanding the math and science, only applying it. In addition, this finding is consistent with related work in pre-collegiate science classrooms demonstrating that, while engineering contexts can foster in-depth exploration of science concepts, it is quite difficult to design environments that do so. Instead, in contrast to experts, novices rarely spontaneously discuss underlying science concepts when engaged in design.6

This study suggests an underlying mechanism for that challenge: students collapsed the scientific principles and mathematical axioms into “sound-bytes” that worked as constraints to guide their design requirements (i.e., “prevent light” or “film height”). This collapsing means the math and science concepts are treated non-problematically, enabling students to move forward on their designs without necessarily understanding the relevant concepts.

In this particular case, the participant understandings of the science were solid enough to enable functional designs. However, their understandings of the how the focal object height and distance from the camera relate to the camera size were not. In this case, participants were seen changing the focal object and/or film size when tests revealed their images were inaccurate (this is observed when students are testing and refining their cameras). As such, in instances in which the participants successfully photographed the desired object, they did so through a process of trial and error rather than careful consideration of the requirements and mathematical axioms. Moreover, many groups were unable to photograph the desired object. This suggests that the collapsing of the math concepts into simple design constraints did a disservice to the participants in the long-run as they were unable to systematically construct a camera to meet the desired requirements. Moreover, while we did not have an opportunity to ask them, we speculate that these participants would have been unable to explain why their cameras were (un)able to take the desired picture. Given the little attention that was spent considering the relevant mathematical axioms, it seems likely that these students did not realize the source of their problems because the problematic math understandings were buried in their discussions of design requirements, rather than being a focus of their thinking.

In addition to our hope that students would explore the relevant math and science concepts in more depth, we also entered this study with the expectation that the design context would provide students with an opportunity to practice particular ways of thinking that are commonly used across engineering, math, and science. In particular, we hoped to see students engaging in systems thinking, testing/modeling, and consensus-building through argumentation. This study
revealed both groups engaged in limited “group think” and extensive argumentative interactions. In addition we see one group (the pair) emphasizing systems thinking while they built their camera and both groups modeling and testing their cameras through the build process as well. Thus, this study suggests that the engineering design challenge can be a context that successfully motivates students to engage in these ways of thinking. This might be one of the most powerful aspects of engineering education with respect to integrating mathematics and science.

We attribute the focus on modeling and testing during the build phase to the availability of materials during these particular phases and the differences between novices and experts. It has been seen that inexperienced designers need to get acquainted with the materials before doing the actual designing; and we saw that the participants made design decisions when they had the materials in hand. This is based on the idea of “messing about with the materials” and suggests that one valuable aspect of engineering courses is the physicality of the materials. That the pair was able to engage in systems thinking as extensively as they did is hopeful: it suggests that this particular context can support/enable that approach to problem solving. Future design work will consider how the problem context enabled the pair’s focus on systems thinking but not the group’s and whether we can more consistently support this work across groups.

Implications

Given the likelihood of challenges that can emerge when designers collapse science and mathematics concepts without exploring them first, this study raises questions about how one can better foster the explicit exploration and use of these concepts. What could be done to make this context elicit that sort of thinking more reliably? One suggested strategy is borne from the very difference between the way a scientist and an engineer think, namely that a scientist questions “how” something works as compared to an engineer who contemplates “if” something works. Moreover, as students tend to ask low-level questions in these inquiry learning situations as well as not think metacognitively about the work they are doing, it is likely that they would focus on the engineering question of “does this work,” rather than the deeper questions of “how” or “why.” To ameliorate this challenge, the learning environment can be designed to focus the learners’ attention on the “how”. This learning environment emerges through a combination of teacher scaffolding and the slow development of classroom norms. For example, one strategy would be to hold a pin-up gallery walk of the finished designs (much like was done in the generation of concepts phase) to allow an opportunity for peers to question the group’s methodology.

It is important to recognize that, much like we saw in this challenge, creating a learning environment to foster student focus on “how” their designs work will be even more challenging because trial and error can eventually create the desired photograph. As discussed in Berland et al, this raises questions about whether we should expect students to delve into science and math concepts that are not necessary for the success of the project, and, if so, how we can facilitate this work.

While engineering design approaches provide a real-world context to apply mathematics and science concepts as well as a vehicle for integrated STEM learning, the ability of the design activity to do accomplish this goal may vary. We have identified one mechanism for this
challenge, namely the collapsing of the science and math concepts to sound bytes and their treatment as design constraints and requirements. In addition, this study demonstrates that engineering design challenges can motivate systems thinking, a focus on testing and consensus building—three key ways of thinking that are common across the disparate domains of science, math and engineering. We suggest that this may be where the power of engineering curricula lies with respect to supporting more traditional math and science courses: that is, rather than in exploring particular content, it might be that engineering curricula is best situated to support students in engaging in particular ways of thinking that are consistent across mathematics, science and engineering.

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