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Engineering for Colonial Times

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Engineering for Colonial Times (Research to Practice)

Strand: Addressing the NGSS: Supporting K-12 Teachers in Engineering Pedagogy and Engineering-Science Connections

Introduction

The *Framework for K-12 Science Education* (Framework) [1] and the *Next Generation Science Standards* (NGSS) [2] are grounded in the notion that "children are natural engineers," and that education must involve preparing them to "undertake more complex engineering design projects related to major global, national, or local issues." [1] In contrast to many of the previous standards that list requirements in content areas or steps of an engineering design process (e.g., Massachusetts State Frameworks [3]), the NGSS are designed to encourage development of holistic learning experiences that encompass practices that "all citizens should learn," such as defining problems, identifying situational criteria and constraints, generating and evaluating multiple solutions, testing prototypes, and optimizing a solution[1]. The writers of NGSS seek educational innovation, maintaining that learning targets for students should not be focused on knowledge of specific subject matter, but rather on students' abilities to operate at the intersection of practice, content, and connection. Accordingly, NGSS is organized by grade-level learning goals, or *performance expectations*, that characterize students' abilities to engage in science and engineering practices, access disciplinary core ideas, and recognize crosscutting concepts (see Table 1 for Grades 3 through 5). The paradigm shift from specific content knowledge to performance expectations is motivated by the need to prepare students to engineer "solutions to particular human problems," while inciting their interest and persistence in science and engineering[2].

New challenges for teachers

While the NGSS's integrated approach to teaching and learning provides opportunities for teachers to be creative and flexible in developing curricula and assessment methods, it may also present new challenges for teachers, many of whom do not have experience with engineering [4]. These teachers are charged with supporting students in complex thinking and engineering practices, but are not provided with curricular examples or classroom-based evidence to guide them in identifying student learning or progress in meeting performance expectations. Teachers who are reading the Executive Summary of NGSS learn only that:

> "If implemented properly, the NGSS will result in coherent, rigorous instruction that will result in students being able to acquire and apply scientific knowledge to unique situations as well as have the ability to think and reason scientifically." [2]

Further, teachers are expected to focus curriculum and instruction on "bundles" of performance expectations by developing contextualized learning experiences for students. The loosely structured, integrated approach suggests that classroom instruction should not involve successive presentation of isolated performance expectations; instead, it should involve the development of holistic learning experiences that enable students to access bundles and help them to recognize the connected nature of science and engineering. The description of performance expectations bundles is meant to convey to teachers that there is no "one size fits all" learning experience;

students' abilities to engage in engineering practices, core ideas, and crosscutting concepts may cover a wide spectrum and vary with different learning experiences.

Table 1: Performance Expectations of practices, core ideas, and cross cutting concepts, which are described in detail in the document. [2]

3-5-ETS1-1	Define a simple design problem reflecting a need or want that includes specified criteria for success and constraints on materials, time, or cost.
3-5-ETS1-2	Generate and compare multiple possible solutions to a problem based on how well each is likely to meet the criteria and constraints of the problem.
3-5-ETS1-3	Plan and carry out fair tests in which variables are controlled and failure points are considered to identify aspects of a model or prototype that can be improved.

A Literature-based design context

In this study, we explore a promising approach to bringing contextualized engineering experiences to elementary classrooms: through the integration of engineering and children's literature. In an integrated engineering and literacy experience (IEL), teachers introduce engineering to their students by providing them with opportunities to solve the problems that arise in children's literature. The stories that teachers use for IEL experiences typically correspond to the appropriate grade-level literature, providing a rich setting, complex characters, and multiple interacting problems.

To illustrate the premise of an IEL activity, we describe how it might look in a fourth grade class. In this example, the fourth graders are reading Tales of a Fourth Grade Nothing by Judy Blume. Rather than reading the story from beginning to end, the teacher informs the students that they are going to keep track of problems that arise for different characters, and will then act as engineers to develop engineering solutions to the problems. As they generate a list of problems, the students may assume different characters' perspectives. For this example, we assume that students take the perspective of the main character, Peter, a fourth grade boy who faces many obstacles in school and at home, often having to do with his curious younger brother, Fudge. At any of these problem points or after finishing the book, the teacher may provide students with an opportunity to brainstorm possible solutions for their selected problems, encouraging them to consider availability of resources and building materials in the story setting. For instance, students may decide to construct prototypes to prevent Fudge from entering Peter's room (a big problem for Peter). In doing so, they may go back to the book to identify things that Peter has in his room or school, while considering issues of feasibility in the design context. The students may then spend a day or two, often in pairs or groups, building their prototypes, iteratively testing and evaluating how their prototypes might work within story context and for their clients (e.g., Peter, Fudge, or another character), while accounting for potential contingencies (e.g., Peter's parents getting angry, ensuring that Fudge is not hurt).

Students' solutions may take a variety of forms, such as paper or virtual sketches, scaled models, or life-size designs. Throughout the process, the teacher may foster student engagement in engineering practices and disciplinary core ideas by encouraging iterative testing, revising, and evaluating of design solutions with respect to the design context (i.e., Peter's bedroom) and their client (i.e., Peter and/or Fudge). Depending on available time, an IEL unit may unfold over the course of multiple days, or even weeks, as the students conduct research investigations and revise their designs. Alternatively, an IEL unit may be structured to occur within a day or two, in which case the teacher may underscore the role of optimization and working within engineering constraints, such as time and materials.

In IEL activities, engineering problems are not given to students in neatly packaged forms, and there is no prescribed design process for students to follow. Instead, students must grapple with many interrelated problems that are deeply embedded in a rich, multidimensional problem context; further, they must consider characters with needs, personalities, and emotions, implicit constraints related to setting, characters, and resources, and a range of overlapping solution criteria. Our early findings of the IEL approach suggest that students, when immersed in a story, may engage in engineering design reasoning and practices[5], such that they strengthen their nascent engineering "ways of knowing" [6] or "habits of mind." [7] In such instances, students may achieve performance expectations at different levels as they problem solving. However, we have also found that this is not always the case. In other instances, students engage in an IEL activity similarly to a "classroom game," [8] assuming that there is a right solution or a prescribed sequence of steps to follow. Alternatively, students may assume that the activity is not constrained to requirements of functionality or feasibility in a story or classroom context, and may simply construct representations to illustrate imagined solutions. In these cases, students may not reach performance expectations during IEL activities simply because it is not necessary in their versions of the task; while they may have abilities to engage in engineering design practices, or may have knowledge of disciplinary core ideas, they may not recognize a need invoke these abilities.

From these early findings, we recognize that research efforts should be directed towards understanding how students form a sense of, or *frame*, an IEL activity[9, 10]. We are interested in the construct of framing, in particular of epistemic activity[11, 12] in a classroom setting and as applied to research on engineering[13, 14, 15]. More directly, in considering framing, we ask, *what are students' expectations of the IEL task, and how do their expectations influence their engagement in engineering practices, disciplinary core ideas, and crosscutting concepts*? We believe that investigating student framing will allow us to gain insight as to why some students spontaneously demonstrate NGSS performance expectations, while others drift into activities that resemble a "classroom game," or a form of imaginative play.

Research questions

The purpose of our exploratory, descriptive study is to add to the research base on how children engage in engineering design, specifically their abilities to meet NGSS performance expectations. Our broad research questions include:

1. What does it look like when students demonstrate engineering reasoning and practices during and IEL activity, specifically related to NGSS performance expectations?
2. How do students' framing of an IEL activity enable the emergence of engineering reasoning and practices?

By investigating the dynamics of student framing during IEL experiences, specifically as they relate to students demonstrating NGSS performance expectations, we aim to (1) inform the practice of teaching elementary engineering and (2) contribute to educational research. First, by providing classroom evidence of what it looks like for students to be engaging in "bundles" of performance expectations, we aim to support teachers in developing holistic learning experiences, identifying productive student engagement, and cultivating students' nascent abilities for engineering. Second, we aim to contribute to educational research through the development of empirical descriptions of the dynamics of student framing and the emergence of engineering design abilities within productive frames.

Study overview

In the following, we discuss the construct of framing, or how individuals form a sense of "what it is that's going on" in a given situation [9,10], particularly as it relates to students' understandings of classroom-based engineering experiences. We then provide a descriptive case study[16] of third grade students based on our video analysis[17] of three students engaging in an IEL activity based on informational text about the colonial time period of 1565-1776. In our analysis, we consider how they are framing the task by attending to the substance of their reasoning, decisions, how they identify the criteria and constraints of the problem, and the basis on which they evaluate their solution. We then highlight how their reasoning and actions are demonstrative or relate to NGSS performance expectations for their grade level.

In our discussion, we turn briefly to a comparison case involving another group of third grade students who embark on a similar solution, but take a more imaginative approach to developing it. By highlighting the contrast in the groups' engagement in engineering practices and disciplinary core ideas, we underscore the need for greater attention to elementary students' framing of engineering-based activities. We close the paper with a discussion of further questions for research and implications for instruction.

Framing in a classroom setting

In a given situation, an individual is continually striving to make sense of what it is he or she is experiencing. The individual's interpretation, or framing, of the situation involves tapping into previous patterns of experiences, which then interact with the present situation, shaping one's expectations, what he or she notices and considers, and how the person orients to goals or intentions within the experience[18, 19, 20]. The central idea of framing is that individuals generalize information from past experience, creating and organizing knowledge structures or "schemata,"[21] which they then use in making sense of subsequent situations that they perceive to be similar. From this theoretical position, one's structures of expectation make interpretation possible, but in the process, they also reflect back on the perception of the world to justify that interpretation. [10]

Researchers have employed the term "framing" to describe related phenomena in sociology[9], sociolinguistics[10], and cognitive science[22], and, more recently, education[12, 23, 24]. Tannen discusses various forms of evidence of framing in speech, including pitch, tone of voice, negations, and word choice, illustrating a range of ways in which a given situation can be framed, and how slight differences in framing influence and are revealed in the way individuals respond to prompts[10]. The framing lens we invoke here assumes that expectations are not static, rigid structures, but are responsive and perpetually evolving as they are informed, shaped, and tuned by an individual's perception of what is happening[9, 10, 21]. As Tannen[10] describes, "one's structures of expectation make interpretation possible, but in the process, they also reflect back on the perception of the world to justify that interpretation."

Productive framing in engineering

Like framing more generally, an engineer's framing of a design situation involves activating patterns of familiar experiences, which then shape, interact with, and adapt his or her sense of what is taking place. For the engineer, however, structures of expectation from previous experiences are limited in that every design situation is unique, "open-ended," and "ill structured."[25] As Schön [8] describes, engineers "are not confronted with problems that are independent to each other, but with dynamic situations that consist of complex systems of changing problems." The engineer's design process is not an *a priori* sequenced set of steps, but rather unfolds as he or she interacts with the social, physical, and economical aspects of the "messy" design context. At each decision juncture, the engineer assesses, or "makes sense of a situation," [14] by maintaining a heightened awareness of the global design objective, while attending to local, interacting subtasks. Accordingly, an engineer's framing of a design task inherently involves coordination of nested subtasks. For example, in framing a bridge design project, a civil engineer may investigate ways of optimally meeting the client's needs while adhering to situational constraints. Within this overarching framing of the task, the engineer prioritizes and acts on multiple subtasks, such as researching the environment, developing and analyzing computer models, and negotiating with contractors and community members. In an ethnographic study on engineers in practice, Trevelyan[26] summarized the following:

> "Engineers coordinate, monitor, and evaluate the work while it is being performed, adapting plans and organization of circumstances, explaining what needs to be done, making sure that the work is performed safely, to an agreed schedule, within an agreed budget, and within negotiated constraints, such as regulatory approvals, effects on the local community, and the environment. Although engineers carry these responsibilities, they are reluctant to use formal authority (and it is only rarely available to them). Instead, they rely on informal technical coordination. The aim is to deliver the intended products and utility services with the predicted performance and reliability."

Analogously, students' framing of an IEL task may involve maintaining an overarching awareness of the design context and potential solutions, while addressing local subtasks, such as procuring materials (e.g., cardboard, tape, glue) or testing the functionality of specific components. We contend that when students are framing a complex design task as beginning engineers, they may recognize a need to reason, make decisions, and act as engineers, such as developing an optimal solution for their client. In this light, when students' framing reflects engineers' framing, they may demonstrate NGSS performance expectations, not because it is what their teacher is assigning them to do, but because the practices and ideas serve them in solving a complex engineering problem.

Research aim

This study is part of a larger NSF funded project at Tufts University geared towards integrating engineering and literacy in elementary classrooms. Over the last three years, our research team has collaborated with teachers to explore many different ways of implementing IEL activities in elementary classrooms, varying the book genre, materials, and lesson structure. Our collective research aim is to discern how methods of implementation influence students' learning of engineering design and development of literacy skills. Within this endeavor, we aim to understand the dynamics of student framing of IEL tasks, with particular interest in how their framing enables them to reason and act as beginning engineers. In classrooms, we have noticed a wide spectrum of ways in which students engage in IEL tasks; while some stay anchored in the story, others focus on what they think their teacher wants to see, or incorporate imaginary elements in their design. In our analyses of data, we have come to interpret these variations as occurring within unique and evolving ways of framing the task. This analysis is motivated by better understanding how students' framings of the task influence their engagement in engineering design practices, access to disciplinary core ideas, and understanding of crosscutting concepts.

Research setting

There are currently fifteen participating teachers from urban, suburban, and rural areas on this research project. As part of teacher preparation, they are required to attend approximately forty hours of professional development during the summer before implementing IEL in their classrooms, and to have monthly meetings with members of the research team during the school year. Our aim in professional development is to support teachers in (1) developing engineering activities and implementation strategies using their choice of literature, and (2) noticing, attending to, and supporting student thinking and reasoning during the engineering activities.

This case study takes place in a rural town in Massachusetts, approximately forty miles south of Boston. The teacher, Ms. M, had attended approximately thirty-five hours of professional development as part of the IEL project and was excited to try an IEL activity using the book <u>If You Lived in Colonial Times</u>[27] with her class. In the nonfictional text, McGovern provides information about the lifestyles of people who lived during the colonial era (1565-1776), including what they did for work, what the children learned in school, the type of clothes they wore, the food they harvested and ate, and the range of farm chores they did every day using simple tools[27]. The time span for this particular IEL unit was three days, and students were given up to ninety minutes per day. The first day involved discussing the major problems, or hardships, faced by the people of the colonial era, and collaborating in groups choose a problem to solve; the second day involved working in small groups on design plans and constructing solutions; and the third day involved testing solutions, finishing constructions, and sharing with classmates.

Methodology

Our case study approach to this research is motivated by our research aim and theoretical perspective of student framing as central to engagement in engineering[28, 29]. By conducting an in-depth study, we hope to gain insight to and characterize emergence of students' productive framing during an IEL activity, with particular attention to NGSS performance expectations. Our rationale for a case study approach is best supported by Case and Light in the following:

> "The concrete, context-dependent nature of the knowledge which case studies unearth…is precisely the source of its methodological strength. A case study can therefore be particularly appropriate to address research questions concerned with specific application of initiatives or innovations to improve or enhance learning and teaching." [28]

While qualitative research is a preferred method of conducting systematic investigation of engineers in practice[26], it is not often implemented in investigating children's engineering abilities.

Our primary mode of collecting data is through videotaping of classroom activities. As previous researchers have noted[17, 30] videos provide a medium for analyzing naturally occurring phenomena. Further, video data provides researchers with temporal management in that they are able to see the flow of activity, while also revisiting and reanalyzing moments in greater depth. In this endeavor, video data is a powerful medium for attending to moments of student discourse, interactions, as well as paralinguistic channels of communication, including vocal and spatial modalities, such as pauses, interruptions, and gestures [31, 32].

Our research team's approach to collecting rich *in situ* data reflects our interest in capturing the evolutionary nature of students' engineering design processes. During classroom activities, we typically set up small, tripod-based cameras on randomly selected student groups, often with additional microphone units to capture sound adequately. We then act as extra sets of hands for teachers, offering materials, answering questions, and asking students about their design solutions. In this study, two researchers, including first author, were present in the classroom, supporting Ms. M and observing an interacting with students. As the data show, both researchers asked the students about their design decisions and rationale at different points of their process.

In our analysis of video data, we draw on tools from discourse [4, 18, 19] and interactional analysis [20] with attention to both verbal and non-verbal aspects of the data to interpret students' framing of the IEL task throughout their design process[8, 9, 12]. Collaborative analysis of student video play a central role in our research process, often spawning iterative reevaluation and/or a refinement of interpretations, in light of new findings and insight from alterative theoretical perspectives[30]. In our collaborative viewing of the data, we found collective analytic stability in attending to students' framing of the activity, particularly with respect to how their framing informed the substance of their reasoning about the design and in making decisions.

Analysis

In the following, we present our analysis of Jonah, Colin, and Brayden, a group of third grade boys who are engaging in an IEL activity, through four chronological phases. We attend first to how Jonah, Colin, and Brayden are framing the activity by examining their interactions with each other, researchers, their teacher, and classroom materials. We then consider how the boys' framing fosters spontaneous engagement in engineering reasoning and practices, specifically as they relate to NGSS performance expectations. We highlight these moments to show evidence of the group's framing, with particular attention to how their reasoning and actions within stable frames reflect NGSS practices, disciplinary core ideas, and crosscutting concepts.

Phase 1: Defining and delimiting the problem

In the days previous to this excerpt, Ms. M's class had read If You Lived in Colonial Times as part of an integrated Social Studies and English Language Arts unit. Excited by her students' interest in the historical context, Ms. M decided to do an IEL activity, posing the question to her students, *As engineers, what could we design that would make their lives easier?* Three boys in Ms. M.'s class, Colin, Jonah and Brayden, immediately began designing and building a water filter for the people who lived during colonial times.

In the following, Jonah, Colin, and Brayden are working on their water filter project when a researcher in the classroom, Mary, approaches them to ask about their idea.

Mary: Do you guys mind telling me about your idea?
Colin: Well we're trying to purify water. We need a coffee filter though.
Jonah: Yeah um well
Mary: You're trying to purify water?
Colin: Yeah
Mary: That's awesome!
Jonah: So anyway we're gonna put a coffee filter in one of the pipes (referring to paper towel tube) and so when we put water, contaminated water in there (pointing to paper towel tube), all the gunk and stuff will stay on the filter. And all the water will go into here (referring to cardboard base) and we're putting, we're putting, I'm putting tinfoil around the pipes (paper towel tube) so they won't leak.
Mary: Great idea!
Brayden: Wait, it'll need to be angled up!
Colin: We need to tape this...

At an early point in their design process, the boys are clarifying the engineering design problem and narrowing the range of potential solutions. Their verbal descriptions evidence their implicit assumptions regarding the limitations and goals of the task. When Jonah describes their project, he refers to the coffee filters and tinfoil by name, but the paper towel tube as a "pipe." His description of the materials evidences the ambiguity of the engineering task, and subsequently, the multiple ways in which he and his group members may be framing the task. For instance, the tin foil serves the purpose of looking like a pipe, creating a metal-looking layer on the paper towel tube, but is also functioning as leakage prevention. Thus, they may assume the task involves prototyping the actual filtration system that would exist in colonial time period (assuming people of colonial era use tin foil and paper towel rolls), or that they are prototyping a filtering system with the aim of understanding how the system will function, but realize the material limitations of their prototype.

These subtle differences in framing may have greater implications when it comes to defining the engineering problem and evaluating solutions; while the former assumes it will need to work in a third grade classroom context (using materials such as cardboard and tinfoil), the latter should theoretically be feasible and functional in the colonial time period, but not necessarily in their classroom. In this early stage, the group's framing of the task appears multidimensional and complex; because they are still defining and delimiting the problem, their framing may dynamically shift and evolve as they interact with each other, materials, and the contexts of colonial times and their classroom.

This excerpt provides a glimpse of the boys' definition of problem and their proposed mechanism for a solution. According to their understanding of the setting of colonial times, accessing pure water was a problem. In line with NGSS Practice (3-5-ETS1-1), Jonah, Colin, and Brayden have defined a problem that can be solved through the development of a tool (i.e., small-sized water filters). They then construct a coherent explanation around the filtration mechanism: as "contaminated" water is poured through a "pipe," that is lined with coffee filters, the "gunk" will stay on the filter, and the purified water will flow through to a container. Like engineers, they maintain an overarching awareness of the design task, but pay close attention to aspects of functionality, such as structural stability ("angled up" and "tape" as reinforcement) and preventing leakage ("tinfoil around the pipes").

Phase 2: Identifying criteria

Shortly after, the boys are working on their water filter. They have positioned themselves in a small circle on the classroom floor, huddled around three small jars filled with dirty water. They are surrounded by scraps of materials that they are using to construct their water filter, such as cardboard box cut-outs, paper towel and toilet paper rolls, paper, cotton balls, coffee filters, rubber bands, tape, glue. As they are discussing their solution, Kathleen, the other researcher from Tufts University, curiously asks the boys about their work.

Jonah: So the only problem with it is it might take a long time for the water to drip through the filter into here, but —
Colin: That's why we didn't use the cloth I brought.
Kathleen: Why did you not choose the cloth?
Colin: Well, the cloth didn't work. None [of the water] went through it. We haven't tested the lighter material yet. If it doesn't work…
Kathleen: How would, how would you test it?
Colin: Well I test it by running water through it on the sink.
Kathleen: Oh. How fast does it need to go?
Colin: Well, well we need to get enough water into it for it to go—
Jonah: (*overlap*) Um, maybe, maybe like, a cup every 20 minutes or so?

In this moment, the boys are intensely focused on their experiment, closely watching and comparing the rate of water dripping through filters and into each jar. They do not appear concerned that they have made a mess or what anyone else in the classroom is doing. The boys appear to have a shared sense of what is taking place during this phase; their actions suggest a tacit recognition that engineering design necessitates research, planning and carrying out scientific investigations, and iteratively constructing, testing, and evaluating. Their evaluation criteria suggest that their scientific investigation is driven by their engineering design objectives: Colin suggests that they need “enough water,” and Jonah then approximates a minimum flow rate. While Jonah’s estimate may not be realistic for people living during colonial times, it is evidence that they are thinking about the design context and the needs of their clients.

Many of the boys’ actions and reasoning in this phase align with NGSS performance expectations. They are planning and carrying out investigations (3-5-ETS1-3): they have developed a test (“running water through it on a sink”) to test the permeability of multiple materials (e.g., “cloth” and “lighter material”) with the intent of identifying an optimal solution for a required flow rate (“a cup every 20 minutes”). In doing so, they are also accessing disciplinary core ideas, such narrowing the scope of their problem space (ETS1.A) and developing possible solutions (ETS1.B). Additionally, the boys are taking constraints into account, such as availability of materials, (3-5-ETS1-1), communicating with each other as they test (3-5-ETS1-2), and evaluating test outcomes based on failure points, such as inadequate water flow (3-5-ETS1-3).

Phase 3. Testing and evaluating

Approximately twenty minutes later, the boys are all intensely focused on watching water drip through each of the filters and into a jar. They begin to compare the water cloudiness in each of the jars, as well as soggy cotton balls, wet coffee filters, and a dampened, dirty facecloth. In the following, Mary returns to check in with the group and asks what they have found.

Mary: What results have you guys found are the best so far?
Colin: Well, first of all,
Jonah: So the towel was good at first, but it tires out easily, so under sustained water it, like towel works good if you just want like half a cup. So it's not good if you want to try sustained purifying.
Mary: Cool.
Colin: But cotton balls, that's what works!
Mary: Cotton balls have been working for you guys?
Colin: Cotton balls have the best results.
Jonah: Yeah but I think those cotton balls are a little dirty for—

(*Long pause as Jonah pensively looks up to the ceiling with his hand on chin. Ms. M then joins into conversation.*)

Jonah: Wait, uh, guys can we step back a second? They didn't have cotton balls in colonial times.
Ms. M: Well, what could, what would they have used instead do you think?
Colin: Probably wool.
Jonah: Yeah, but wouldn't that be sort of like the towel or cloth?
Ms. M: Well, I think wool could be a similar type of material, right? So, we don't have, I think we could say for now that we could consider it wool.

Jonah’s evaluation of cotton balls leads him to a realization: cotton balls may have not existed in colonial times. He is suddenly aware of the limitation of classroom materials, recognizing that his evaluation of the solution, particularly of functionality and feasibility, does not make sense in a classroom context. Ms. M attempts to clarify by asking him what the colonial people might have used in colonial times, and suggests that they "consider it wool." In doing so, she insinuates that this prototype is representative of a tool that might have been used, but does not necessarily need to abide by the resources limitation of colonial times. We believe that this exchange evidences a juxtaposition in framing between Ms. M and Jonah: for Ms. M, the objective is for students to develop and construct an explanation around a solution; for Jonah, on the other hand, the primary objective is to develop a useful, authentic tool that is historically situated.

The boys' framing of the task during this exchange is seemingly unstable, teetering between classroom and colonial contexts. In our initial analysis, we perceived this as inhibiting engagement in engineering. However, upon deeper review and analysis of the data, we came to see their framing instability as a potentially productive learning moment; that is, the boys' recognition of a need to make assumptions explicit causes them to grapple with crosscutting concepts. They realize that the materials they are using for their prototype may not make sense for the design context, and in realizing this, uproot a rather profound idea: technology is not constant with respect to time. Rather, technologies evolve to meet societal needs, and societal needs may spawn technological innovation (Crosscutting Concept 3-5-ETS1-1). The engineers of colonial times were confronted with unique and complicated obstacles: to meet the societal need for clean water, they could not use paper towel tubes, tape, or tinfoil, but had to procure or develop a filter using the tools and materials that were available. For the boys, the emerging complexity of the task prompts further investigation of the problem context, such as the availability and properties of wool, to narrow their realm of possible solutions (Practice 3-5-ETS1-1).

Figure 1: Testing Filters

In considering the substance of the students' reasoning and actions, it is clear that they are engaging in engineering practices while addressing disciplinary core ideas. Their curiosity for determining the material that "works" best has motivated them to collect and line up small glass jars (Figure 1) for more accurate comparisons across materials. They are collaboratively planning and carrying out investigations, in which the water jars are constants and the filtering material is varied (Practice 3-5-ETS1-3). They are evaluating the test on multiple dimensions, including the minimal rate of water flow, end volume of clean water (a cup every 20 minutes or so), and durability (or life cycle) of filter material ("tires out easily," "good if you want half cup or so," "not good if you want sustained purifying"). In doing so, the boys are also prioritizing evaluation criteria and discussing trade-offs (Core Ideas ETS1. A, ETS1.B): Jonah states that the towel filters well, but is slow and inefficient for larger volumes (it "tires out"), while Colin suggests that cotton balls have the best results, even though they collect a lot of debris in a short period of time. As a group, the boys are further delineating the problem (Practice 3-5-ETS1-1), while narrowing the space of possible solutions (Practice 3-5-ETS1-3).

Phase 4: Optimizing for the specific context

On the third and final day, the students are all finishing their engineering design solutions. In this excerpt, Kathleen hears tension rising in the group and asks about their problem.

Colin: Well, the coffee filter didn't work.
Kathleen: Why didn't it work?
Colin: It let the dirt in.
Kathleen: It let the dirt in.
Jonah: (*to Colin*) We cannot, we can't fix our project. It's a *dead* project. I mean, I mean, it's not just that the cloth won't work. The cloth won't work, that project doesn't work. Even with the coffee filter and the cloth through the bottom, there'd still be a huge puddle.
Colin: We could try — we could at least try this. It was the other cloth that absorbed it all. This one is a lot thinner.
Jonah: (*Acting frustrated*) It doesn't work enough, though. It leaks, it, there's huge puddles everywhere, and from the bottom, and we don't have anything to stop it. Tin foil does *not* stop it, and tape does *not* stop it.
(*moments later*)
Kathleen: Ok, what, what would stop it?
Jonah: What would stop it, is if we added a lead pipe or something.

With limited time, the boys are arguing about how to optimize their design; however, because they are framing the task in slightly different ways, and have different assumptions regarding their objective, they are struggling to find a compromise. For Colin, ensuring that there is a functional filtering component is the priority. He accepts that the materials they are using serve a representational purpose and is determined to identify an optimal filtering material among classroom resources. For Jonah, the leaking problem outweighs the filtering problem; if the container leaks, what is the point of filtering anything? Further, when Kathleen asks what he would use if the classroom were not the constraining factor, Jonah suggests "lead pipe." Jonah's frustration is rooted in the discontinuity between classroom and colonial settings, particularly the lack of correspondence between availability of materials and testing requirements.

As they are optimizing the solutions (Core Idea EST1.C, 3-5-ETS1-3), it becomes clear that their ideas for what is optimal are different; subsequently, they find themselves on different reasoning trajectories. Colin accepts the limitations of classroom and aims to understand how the available materials function as filters. In contrast, Jonah has difficulty reconciling the fact that they are trying to construct a functional tool in a classroom environment, but do not have necessary resources at their disposal. For him, developing a prototype necessitates using the resources that were available *at the time* and the classroom presents unnecessary limitations to their engineering solutions. To resolve their differences, the boys take part in something that is not usually encouraged among elementary students: argumentation. However, rather than only arguing about who is right, the boys invoke evidence from the test to justify their claims about the optimal design criteria. For Colin, effective filtering capacity is the priority, while for Jonah, it is most important for the filtering system to contain all water, regardless of its filtering efficacy. Although compromise is difficult for them to come by on their own, the boys are listening to each other, comparing, and evaluating the other's ideas.

Discussion

Our initial interest in Jonah, Colin, and Brayden was in characterizing their engagement in engineering practices and reasoning, specifically aligning them with NGSS. However, the more deeply we analyzed their patterns of reasoning and actions, the more interested we became in understanding how they were framing the task at different points, and how their framing motivated their decisions. In the early phases, the boys seemed to have a shared framing of the task: they were designing a functional water filter for the people of the colonial era. Within this stable framing, they iteratively evaluated components (i.e., the filter materials) for functionality, while maintaining an overarching awareness of their objective and the constraints of the problem context. They made assumptions and gathered data, spontaneously shifting modes between engineering thinking and practices. As they further investigated the design context, the subtle ambiguities in their uses of materials and evaluation criteria emerged. Subsequently, their framing of the task became progressively less stable and more complex as they delineated the criteria and constraints of a feasible design solution. For instance, they were considering the availability of materials and resources during the colonial era, and reflecting on how well their classroom materials would mimic those properties (comparing properties of towel cloth and wool). In turn, they were forced to identify the criteria that would make their design optimal within the constraints of the task (i.e., water containment versus filtration). As their framing became less stable, the boys began demonstrating other aspects of performance expectations, such as connecting crosscutting themes of society and technology tensions, and engaging in evidence-based argumentation.

In navigating an ill-defined, messy engineering design context, the Jonah, Colin, and Brayden engaged in engineering practices, accessed disciplinary core ideas, and connected crosscutting concepts. Their framing of the task shifted and evolved as they interacted with the design context, conducted more detailed analyses and evaluations of their filtration system, and considered its functionality and feasibility in both classroom and colonial settings. Despite the variations in their framing, however, they continually responded to the design context and their clients' needs, arguing when appropriate, to develop an optimal solution. We believe that their constant attention to the design context undergirded their sustained enactment of performance expectations.

A comparison framing

For Jonah, Colin, and Brayden, invoking engineering design abilities made sense and served them in solving their problem. Their patterns of reasoning and actions, however, were not pervasive among the third graders participating in this activity. In reviewing comparison cases, we noticed that the complexities and fluidity with which children frame a situation often cause them to engage in a different type of activity. In this final section, we provide a brief glimpse into another group's activity and discuss pedagogical implications. We do not intend for this analysis to be comprehensive, nor do we attempt to draw substantive findings from the group's work.

In the classroom adjacent to Ms. M's room, Ms. C was teaching a similar lesson. She had instructed her students to design solutions that would "help people of colonial times." A pair of students in her class, Bridget and Kayla, also recognize that clean drinking water may not have been available in colonial times and decide to design a water cleaning system. In the following excerpt, Bridget and Kayla are sitting on the floor in Ms. C's room. Kayla is holding a cardboard box with pipe cleaners attached to opposite sides of box. Bridget is mixing paint in a small paper cup. In the following, Mary asks them about their design:

Bridget: We're making a robot that will, um, separate the bacteria and the water. So, out of one arm (*pointing to pipe cleaner*), clean water will come out, and out of the other, bacteria will come out.
Mary: That would be interesting. So, how does it work?
Kayla: And so, you put the water in here (*pointing to box*), and so the pipes separate the water from the bacteria. And the bacteria comes out there *(pointing the pipe cleaners taped to the side of a box*), and the water comes out there (*pointing to other pipe cleaner*).
Mary: Neat! So, how do the pipes do the separating? Or do you have any ideas?
Bridget: Well, like, there'd be two pipes and when the water and the bacteria would come, and they'd eventually separate, and all the bacteria would come out (*pointing to pipe cleaner*) and all the water would come out (*pointing to other pipe cleaner*).

For the girls, the use of craft materials (e.g., cardboard, paper, glue, paint) may have triggered their expectations for imagining fantastical stories, or making crafts, such as other representational dioramas. Subsequently, imagining becomes an integral part of what they were doing; within their framing, solution ideas are not constrained by availability of resources, functionality requirements, or feasibility issues of colonial or classroom contexts. Instead, they only have to generate an idea to solve a problem and create a representation of that idea. For Bridge and Kayla, a water-cleaning robot is a sensible solution that meets their objective.

The two groups of third grade students, posed with similar engineering design tasks for the same design situation, embarked on solving the same problem: the need for clean water during the colonial period. However, their design solutions stand in stark contrast to each other: while Jonah, Colin and Brayden narrowed their solution space by identifying the criteria and constraints of a colonial times setting, Bridget and Kayla's solution involved imagined mechanisms. We attribute these differences to the range of ways in which students frame engineering design experiences, and underscore the need to further research the dynamics of student framing during engineering activities. By gaining a deeper sense of how students form a sense of the activity, we will be better equipped to develop instructional practices to support and sustain students' abilities to meet performance expectations.

Implications

The broader impact of this exploratory work has wide-reaching effects for K-12 engineering pedagogical methods and curriculum reformation, particularly in relation to NGSS. These early findings from the IEL project elucidate students' abilities to engage in engineering reasoning and practices when they are framing the activity as one in which they are designers, constructors, and assessors of their work, and recognize that their work is meaningful. These findings illustrate how students' productive framing of an IEL task may provide an opportunity for them ask questions, carry out scientific investigations, and engage in engineering design practices as they navigate a complex problem space.[10] For teachers, this study provides classroom-based evidence of students working within the integrated structure of NGSS performance expectations. It is important to note that the aim was not to disaggregate practices from core ideas from themes, but to show them as tightly entwined, embedded in, and driven by the students' pursuit of an engineering design solution. Further, this research adds to the current literature by illuminating the potential emergence of a productive engineering framing, in which reasoning and practices are situated in complexity.

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