Navigating Open-Ended Spaces: Writing, Representing, and Speaking in a Fifth-Grade Science and Engineering Unit

by

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Dedication

This dissertation is dedicated to Nainoa Thompson and all of the members of the Polynesian Voyaging Society; past, present, and future; for showing us ways forward; and to David K. Cohen, for reminding us where we have been.

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As I write this, I am a few months shy of my 43rd birthday. I have spent 23 of those years in school. So, although I have been a teacher for the majority of my adulthood, the fact of the matter is that I have been a student for far longer. As graduation nears for the last time, I am grateful to so many people for being part of my unusual and winding journey. Luckily, this is not the Academy Awards, so I don't have to worry about the orchestra playing me off the stage!

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Abstract

Recent reforms in elementary science and engineering standards present intriguing new opportunities for the development of project-based interdisciplinary curricula. Although project-based learning has a long research tradition, the field could benefit from more observations and analyses of classroom-level lesson enactments to provide support for the notion that a project-based integrated science and engineering unit may provide a fertile context for students to be supported to engage in sense-making and communicate their thinking through disciplinary literacy practices that are novel to elementary instruction. Therefore, I studied the enactment of a fifth-grade unit on Polynesian wayfinding that I developed in collaboration with my advisor. I collected the data for this study during 2019-20 in a single classroom at a public school in the Midwest. This dissertation is comprised of two manuscripts that explore different aspects of the project-based integrated unit.

In the first study, I explored the practice of scientific modeling and how students, with the support of peer feedback, transformed observations of a physical investigation into a drawn/written model. Through a conceptual analysis of student artifacts, classroom videos and field notes, and student interviews, I constructed explanations of students' sense-making, and changes in their thinking, while engaged in the practice of modeling and peer review. The findings highlight that students created models that addressed spatial, temporal, and conceptual features of the phenomenon. Even as novice writer-designers, students used sophisticated techniques like multiple views and multiple timepoints. Students included invisible elements, such as evaporation and heat transfer, but they were not always successful in making clear

connections among the components. Students improved the accuracy and completeness of their models by engaging in a one-on-one feedback process using a structured protocol. Findings from this study indicate that modeling, especially when supported by peer feedback, is an interdisciplinary practice wherein elementary students can bring to bear written and drawn elements to communicate sophisticated ideas in science.

In the second study, I explored the practice of engineering design and how students used drawn/written plans to create physical models. Through a careful review of recordings from multiple cameras, supplemented with student artifacts, interviews, and surveys, I analyzed the enactment of a project to plan, build, and test physical models of long-distance voyaging canoes. The findings highlight that the use of a written design planner with embedded guiding questions supported students with many aspects of design, including discussing and providing reasoning for decisions about materials. Working with university mentors allowed students to receive focused attention from adults with specific disciplinary knowledge. Findings from this study indicate that the use of written design planners and the participation of university mentors supported students in successfully constructing canoe models and in deepening their conceptual understandings of the physics concepts related to sailing.

Together, these studies provide illustrative examples of disciplinary literacy within the enactment of a fifth-grade project-based science and engineering unit. The findings add to existing research focused on the science practice of the development and use of models, and the engineering practice of design, at the elementary level. Overall, these studies offer ideas and inspiration for future educators, researchers, and curriculum designers.

Chapter 1: Introduction

Gaps are an inevitable byproduct of the imperfect world in which we live. Whether a mental goal or a written plan, the eventual reality never quite matches the intention. In typical usage, the concept of a "gap" has a negative connotation, most notably in education in the persistent use of the term "achievement gap" (e.g., Gutiérrez, 2008; Ladson-Billings, 2007). But, what if the concept of a gap can be reframed? In the case of the "achievement gap," there are many who advocate relabeling that phenomenon as an "opportunity gap" (e.g., Flores, 2018; Milner, 2013). That is a start: a way to see potential rather than a shortcoming.

I propose two additional ways of looking at gaps. One is an opportunity for connection. It may be impossible for a few individuals to pull two islands closer together. But, they can cross that space in-between with their ingenuity. A single bridge can connect those two lands, which can increase in number, size, or complexity over time. They could also build an infinite variety of boats, which can similarly evolve in number, size, or complexity. A slight change of perspective may even reveal that those two islands are already connected: the water itself as a bridge rather than a barrier.

Another way of looking at the gap between intention and reality is to embrace the messiness. The space between the idea and the outcome, the plan and the product, the lesson and the enactment: this space, ephemeral and somewhat magical, is where the playground of ideas meets the rules of physics, politics, and psychology. In the moment, it often becomes apparent that what made sense on the page needs to be adjusted. Decisions made in that gap, whether by a student, a teacher, or an astronaut on a spacewalk, are nearly impossible to see. They happen so quickly, sometimes dozens arriving in a flurry (Borko et al., 1990; Ferrè, 2019; Wendell, Wright, & Paugh, 2017). Fundamentally, this dissertation is about those open-ended spaces: the gaps between a designed unit and its enactment, the gaps between what students record and what they understand, and the gaps between what students plan and what they build. I admit that this is an imperfect undertaking, as I myself navigated the uncharted spaces between the ideas in my head and the words on these pages, but I have done my best to explore those gaps nonetheless.

Specifically, I examined the enactment of a Grade 5 interdisciplinary project-based unit on Polynesian wayfinding. My advisor and I developed the Wayfinding Unit as a component of the Grade 5 curriculum for *Multiple Literacies in Project-Based Learning* (ML-PBL)[1], a design-based endeavor (Brown, 1992) to create a literacy-forward science and engineering curriculum for the upper elementary grades aligned with the *Next Generation Science Standards* (NGSS, NGSS Lead States, 2013). Our initial version of the Wayfinding Unit was piloted in 2018-19. The focus of this dissertation is the revised version enacted during the 2019-20 academic year.

Although project-based learning has a long research tradition (Condliffe et al., 2017; Thomas, 2000), the field could benefit from more observations of classroom-level lesson enactments integrating science, engineering, and literacy, particularly at the elementary level. The goal of my dissertation is to provide support for the notion that a project-based integrated science and engineering unit may provide a fertile context for students, particularly students with identities that have not historically been privileged in school settings in the United States, to be supported to engage in sense-making and communicate their thinking through disciplinary literacy practices that are novel to elementary instruction.

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[1] The research and development for my dissertation study is supported by a grant from Lucas Education Research awarded to Co-Principal Investigators Joseph Krajcik, Annemarie Palincsar, and Emily Miller.

The Urgency to Center Equity Pedagogy

At this point, before providing more information about the Wayfinding Unit, or detailing the two papers that will comprise this dissertation, I would like to pause. Between the time I concluded data collection in December 2019 and finalizing this document in early 2021, the United States was shaken by a series of historically traumatic events. The unrelenting COVID-19 pandemic, protests over police brutality sparked by the murder of George Floyd, and the attempted coup at the U.S. Capitol by right-wing insurrectionists and White supremacists provided stark evidence to those with privilege, as it has always been clear to those being oppressed, that structural injustice, particularly systemic racism, has deadly consequences. We, in the field of education, are too often complicit in maintaining the status quo. To help the next generation reach their full potential, we must actively work to dismantle structures of oppression.

As part of that commitment, this work is centered around the concept of *equity pedagogy*. As defined by Banks and Banks (1995), equity pedagogy consists of:

> teaching strategies and classroom environments that help students from diverse racial, ethnic, and cultural groups attain the knowledge, skills, and attitudes needed to function effectively within, and help create and perpetuate, a just, humane, and democratic society. (p. 152)

Expanding upon that definition, my notion of equity pedagogy includes *all* students, including those marginalized or minoritized because of biological sex, gender identity, language, socio-economic status, or perceived academic ability. Through this dissertation, I hope to heighten awareness of contextual factors that may, or may not, increase sense-making opportunities for all students as well as spur deep and critical reflection about decisions we make as educators that promote or deny the equitable participation of all members of the classroom community.

My Positionality

With the commitment to equity pedagogy guiding this work, I find it essential to be absolutely transparent regarding my positionality. I am a White, heterosexual, cisgender, abled, native English-speaking, middle-class male born in the last part of the 20th century in the United States, during a time and in a place where all of those identity markers, individually and in intersection, represent dominance and oppression. As such, I am the last person who should be developing a unit about Polynesian culture and focusing on students with intersectional minoritized identities. I do not want this work to be an extension of settler colonialism. I do not want to essentialize or reify stereotypes about the students who participated in this study.

However, I have two reasons for proceeding with this work, while acknowledging that I am not the ideal person to do so. First, my work is, was, and always will be motivated by passion for students, and their messy realities. I know that our field can do a better job of representing the intersectional identities of the children we work with, so I want to take a step towards creating that more representative body of research. While I can't pretend to understand the struggles of minoritized students, or to speak for them, I can make sure that their accomplishments are highlighted in my work. In that way, I can use my privilege, and my positionality as a doctoral student at a well-regarded university, to communicate their brilliance and amplify their voices.

Second, the development of the Wayfinding Unit was motivated by a sense of justice. The Polynesian sailors who explored the Pacific were incredible scientists and engineers, as are the modern navigators who have followed in their path. My advisor and I saw this story, both ancient and modern, as a way to explore Indigenous ways of knowing with students who are growing up thousands of miles from the nearest ocean. Recognizing that about 80% of elementary school teachers are White (NCES, 2019), and that we were enacting this unit in a majority-White school, we set out to design a unit that could help non-Polynesian students and teachers broaden their ideas of what science and engineering look like, and who can participate in those disciplines, without being didactic or reductionist.

Let us pause for one more moment to thank all of those who have resisted oppression and advanced justice. Let us acknowledge those whose contributions we will never know because they were silenced.

Now, let us proceed.

Overview of the Wayfinding Unit

As the context for this study, my advisor and I designed an interdisciplinary project-based unit for Grade 5 about the art and science of Polynesian wayfinding: navigating vast oceans using only clues from nature. Beyond addressing academic standards, our intention in crafting the unit was to introduce students to the beauty and wonder of engaging with science and engineering through literacy. Over the course of the unit, students read a wide array of genres, including blog posts, newspaper articles, informational texts, and mythology. In response, students produced an equally wide array of writings and representations: from persuasive letters and public-service announcements to models and scientific explanations. When crafting the unit, we intended to create a continuous storyline wherein the disciplinary literacy practices were organic: arising from authentic contexts and necessary for meaningful purposes.

The initial version of the Wayfinding Unit was piloted during the 2018-19 academic year from January through March. The revised version of the unit was enacted during the 2019-20 academic year over 9 weeks in October and November. Like all of the ML-PBL units, the Wayfinding Unit was organized around a driving question (Krajcik & Czerniak, 2014); in this case, *How can we find our way in the world by using only the clues that are in our environment?*

The unit launched with 20 content lessons, four lessons per week for 5 weeks (see Appendix A for the Table of Contents). Each lesson was meant to be taught for 90 minutes, each containing literacy, science, engineering, and social studies components (see Appendix B for a sample lesson plan). Then, the unit segued into 4 weeks dedicated to the creation of a pair of final projects: (1) planning, building, and testing models of Polynesian-style double-hulled canoes and (2) creating videos identifying an environmental problem and possible solutions.

With sailing as a major theme of the unit, the weeks were organized around the stages of a journey: deciding why to go, planning the trip, gathering knowledge and skills, then finding your way. The inspiration for this organization came from the online exhibit *Never Lost*[2] presented by the Exploratorium, a museum in San Francisco. The informational texts included in their exhibit became key resources for our unit, after being modified for fifth graders.

A major focus of the *Never Lost* exhibit was the Polynesian Voyaging Society. Starting in the mid-1970s, this organization sought to rebuild the canoes their ancestors used to navigate to Hawaii. Their flagship canoe, the Hokule'a, sailed 26,000 miles from 2014-2017 while circumnavigating the globe using no electronics or fossil fuels. Wanting to make this story a centerpiece of the unit, we included newspaper articles from throughout their worldwide voyage. We also made extensive use of original blog posts that were authored by the crew of the Hokule'a during the journey. These original artifacts not only heightened the authenticity of the unit, but they provided repeated opportunities to present people of color, women, and importantly, women of color as individuals with extensive scientific and engineering knowledge.

[2] The *Never Lost* website (http://annex.exploratorium.edu/neverlost/) was built using Adobe Flash. Adobe stopped supporting Flash Player and blocked Flash content as of January 12, 2021, so the website is no longer available.

In addition to informational texts, newspaper articles, blog posts, and a trade book, we included electronic resources. The students watched a number of *Ask the Crew* videos, recorded by members of the Polynesian Voyaging Society while on the worldwide voyage, as well as other informational videos. We created visual inquiry slideshows and students spent two lessons working with an online virtual planetarium. Their computer-based explorations also included collecting notes from a variety of websites dedicated to solving environmental issues.

As a project-based learning experience, the Wayfinding Unit culminated in a pair of final projects. The first project was the "Mālama Honua Challenge," which was originally offered by the Polynesian Voyaging Society as a way for the public to participate in their mission. *Mālama Honua* is a Hawaiian phrase meaning to "take care of Island Earth." For the challenge, students identified a problem facing the environment. They then brainstormed ways to address that problem, and developed a video to communicate the problem and proposed solution(s) to a specific audience. In 2018-19, the resulting videos were shared with partner STEM educators in Hawaii, who provided feedback to the students. In 2019-20, students received written feedback from university student volunteers enrolled in an environmental science course.

The other final project was planning, constructing, and testing models of Polynesian-style double-hulled canoes. For this project, teams of three were partnered with an undergraduate mentor from a university Naval Architecture and Marine Engineering department. After planning and building their models, the students had a field trip to the university's Marine Hydrodynamics Lab where they tested their models in a Wind/Wave Tank. After conducting time trials, the students worked with their undergraduate mentors to discuss and modify their models, testing multiple iterations in rapid succession. The day after the trip, the students presented their models to their peers, and discussed the results of their testing.

Overview of the Dissertation

My dissertation is composed of two journal-length manuscripts that look at different aspects of the same interdisciplinary Wayfinding Unit. The first manuscript highlights the integration of literacy with science, while the second looks at the integration of literacy and engineering. Each study explores modeling, but from opposite starting points. The first paper focuses on students conducting a physical investigation, then developing drawn models. The second paper starts with students creating drawn plans, then using those plans to construct and test physical models. Despite these different starting points, both studies explore how students leverage literacy skills to combine text and visuals to create multimodal compositions (Kress, 2010) that communicate information. Although they are both case studies (Stake, 1995), and present interesting symmetries, the two manuscripts are independent and have their own literature reviews, draw from different data, and include their own references. Following these two papers, I have included a conclusion that looks across the two studies. The dissertation ends with appendices that provide additional information for each paper as well as a final iteration of the Wayfinding Unit that I prepared based on data collected from the second enactment.

The first paper is titled *Modeling as a Literacy Practice and a Science Practice in a Fifth-Grade Project-Based Unit*. This manuscript focuses on the development and peer revision of drawn models as the students engaged in an investigation of solar stills as a method of extracting freshwater from saltwater. While modeling is a natural fit for integrating literacy and science, it is new to the elementary curriculum (Bybee, 2011). As a result, the rigor of this practice holds promise for being a site of complex sense-making (Evagorou et al., 2020; Manz, 2012; Marcum, 2018), but the novelty of engaging young students in modeling means that the research base is still developing (Chang et al., 2020). The data for this study includes a close look at students' drawn models and peer feedback sheets, supplemented with video and fieldnotes from whole-class discussions as well as one-on-one interviews with focal students.

The second paper is titled *Designing Models of Long-Distance Voyaging Canoes: Imagining the Framework for P-12 Engineering Learning in Action in Elementary Schools.* This manuscript takes a close look at the design of a curricular project intended to integrate literacy and engineering as students plan, build, and test their models of Polynesian-style canoes with the mentorship of university volunteers from a Naval Architecture & Marine Engineering program. As engineering is a new subject at the elementary level in the United States, researchers and curriculum developers have many questions about what engineering design looks like with young children (Cunningham, 2018; Lachappelle & Cunningham, 2014; Marshall & Berland, 2012). A recently released vision for engineering education, with a taxonomy much more specific than the standards contained in the NGSS, is the *Framework for P-12 Engineering Learning* (AE3 & ASEE, 2020). I use the enactment of the canoe project as an illustrative example of how suggestions from prior research on engineering design, as well as the components enumerated in the *Framework*, might be operationalized in an elementary classroom. Data for this paper include written plans, photos of work sessions and canoe models, surveys completed by undergraduate mentors, transcriptions of small group videos, and the transcript of a whole-class discussion when students reported the results of testing their canoes.

In summary, my dissertation explores the ways in which fifth graders communicated their thinking through disciplinary literacy practices while engaged in an interdisciplinary project-based science and engineering unit. Together, the papers address ways in which modeling, as a science practice and an engineering practice, meaningfully intersects with literacy instruction. The first paper builds on existing research on supporting young learners to develop and use drawn models, and the second paper draws on engineering education research to look at how students use written plans and the support of mentors while engaging in the engineering design process. Both papers share much-needed classroom-level observations of what an integrated project-based unit could look like in practice. By doing so, I hope that this work provides ideas and inspiration for future educators, researchers, and curriculum designers.

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Chapter 2: Modeling as a Literacy Practice and a Science Practice in a Fifth-Grade Project-Based Unit

Introduction

> *When I draw I think I can get everything I'm trying to say, but just not in words. In words, sometimes there won't be enough space to do it. Or I try to write something, but it doesn't sound right. So, in pictures, they can understand what I'm trying to say.*
>
> ~ Brianna, 10

Over the decades, a number of researchers have explored the affordances of integrating literacy instruction with science education. A few notable examples include *In-depth Expanded Applications of Science* (Romance & Vitale, 1992, 2001, 2008, 2017), *Seeds of Science/Roots of Reading* (Cervetti et al., 2012), and *Concept-Oriented Reading Instruction* (e.g., Guthrie, Anderson, et al., 1999; Guthrie, McRae, et al., 2009; Guthrie, Wigfield, et al., 2004). However, these programs were developed before the release of the *Next Generation Science Standards* (NGSS, NGSS Lead States, 2013), a blueprint for reforms in U.S. science education that promote significant changes in how science is approached in K-12 instruction. As a result, integrated literacy and science materials released prior to the NGSS are rarely aligned with the new standards' conceptualization of "three-dimensional learning."

The three dimensions, which differentiate the NGSS from prior reform movements in science education, describe an approach to science learning through a combination of *disciplinary cores ideas* (DCIs), "what" students are learning; *science and engineering practices* (SEPs), "how" students interact with that content; and *cross-cutting concepts* (CCCs), "lenses" that support students to see connections among the various disciplines in science (NGSS Lead

States, 2013). The three dimensions are an attempt to break science education away from instruction that is focused on the memorization of facts, and too often presents the discovery of new knowledge in the past tense, in favor of *doing* science (Krajcik & Czerniak, 2014). This process-oriented approach, particularly the emphasis on practices as an inextricable component, presents significant opportunities to thoughtfully integrate literacy instruction with science.

Although all eight of the science practices identified in the NGSS have clear connections to literacy, one of them, *Developing and Using Models*, is of particular interest for the role it may play in an integrated curriculum. First, modeling requires multimodal composing, involving the successful blending of written and drawn elements (Lehrer & Schauble, 2006; Schwarz et al., 2009). In a world increasingly driven by technological communications that are similarly multimodal, experience with this practice is surely a benefit for 21st century citizens (Kress, 2010). Second, modeling is a disciplinary literacy, involving ways of organizing and communicating information valued by professional scientists (Moje, 2008; Shanahan & Shanahan, 2008). Disciplinary literacy in science has an extensive research base at the high school level (e.g., Tytler, Prain, & Hubber, 2018), but remains underexplored at the elementary level. The third reason that modeling is worthy of study follows from the second. In a similar way that the literacy research community is still learning about disciplinary literacy at the elementary level, science education researchers are still learning about how modeling unfolds in classroom settings with that age group (e.g., Baumfalk et al., 2019; Evagorou et al., 2020).

The research that does exist suggests that elementary school students can successfully develop and use models (e.g., Baek et al., 2011; Zangori et al., 2017) but many questions remain about effective ways to support young learners in this practice. In this study, I examined two potential supports. The first was to embed modeling not only within an integrated literacy and science unit, but within an integrated literacy and science *project-based learning (PBL)* unit (Condliffe et al., 2017; Thomas, 2000). In this way, modeling was not taught as an isolated skill, but as a meaningful activity unfolding organically within a larger PBL storyline. The second support was taking a closer look at peer consultation and feedback (Herrenkohl, Tasker, & White, 2011), recognizing the importance of providing an audience for students as they translate their private and individual *mental models* into public and shared *expressed models* intended to be understandable to others (Gilbert, 2004, p. 117). Acknowledging that models can also be used as tools for individual sense-making, I looked at the social function of modeling and the role that one-on-one peer feedback could play in helping students to refine their models. Few studies have examined these two supports: embedding modeling in a PBL context or engaging in paired peer consultation as a method of supporting elementary students' model revisions and improvements.

In summary, integrating literacy and science instruction has shown promise in supporting students in both literacy outcomes (Cervetti, Wright, & Hwang, 2016; Guthrie, McRae, & Klauda, 2007; Vitale & Romance, 2012) and science outcomes (Connor et al., 2017; McNeill, 2011). So, it is reasonable to expect that embedding modeling within an integrated PBL curriculum would be beneficial for students. Furthermore, as a key function of models is their explanatory power when communicating with others about a phenomenon (Manz, 2012), it is also reasonable to look at peer feedback as an avenue for supporting students in refining their models and enhancing their facility with the practice of modeling. Based on these dual assumptions, I asked a pair of research questions for this study:

RQ1. What do fifth-grade students communicate through models within a project-based integrated literacy and science unit?

RQ2. What are ways in which peer feedback influences fifth graders to revise models?

Literature Review

I present the following literature review to help illuminate and frame this study. In addition to providing a definition for "literacy" and a brief overview of the turn toward multimodality, the review includes selected research, from elementary school contexts, on disciplinary literacy, developing and using models, integrating literacy and science, project-based learning, and peer feedback in modeling.

Definition of "Literacy"

"Literacy" is a slippery term. Especially in the popular press, it is common to hear discussions about "media literacy" or "computer literacy" as a way to characterize a general familiarity with a subject. "Scientific literacy," a similar usage that appears everywhere from policy documents to the evening news, makes it sound as if literacy and science are already integrated. Although this study is rooted in the conviction that literacy and science are mutually beneficial, literacy does have its own identity.

I begin with a definition of literacy proposed by Frankel, Becker, Rowe, and Pearson (2016): "the process of using reading, writing, and oral language to extract, construct, integrate, and critique meaning through interaction and involvement with multimodal texts in the context of socially situated practices" (p. 7). While this modern definition addresses abiding perceptions of literacy as a synonym for reading, I suggest that it still does not quite capture literacy in all of its complexity. To wit, scientists, whether recording fieldnotes, drafting a diagram, writing for a journal, or developing a model, draw upon a variety of genres and modalities to communicate with others (Shanahan & Shanahan, 2014). A supplement to the definition above is needed, a task to which I turn next.

Transposing science practices from the professional sphere to the classroom, it quickly becomes apparent that young children need an extensive repertoire of semiotic resources (Kress, 2010) in order to share the complexity of their sense-making beyond the modes asked of them in "school science" (Windschitl, 2019). For instance, a written paragraph about an experiment may not reveal a student's grasp of scientific principles and a multiple-choice test might not capture how students apply scientific content knowledge to predict the outcome of an investigation. Therefore, I augment the Frankel et al. definition of literacy with the concept of *multiliteracies* offered by Alvermann:

> multiliteracies broadens the meaning of text and relates textual reading to oral, aural, visual, tactile, and digital modes of learning as well as to the social skills necessary for communicating and collaborating while engaged in such learning. (2004, p. 227)

The resulting, combined definition of **multimodal literacies** guiding this study is *the process of using oral, aural, visual, tactile, and digital modes of learning to extract, construct, integrate, and critique meaning through creation, interaction, and involvement with multimodal texts in the context of socially situated practices to communicate and collaborate with others.*

The increasing attention to multimodality, in large part due to seismic changes wrought by technological advances, needs to be grounded in the acknowledgement that humans have used multimodal communication throughout history and that all cultures are multimodal; therefore, the increasing focus on visuals and other modes resulting from new media is best understood as a *turn* (Jewitt, 2011, p. 4). Grounded in a program of research going back to the 1980s, at the very beginning of the multimodal turn, Mayer and colleagues (1995) proposed a *generative theory of textbook design*, looking at how text, illustrations, and annotations worked in concert to foster comprehension. More recently, building upon Mayer's work, Serafini (2012) offered the term "reader-viewer" to more accurately reflect the roles necessary when interacting with a "multimodal ensemble" (p. 26). As important as it is for young people to comprehend existing multimodal texts (Danielsson & Selander, 2016), it is equally important that they have the opportunity to produce them. Therefore, I suggest a complement to Serafini's term: that students engaged in modeling are not only reader-viewers, but also *writer-designers*. This study examines the choices made by upper elementary students as they work as writer-designers.

Disciplinary Literacy

Equipped with a definition of multimodal literacies, and thinking about the role students play as writer-designers, we can shift our attention to the classroom. It may be useful to think of the definition of multimodal literacies stated above as the full palette, set of equipment, and suite of techniques available to a visual artist. However, even when using the same paints and the same brushes, an abstract expressionist is going to approach a canvas differently than a neo-impressionist or a classicist. Similarly, a scientist is going to utilize multimodal literacies in different ways than a novelist or a historian. As a result, we need to consider *disciplinary literacy* (e.g., Moje, 2008; Pearson, Moje, & Greenleaf, 2010; Shanahan & Shanahan, 2008), the discipline-specific habits of mind used by practitioners in a specific field, to get a better sense of how scientists use multimodal literacies.

Research involving disciplinary literacy in science tends to focus on high school and university-level instruction (e.g., Ariely, Livnat, & Yarden, 2019; Hurley & Henry, 2015; Putra & Tang, 2016; Rainey et al., 2018). About a decade ago, literacy scholars began presenting the case that disciplinary literacy was not too complex for the elementary level (Cervetti & Pearson, 2012; Shanahan & Shanahan, 2014). Since then, research on disciplinary literacy in science at the elementary level has explored classroom discourse (e.g., Seah & Yore, 2017; Wright &

Gotwals, 2017), the reading and comprehension of text (e.g., Colwell, 2019), and writing in science (e.g., Clark et al., 2020; Goldman et al., 2016; Welsh et al. 2020).

In addition, researchers who don't necessarily use the term "disciplinary literacy" have looked at what it means to write in science or to write like a scientist (e.g., Hand, 2008; Freeman & Taylor, 2006), particularly the writing of scientific explanations and arguments (e.g., Forbes et al., 2014; Newell et al., 2011; Reiser, Berland, & Kenyon, 2012; Songer, Shah, & Fick, 2013; Zangori, Forbes, & Biggers, 2013). A number of studies have looked at the affordances of students maintaining science notebooks, which combine writing with graphic elements (Campbell & Fulton, 2003; Fang et al., 2010; Grysko & Zygouris-Coe, 2019). However, the existing research on writing in science does not address the creation of multimodal texts. In particular, I could not locate any studies using a disciplinary literacy lens to explore modeling, a form of composition that often leads with the visual representation rather than with words.

I argue that modeling is worth examining not only as a disciplinary literacy practice in science, but also in technical drawing. Of course, scientists often create their own models, but technical drawings, such as models, are often produced by drafters who specialize in creating visual representations. Models certainly exhibit a great deal of diversity in design (Passmore et al., 2014), but the wide range of designs is not mutually exclusive from students becoming more familiar with commonly used symbols, perspectives, layout, and other conventions of technical drawing. While the visual form of the model has been explored by some science education researchers (discussed in the next section), this paper will contribute to the literature on disciplinary literacy by taking a very close look at students' choices in multimodal composition.

Developing and Using Models

Recognizing disparate and wide-ranging notions of a "model," this study defines a model as an explicit and visible external representation that provides insight into sense-making (National Research Council, 2012, p. 56). The roles of a model, according to the NGSS, are "to represent a system (or parts of a system) under study, to aid in the development of questions and explanations, to generate data that can be used to make predictions, and to communicate ideas to others" (NGSS Lead States, 2013, Appendix F, p. 6). Historically, modeling was considered too difficult and abstract for young learners (Duschl, 2008; Manz, 2012). However, the inclusion of modeling as a practice in the NGSS has resulted in an increasing number of empirical studies at the elementary level showing that this is not the case (e.g., Baumfalk et al., 2019; Forbes, Zangori, & Schwarz, 2015; Zangori et al., 2017).

One of the most extensive research projects on modeling at the elementary level, and the most salient to the modeling experiences included in this study, was *Modeling Designs for Learning Science* (MoDeLS, e.g., Baek et al., 2011; Kenyon et al., 2008; Schwarz et al., 2009; Schwarz et al., 2012). A primary goal of the MoDeLS longitudinal 5-year project in the intermediate grades was to develop a learning progression framework to represent trajectories of progress along what the researchers described as a "construct map" with two dimensions: *models as generative tools for explaining and predicting* and *models change as understanding improves* (Schwarz et al., 2009, p. 632). Each dimension was created to include elements of the practice of scientific modeling (construct, use, evaluate, and revise), as well as *metamodeling knowledge* (Schwarz & White, 2005): understanding what models are and how and why models and modeling are necessary. Eventually, the MoDeLS team revised their learning progressions into an *Epistemologies in Practice* framework (Berland et al., 2016). Based on this framework, Ke and Schwarz (2021) crafted the following four questions to support students, and their teachers, with sense-making around the purposes and goals of modeling:

1. What kind of answer should our model provide?
2. How do we justify our model?
3. Who will use our model and how?
4. How does our model relate to other scientific phenomena and ideas?

(Ke & Schwarz, 2021, p. 6)

Among a variety of contexts that the MoDeLS team studied to develop and refine their frameworks, they conducted numerous observations of Grade 5 classrooms engaged in a 6-week researcher-designed modeling-centered unit on evaporation and condensation (Kenyon et al., 2008). Coincidentally, and rather serendipitously, the modeling activities focused on observations of solar stills, the same phenomenon under exploration in the current study. Among the generative and valuable findings of their project, the researchers repeatedly found that, developed in an iterative manner, students' models became increasingly sophisticated (e.g., Kenyon et al., 2008; Schwarz et al., 2009; Schwarz et al., 2012). More specifically, two of their findings are of particular interest for the work described in this paper: (1) an increase in the inclusion of invisible elements and (2) models with increased abstraction (Hoyakem & Schwarz, 2014).

These two qualities appear elsewhere in the literature and bear a closer look. Concerning *invisible elements* (e.g., representing heat transfer from a source to water that increases the rate of evaporation), students engaged in a scientific investigation can typically observe the cause and effect, but the mechanism is often invisible and needs to be inferred (Forbes, Zangori, & Schwarz, 2015; Seah, 2016; Zangori & Forbes, 2014). As challenging as this may be to write about, it is even more complex when students need to decide on a symbol system to represent these invisible mechanisms. This process becomes yet more complex if students are unfamiliar with common symbol conventions in scientific models and therefore have to devise their own (Lehrer & Schauble, 2012; Louca & Zacharia, 2015).

Regarding *abstraction* (e.g., drawing a generalized symbol, such as a square labeled “heat source,” rather than a realistic representation, like a picture of the sun or a heat lamp), the models created by professional scientists often bear little resemblance to the underlying phenomenon (Passmore et al., 2014). Even a model intended to look “realistic” does not truly reflect reality, as the designer makes choices about what to include and exclude (Manz, 2012). As a model becomes increasingly abstracted, it is unclear if the construction and interpretation of those abstracted models require the same cognitive processes as one that is more “realistic” (Van Meter & Garner, 2005), especially when the model no longer shares literal similarities with the phenomenon under investigation (Lehrer & Schauble, 2012).

To clarify, a model created by a professional scientist would not be a depiction of the particular investigative set-up (Manz, 2012). Rather, a model is a simplified representation to explain underlying mechanisms and processes, highlighting relationships between elements and the rules of the system (Louca et al., 2011; Manz, 2012; Nersessian, 2008; Passmore et al., 2014). As such, the components of the model would be abstracted to generalize the phenomenon under investigation. For example, let’s say that students were modeling the relationship between the slope of a ramp and the speed of an object. In the classroom, perhaps the children would be using a toy car and a piece of cardboard propped on a variable number of wooden blocks. In a novice model, the writer-designer might try to draw the car and the wooden blocks, labeled as such, along with a label for the cardboard. In an abstracted model, the car could be replaced with a circle labeled "object" with the ramp represented as an angle. Perhaps the writer-designer would choose to draw more than one ramp, displaying different angles, or perhaps they would include an arrow and a label to show that the slope of the ramp could be increased. Finally, they would add arrows to represent gravity, the invisible component of the model that helps to explain why the phenomenon occurs.

Based on consistent findings from existing studies, one of the primary goals for modeling at the elementary level is to support students to include invisible elements. The inclusion of those elements may reflect students improving their grasp of the underlying causal forces and developing their mechanistic reasoning (Schwarz, Ke, et al., 2014). Researchers are still exploring effective techniques for supporting students with this goal. While increasing the representation of invisible elements is a desired outcome, I argue that the level of abstraction that could, and should, be expected of novice designers is a more unsettled question. Especially when working with pencil-and-paper on these sorts of "2-D diagrammatic models" (Zangori et al., 2017), particularly during their first experiences with this practice, it makes sense that students would create something more akin to a dynamic diagram (i.e., a "realistic" labeled drawing accompanied by symbols intended to represent movement and change) than an abstracted representation. The issues of invisible elements and the desired level of abstraction are ideas we will return to in the discussion section.

Along with their encouraging findings, the MoDeLS researchers identified three challenges (Schwarz et al., 2009, p. 652). First, they identified the difficulty in devising an authentic reason for students to engage in modeling beyond simply "doing school" – as Berland and Reiser (2009) have suggested, the learning experience has to create a need for the practice. Second, the researchers acknowledged the challenge in providing students with a genuine audience. Third, the MoDeLS team discovered that, while students identified needed revisions, it was difficult to motivate students to make those revisions. Later in the paper, I will address how the Wayfinding Unit addressed these three challenges.

A key concept guiding the MoDeLS work was the notion of *meta-modeling knowledge* (Schwarz & White, 2005). According to this concept, not only do students need to develop proficiency with the construction, evaluation, revision, and use of models, they also need to understand the nature and purpose of models (Baek et al., 2011). This means that, as important as it is for students to reason *with* models, by using them to make sense of the world, it is equally important for students to reason *about* models, by engaging in meta-cognitive sense-making about the effectiveness of a given model and possible ways to refine it (Passmore et al., 2014). Exploring both the skills involved in a practice, as well as the knowledge about how and why a practice is necessary, echoes a disciplinary literacy lens.

Using a similar disciplinary literacy lens to look at technical drawing, a program of research from abroad, while not explicitly about modeling, indicates the type of instruction students need to construct visual representations such as models. About 30 years ago, Australia was in the midst of standards reforms that were similar to the NGSS. Anning (1994, 1997, 1999), looking at students in kindergarten, documented challenges that teachers and students had in making the transition. Anning reported that young students nearly always used drawing for decorative purposes. As a result, she found that students needed specific instruction in techniques for representing features, like occlusion and perspective, necessary for creating technical drawings.

Work to date on the practice of modeling at the elementary level indicates that it may serve as a powerful tool for individual sense-making, as well as serving as a tool for supporting conceptual and epistemic dialogue (Manz, 2012). Although the research base is expanding, we still have much to learn about how students engage in modeling. Outstanding questions involve the ways in which students include invisible elements and the desired level of abstraction in a model from a novice writer-designer. Other questions include how to provide authentic contexts to motivate the creation and revision of models, as well as how to provide an authentic audience. Finally, more work is needed on the development of meta-modeling knowledge (how and why models are used), as well as the development of technical drawing skills.

Integrating Literacy and Science

After discussing literacy and scientific modeling separately, we now consider what is means to bring them together in an integrated way at the elementary level. Part of the impetus for this integration is practical. First, the majority of elementary teachers dedicate the largest percentage of their instructional time to English language arts (Smith, Trygstad, & Banilower, 2016). Combining science instruction with literacy takes advantage of existing time allocations, reducing pressure on teachers to find "extra time" for science while also providing rich content. Second, teachers report feeling better prepared to teach literacy than STEM (Smith, Trygstad, & Banilower, 2016). By weaving together science content and practices with literacy instruction, teachers are positioned to build from an area of strength.

The argument for integrating literacy and science instruction is not merely practical at the classroom level, but is also driven by ongoing standards reform at the state and national levels. In the United States, elementary school subjects have historically been taught in silos. With the call for greater use of informational text in the *Common Core State Standards for English Language Arts* (CCSS-ELA, National Governors Association, 2010), and as the NGSS, or some variant thereof, are adopted by more states, it stands to reason that the integration of literacy and science will accelerate (Palincsar, 2013). However, many recent CCSS-ELA-aligned programs, such as *National Geographic Reach for Reading* (Frey et al., 2016), integrate the subjects by including science readings in English language arts curricula. Less common is the opposite integration: looking at what it means to include literacy instruction in a science curriculum.

That being said, modeling as embedded within the Wayfinding Unit is a supplement to, and not a replacement for, more traditional forms of literacy instruction. For example, modeling, as a form of organizing knowledge, has similarities to literacy practices such as summarization, self-questioning, and prior knowledge activation (Van Meter & Garner, 2005). While modeling, students have opportunities to apply these literacy practices in ways that look very different than how they tend to be presented in ELA textbooks or worksheets. As I mentioned earlier, modeling also provides a meaningful context for multimodal composition, helping young people understand that literacy is about more than words alone (Lemke, 1998; Osbourne, 2002).

Project-Based Learning

Calls for integrated instruction in the United States go back as far as the progressive education movement at the turn of the last century (Peterson, 2012). In the decades since, interest in a collection of related approaches such as inquiry-, problem-, and project-based learning has continued without ever coalescing around a single accepted set of practices, or even a clear distinction among approaches (Thomas, 2000). This study is grounded in the design principles of project-based learning suggested by Krajcik and Czerniak (2014), including: using a *driving question*, encouraging students to *figure out phenomena*, providing *student choice*, and working towards the creation of a *final artifact*. By deploying PBL, the goal is to shift activity in the classroom from *doing things* towards *doing things for a purpose* (Krajcik & Czerniak, 2014) by placing an emphasis on authentic tasks, including designing meaningful reasons for students to communicate with one another.

Despite its long history, research on project-based learning at the elementary level, especially materials integrating science and literacy, is surprisingly thin. An exciting recent study by Puig and Evagorou (2020) was a socioscientific unit for Grade 2 on the importance of bees that included students working in a small groups to develop drawn models showing both the relationships between the bees in the hive and their interactions with the outside environment. Students then transformed those 2-dimensional representations into 3-dimensional physical models which they used to illustrate scenarios resulting in bee population decline (Puig & Evagorou, 2020). Other recent work at the elementary level comes from our ML-PBL project, with encouraging results in Grade 3 involving the purposeful matching of researcher-designed texts to tasks (Fitzgerald, 2018), social-emotional skill development (Fitzgerald, 2020), and the use of computer simulations during investigations (Easley, 2020). The current study extends the work of the ML-PBL team on modeling in Grade 4 (Marcum, 2018), including the use of *physical microcosms* (Lehrer & Shauble, 2012), extensive development of *2-D diagrammatic models* (Zangori et al., 2017), and using a specific protocol for *one-on-one peer feedback* (Marcum, 2018).

Peer Feedback in Modeling

Receiving peer feedback and making revisions are established practices in elementary writing instruction (e.g., Calkins & Collins, 2006; Calkins & Tolan, 2010; Fountas & Pinnell, 2012). These practices are much less common in science instruction (Freeman & Taylor, 2006). Although students are often grouped to complete lab assignments (Howe et al., 2007), this often seems to be a practical consideration rather than an opportunity for dialogue (Webb, Baxter, &

Thompson, 1997). Science assignments at the elementary level typically end with the completion of a data collection sheet or possibly writing a lab report. However, ending the investigation with a worksheet or a lab report leads to a sense that a single answer has been found, much like a math equation. As Reiser, Berland, and Kenyon (2012) argued, arranging for students to compare and critique their data and conclusions helps students to strengthen their reasoning, reconcile competing conclusions, build consensus among participants, and clarify their work. In a similar way, Zangori and Forbes (2014) suggested that comparing and evaluating the work of peers provides students with an array of examples about how information can be presented, as well as opportunities to recognize multiple answers to the same question.

Returning to the work of the MoDeLS team, their evaporation-condensation unit included a structure for peer feedback (Kenyon et al., 2008). Students individually constructed their models, then discussed them in small groups of three or four. After they shared and decided on a single model, two of the small groups would combine and again discuss, persuade, and decide on one model. The researchers found that groups tended to choose a model quickly based more on impulses like “pick mine” or “I like his” rather than providing justifications about the merits of any given model (Kenyon et al., 2008, p. 10). However, by looking very closely at the group discussions, researchers were able to identify some examples of the emergence of specific reasoning that was guiding decision-making (Baek & Schwarz, 2015; Kenyon et al., 2008).

The findings of the MoDeLS project regarding their peer-sharing structure raise important questions. Although selecting a single model to represent the group is intended to mimic the push-and-pull of a true scientific dialogue (Kenyon et al., 2008), I question if this format is developmentally appropriate for young children. This form of unstructured discussion can be difficult for elementary-aged students. Also, small group work can be intimidating for shy children, and asking groups to converge on a single consensus model involves power dynamics based on gender, race, perceived popularity, and/or other personal qualities that may not result in choices being made based on scientific merits. Most of all, sending the message that there is a single "better" model is counter-productive to the concept that multiple models are possible. The Wayfinding Unit explored ways to provide structure for feedback and to lessen power dynamics. Including peer feedback in the modeling process was guided by a commitment to social constructivism, described in more detail in the following section.

Theoretical Framework

This study draws from a social constructivist perspective (Palincsar, 1998). In this view, individuals "construct" their own understanding of the world in an active sense-making process. Somewhat paradoxically, this personal and individual understanding of the world is impossible in the absence of interactions with others. This is because learning is not located solely within the individual, but is rather a complex interplay among relationships, language, time, and other socially-mediated constructs. In particular, this study was influenced by three themes about the sociocultural nature of learning derived from Vygotsky (1978): the notion of cognitive tools, the centrality of social interaction, and attention to the zone of proximal development.

The first key concept adopted from Vygotsky is his concept of *cognitive tools*, which humans use to mediate their interactions (Wertsch, 1991). While language is a primary cognitive tool, drawings, photos, gestures, or other representations can be imbued with meaning (Yore et al., 2003). Modeling calls for these modalities to be combined in ways not typical in traditional literacy instruction insofar as the centrality of visuals, combined with print text that may or may not be in complete sentences. While school-based literacy instruction at the elementary level continues to prioritize print text (Lieberman, 2020), technology-mediated interactions, particularly social media, tend to be image-focused (Kress, 2010). As a result, multimodal composing is an increasingly necessary practice. Taking a wider view, the learning context itself, the totality of texts, tasks, interactions, pedagogical techniques, scaffolds, and other choices, may also be viewed as a tool for sense-making (Kelly & Cunningham, 2019).

Second, this work is grounded in the idea that *social interaction* is central to knowledge building (Wertsch, 1991). The power of a "text," regardless of mode, is to communicate ideas and contribute to knowledge building. However, the full potential of a text is unlocked when it is used to fuel discussion. As mentioned above, submitting drafts for peer feedback has a long history in writing instruction. This study applies the same reasoning to scientific investigations: modeling is useful insofar as it provides opportunities for dialogue and to ask questions that arise in the moment.

Finally, this project was influenced by the Vygotskian idea of the *zone of proximal development* (ZPD, Vygotsky, 1978). According to this notion, a learner, with assistance from one or more knowledgeable others, is able to navigate material that would otherwise be inaccessible. The ZPD is not a fixed quantity. Rather, the ZPD is an area of opportunity for learning that opens up through the interaction between two (or more) learners and the task at hand. In fact, even within subcomponents of the same task, the role of "more knowledgeable" may shift between the individuals involved in the task. Furthermore, each student brings a unique set of experiences and background knowledge to the task at hand. Encouraging student-to-student feedback fosters a classroom community wherein all students are positioned as knowers.

To conclude this literature review and position this current work, I refer back to the definition of multimodal literacies that I offered previously: *the process of using oral, aural, visual, tactile, and digital modes of learning to extract, construct, integrate, and critique* *meaning through creation, interaction, and involvement with multimodal texts in the context of socially situated practices to communicate and collaborate with others*. That is a complex definition and classrooms are complex places, weaving a potentially tangled web. In this study, I tease out some of those threads. First, I suggest that developing and using models is an ideal practice, both as a literacy practice and as a science practice, for exploring how such a multifaceted definition could be operationalized. However, we are still learning about how students at the elementary level approach modeling. In particular, questions remain regarding how younger children handle invisible elements and levels of abstraction. Second, using a disciplinary literacy lens, we have more to learn about how novice writer-designers approach modeling as scientists, thinking about the purpose and use of models, and also how they approach modeling as drafters, developing the technical drawing skills needed to create visual representations. Third, researchers have raised concerns about modeling being taught in an authentic way, and not simply as another school-like task. I suggest that a project-based unit, focused on a topic intended to make students' imaginations soar, might provide a meaningful context to motivate the need for modeling. Finally, this study looks at the potential of one-on-one feedback, using an open-ended but specific protocol, to provide students with a genuine audience, and to support students to not only identify revisions for their model, but to actually make those changes. Overall, I was curious about the choices made by upper elementary students as they tried their hand as writer-designers engaged in the interdisciplinary practice of modeling.

Method

This study was a part of the *Multiple Literacies in Project-Based Learning (ML-PBL)* project, a five-year endeavor to develop NGSS-aligned PBL science curricula for Grades 3-5. After developing curricula for Grades 3 and 4 over the course of multiple years, we expanded to

Grade 5 and piloted a single unit during 2018-19. The data for this study were collected in 2019-20 during the second iteration of the unit, which incorporated revisions from the initial enactment.

The development of the ML-PBL curriculum followed a design-based research (DBR) approach (Brown, 1992; Collins, 1992). By wading into the messiness of authentic, everyday classroom life, DBR is intended to assist with the development of theory and the improvement of practice, while acknowledging the ever-shifting contextual variables that are an inherent feature of school life and, therefore, an inseparable feature of classroom interventions (Brown, 1992).

Within the context of the larger DBR curricular endeavor, and to begin pulling at the threads identified at the end of the previous section, the pair of research questions guiding this study were: (1) What do fifth-grade students communicate through models within a project-based integrated literacy and science unit? and (2) What are ways in which peer feedback influences fifth graders to revise models? To explore these questions, I used an instrumental case study design (Stake, 1995), with a single classroom, one teacher and her students engaged in this ML-PBL unit, serving as the case. Below, I will describe the participants and context, curricular unit, data sources, data analysis, and trustworthiness for this work.

Participants and Context

The context for this study was a single Grade 5 classroom in Pine Elementary School[3], a public K-5 school in a semi-rural Midwestern town. I had the pleasure of working with a number of teachers at the school starting in 2016-17 in my role as a Graduate Student Research Assistant for the ML-PBL project. I spent two years helping to develop materials and conducting

[3] Names of places and people are pseudonyms

observations in Grades 3 and 4, with four ML-PBL units per grade comprising each year's science curriculum. I then transitioned to Grade 5 to help develop and collect data for a single pilot ML-PBL unit. Ms. Davis, a White woman, was our collaborator for Grade 5 at Pine. She was in her 23rd year of teaching during 2019-20 and in her sixth year in Grade 5. Although she had great interest in PBL, her participation in the 2018-19 pilot was her first experience with teaching a project-based curriculum.

During 2019-20, Ms. Davis enacted a revised version of the Wayfinding Unit, which serves as the case for this study. That year, Ms. Davis had 30 students, 18 males and 12 females. Nine students were Black, one was multiracial, and 20 were White. Six students had Individualized Education Plans (IEPs) with a seventh student under consideration for special education services[4]. Mr. Daniels, a White male paraprofessional who was a retired music teacher, was in the room daily as a one-on-one assistant for a single student, although he would occasionally provide support to others. All of the students in this classroom spoke English as their first language. Schoolwide, Pine had a Title I designation with 62% of students qualifying for free or reduced-price lunch (Michigan's Center for Educational Performance and Information, 2018).

Among the fifth graders in Ms. Davis' class, 16 of the 30 had participated in ML-PBL during 2017-18 when they were in Grade 3: six with a teacher who was an experienced ML-PBL participant and 10 with a teacher who had been enacting ML-PBL for the first time. The remaining 14 students did not experience ML-PBL during Grade 3. For a variety of reasons, none of the students participated in ML-PBL during Grade 4.

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[4] One student from the school's high-needs resource classroom often spent inclusion time in Ms. Davis' room during the afternoon, but his attendance was not consistent, so he was not included in this study.

Focal Students

My time collecting data in the classroom involved collecting artifacts from all students and filming the whole class. However, as a practical consideration for interviews and when I filmed small group work, I selected focal students. When deciding, my prime consideration was to give voice to students who may otherwise be marginalized or minoritized due to race, gender, and/or special education status. Because of persistent underrepresentation of people of color, women, and particularly women of color in the STEM professions (NSF, 2017), I intentionally selected six of the seven Black females in the class: Brianna, Daylah (who had an IEP for reading and math), Harmony, Lexi, Sarafina, and Tameika. I was unable to select the seventh, Florencia, due to attendance concerns, but her written work is featured in this paper. I also included Shawn and Jovani, the only two Black males in the class. In addition, I selected two White females, Trudi and Wendy, who very rarely participated in whole-class discussions. Both girls had mild trouble with articulating certain sounds, but neither was receiving speech therapy services. Finally, I included William, a White male, who had pronounced difficulties in articulation and who was working with the school's speech-language clinician. In all, the focal group included 11 students, about one third of the class. Parents/guardians granted informed consent for the overall study and I received verbal assent from each focal student prior to every interview.

A Snapshot of the Wayfinding Unit

As the ML-PBL project expanded into Grade 5, different sites piloted various potential units. For Pine Elementary School, my doctoral advisor and I designed a unit about the art and science of Polynesian wayfinding: navigating vast oceans using only clues from nature. In addition to addressing literacy and math standards from the CCSS, this topic was well-suited for addressing the five Earth and Space Sciences standards for Grade 5 and the three Engineering Design standards for upper elementary from the NGSS. Beyond addressing academic standards, our intention in crafting the Wayfinding Unit was to introduce students to the beauty and wonder of engaging with science and engineering through literacy. Over the course of the unit, students read a wide array of genres, including blog posts, newspaper articles, informational texts, and mythology. In response, students produced an equally wide array of writings and representations: from persuasive letters and public-service announcements to scientific explanations and models. When crafting the unit, we intended to create a continuous storyline wherein the disciplinary literacy practices were organic: arising from authentic contexts and necessary for meaningful purposes.

Like all of the ML-PBL units, the Wayfinding Unit was organized around a driving question (Krajcik & Czerniak, 2014); in this case, *How can we find our way in the world by using only the clues that are in our environment?* It included 20 content lessons, four lessons per week for five weeks. Each lesson was meant to be taught for 90 minutes, each containing literacy, science, engineering, and social studies components. The unit culminated with an additional 4 weeks dedicated to the creation of a pair of final projects: 1) planning, building, and testing models of Polynesian-style double-hulled canoes and 2) creating videos identifying an environmental problem and possible solutions (see Appendix A for the Table of Contents).

With sailing as a major theme of the unit, the weeks were organized around the stages of a journey: deciding why to go, planning the trip, gathering knowledge and skills, then finding your way. The inspiration for this organization came from the online exhibit *Never Lost*[5]

[5] The *Never Lost* website (http://annex.exploratorium.edu/neverlost/) was built using Adobe Flash. Adobe stopped supporting Flash Player and blocked Flash content as of January 12, 2021, so the website is no longer available.

presented by the Exploratorium, a museum in San Francisco. The informational texts included in their exhibit became key resources for our unit, after being modified for fifth graders.

A major focus of the *Never Lost* site was the Polynesian Voyaging Society. Starting in the mid-1970s, this organization sought to rebuild the canoes their ancestors used to navigate to Hawaii. Their flagship canoe, the Hokule'a, sailed 26,000 miles from 2014-2017 to circumnavigate the globe using no electronics or fossil fuels. Wanting to make this story a centerpiece of the unit, we included newspaper articles from throughout their worldwide voyage. We also made extensive use of original blog posts that were authored by the crew of the Hokule'a during the journey. These original artifacts not only heightened the authenticity of the unit, but they provided repeated opportunities to present people of color, women, and importantly, women of color as individuals with extensive scientific and engineering knowledge.

One of the goals in crafting the Wayfinding Unit was to provide repeated, regular, and contextually-driven opportunities for students to engage with the eight SEPs defined by the NGSS. Unlike the MoDeLS project, which stretched developing a model about a single phenomenon over the course of a 6-week unit (Baek et al., 2011; Schwarz et al., 2009), our goal was to have shorter, but more frequent, modeling experiences, each exploring a different phenomenon. As a result, the Wayfinding Unit included two modeling activities: one earlier in the unit, when the students were exploring the necessity of water, and a second experience later in the unit, tied to discussions around plastic in the ocean. Because I was interested in the initial experiences of novice writer-designers faced with the task of developing a model, and because it involved a first-hand investigation, I selected the first modeling opportunity for close analysis.

The Solar Still Investigation

This study focused on a modeling activity investigating the use of a solar still to distill freshwater from saltwater. The process of assembling and observing solar stills, then developing and revising models about them, emerged from a context established early in the Wayfinding Unit. During Week 1, the students imagined preparing for an extended voyage in a long-distance canoe. After a multi-day math activity calculating the weight of their supplies and the carrying capacity of the canoe, the students turned to food and water needs. At the beginning of Week 2, the solar still investigation launched with Lesson 5 (see Appendix B). The lesson began with a pair of readings: a "Provisions" text, about how Polynesians packed food, and "Water, Water, Everywhere," about the necessity of freshwater. During the previous math activity, students had already learned that each member of the 15-person crew would need 1 gallon of freshwater per day and that a single gallon of water weighs 8 pounds. The "Water, Water, Everywhere" text helped to introduce the question: surrounded by an ocean of saltwater, could freshwater be extracted to relieve the need for packing such a bulky and heavy item?

After reading and discussing the two texts, Ms. Davis and I distributed sets of materials to students for their solar stills. Working in groups of three, the students figured out how to assemble them and answered six questions to guide their thinking about the purpose of the various components and to make predictions about the functioning of the stills (see Appendix C).

As a brief summary for readers unfamiliar with solar stills, the inside of the solar still functions as a *physical microcosm* (Lehrer & Schauble, 2012), demonstrating the three phases of the water cycle: evaporation, condensation, and precipitation. Heat energy from a heat source transfers to saltwater contained in a large bowl. Water, in the form of vapor, evaporates and leaves the dissolved salt behind. The water vapor condenses on the underside of a piece of plastic wrap covering the large bowl. Because of the slope created by weights producing a dip in the center of the plastic wrap, the condensate rolls to the center and drips, mimicking precipitation. After some time, freshwater collects in a small bowl nested within the larger bowl (Figure 2.1).

Figure 2.1: Close-up of solar still – photo from 10/7/19

With their stills put together and the questions answered, students poured saltwater into the stills and placed them in a sunny spot by the windows (Figure 2.2). Over the next few days, the students made informal observations of the stills. They did not record any data because, although condensation was clearly forming within the devices, the yield was only a few droplets.

Figure 2.2: Initial placement of solar stills in a sunny spot near a window at the conclusion of Lesson 5 – photo from 10/7/19

Exactly 1 week later, following a discussion about how the sun was not providing enough heat, Ms. Davis installed heat lamps above the solar stills. In only 24 hours, the stills had more visible condensation than had collected during the entire previous week (Figure 2.3), but very little of the freshwater had collected inside the small bowls (Figure 2.4). Even with the low yield, the changes within the stills were visible enough to begin making predictions about the processes at work. So, the students spent the last two days of Week 3 (Lessons 12 and 13, see Appendices D and E) developing drawn models about the solar stills. Each student was provided with a twosided modeling sheet. During Lesson 12, students developed their initial models using the front of the sheet (Figure 2.5).

Figure 2.3: Condensation collecting on the underside of the plastic wrap covering the solar still – photo from 10/15/19 (8 elapsed days, second day under the heat lamps)

Figure 2.4: Solar stills with heat lamps in place (top); close-up of solar still with condensation (bottom) – photos from 10/15/19 (8 elapsed days, second day under the heat lamps)

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Model of a Solar Still

Draw a model to explain your question. Be sure that your model has all of the parts you need, labels, and a key.

Question: ____

Describe how your model answers the question:

____

____

____

____

Figure 2.5: Student Modeling Sheet

During Lesson 13, Ms. Davis introduced "Five Characteristics of a Model" (Table 2.1). With these characteristics in mind, students completed their initial models. As students wrapped up their models, Ms. Davis paired them with a peer to provide feedback to one another using the form on the back of their modeling sheet (Figure 2.6). Peer feedback was provided in a format called the "3Cs" adapted from a protocol I used in my own classroom when I was a third-grade teacher and which was used extensively in the Grade 4 ML-PBL units[6]. The 3Cs, and their associated prompts, are:

(a) **Compliments:** What are some things you like about this model? What works well?

(b) **Constructive Suggestions:** What could be added to the model to make it better? Use evidence from the unit to support your suggestions.

(c) **Clarifying Question:** What is something you don't understand about this model?

After receiving written feedback, students used prompts to review the suggestions and make revisions. Students identified two revisions and had to declare if they would incorporate the revision(s) or not. They were then prompted to provide a rationale for their decisions. This reflection component of the feedback process was added during the development of the Grade 4 units. Similar to the MoDeLS project (Schwarz et al., 2009), we had noticed that students were very good at providing feedback for one another, but the feedback was not being taken up. We discovered that specifically asking students to identify and choose action items led to increased uptake of suggested revisions. By providing choice about accepting revisions, the reflection section of the peer feedback sheet helped to remind students that not all suggestions lead to improvements and that the original author retains autonomy regarding their work.

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[6] For discussions about how feedback was used with modeling in the Grade 4 ML-PBL curriculum, please refer to the dissertation by Marcum (2018).

Table 2.1

Five Characteristics of a Model

1. All models can be used to explain or predict phenomena.
2. All models have components.
3. Models show relationships among the components.
4. Models are shared for feedback.
5. Models are revised based on new data.

Solar Still Model - Feedback Sheet 71

This model was created by: ______________________________

My partner's name is: ______________________________

***** Give your checklist to your partner. *****

Compliments: What are some things that you like about this model? What works well?

____

____

Constructive Suggestions: What could be added to this model to make it better? Use evidence from the unit to support your suggestions.

____

____

____

Clarifying Question: What is something that you don't understand about this model?

____

____

***** Give this paper back to the creator of this model. *****

Revisions

Choose two of the revisions suggested by your partner. Decide if you will make that revision or not, then provide a reason.

Revision #1: ______________________________

Will you make this revision? **YES** **NO**

Why? ______________________________

Revision #2: ______________________________

Will you make this revision? **YES** **NO**

Why? ______________________________

Figure 2.6: "3C" Peer Feedback Sheet and Reflection

Data Sources

In order to collect a multi-faceted view of the modeling and feedback process, I constructed this case study from a trio of data sources: student artifacts, interviews, and observations[7].

Student Artifacts

I collected solar still models and feedback sheets from all 30 students in the classroom. Twenty-four of the models were complete, with a written investigation question, developed model, and a written description of how the model answers the question. One model was missing a written investigation question and five of the models were missing both a written investigation question and written description. Twenty-three students received peer feedback and reflected on their revisions. Two students received peer feedback, but did not reflect on the revisions. One student received partial feedback (only receiving a compliment) while four students did not receive any peer feedback and have blank sheets.

Interviews

I conducted two sets of interviews to hear directly from students. I interviewed three students between Lessons 12 and 13: Shawn and Wendy, who had both received feedback, but had not yet made changes; and Harmony, who had not yet been paired with a peer. These three interviews were semi-structured and we used their models and feedback sheets to guide our conversations. I filmed these interviews with a small camera placed on the desk to record gestures and facial expressions along with audio.

---

[7] In addition, students completed a pre- and post-test that included a single modeling item. Results for this item were inconclusive, and are therefore not part of the data under consideration. I will discuss the modeling item, and its connection to near and far transfer, in the Implications section

At the end of the unit, I conducted a second set of interviews with 11 students, including the same three students from the earlier set. These conversations occurred more than 6 weeks after the modeling activity. I showed each student their model and asked them to walk me through the model itself, along with asking questions about the practice of modeling. I filmed the second set of interviews with a two-camera set up: a small camera on the table to capture our faces and a second camera on a high tripod to capture gestures and hand movements as the students explained their models.

Observations

To document the talk of the participants, I filmed each lesson with two cameras: one in the front of the classroom and one in the back. The camera facing the front was connected to a microphone worn by the teacher[8], while the camera facing the back was connected to a microphone that I wore. I took ethnographic fieldnotes for the entirety of most sessions. When needed, I suspended writing fieldnotes to assist with small group instruction or as otherwise called upon by the teacher. Although I do not reference the videos or fieldnotes directly, I reviewed them in preparation for this paper. Furthermore, my presence in the classroom for every day of the Wayfinding Unit provided me the time and space to get to know the members of this classroom community and their relationships with one another.

Data Analysis

I used a form of *conceptual analysis* (von Glasersfeld, 1995). Originally rooted in constructivist teaching experiments in mathematics (Steffe et al., 1976), conceptual analysis

[8] I did not conduct a formal measure of fidelity of implementation. However, I had a copy of the lesson plan as I observed each lesson. Ms. Davis followed the plans very closely, only making small adjustments that would be expected from an experienced teacher making informed decisions about enactment in real time.

looks for interactions between the students, the teacher, and the designed curriculum to try and understand the sense-making process students are engaged in during various tasks (Steffe & Ulrich, 2020). This involved creating a picture of student sense-making composed of the final artifact, interviews with students, and classroom observations. Like a pointillist painting, the overall image gains greater resolution based on the number of constituent points. As a result, the conceptual analysis had three steps: (1) review of student artifacts, (2) review of classroom videos and field notes, and (3) review of student interviews.

I approached the first step as a “conversation” with each student as they developed their initial model and as they went through the peer feedback process. I started by examining each student’s drawn model one-by-one. I made note of the written labels as well as the drawn components, then indicating any components that were drawn but not labeled. Then, I wrote a memo with my initial impressions of the model and what I could discern about the student’s understanding from the drawn model alone. With the memo completed, I turned to the student’s written description. I made additional notes about how the written description was related to the drawn model. Turning the paper over, I recorded the feedback provided by their peer as well as the writer-designer’s response to the feedback. Next, I compared the feedback sheet to the drawn model, looking for evidence of revision resulting from the peer consultation. Finally, I wrote a second memo, reflecting on the peer feedback and the original writer-designer’s responses to the feedback.

The second and third steps were related. For the second step, I reviewed the videos and fieldnotes for each of the solar still lessons. I made notes that included scientific vocabulary used (by the teacher or the students), predictions that were discussed, and instructions provided by the teacher about the practice of modeling. By doing so, I was trying to get more detail about the context of the enactment in this time and place. For the third step, I reviewed the videos of the end-of-unit student interviews and made notes about what students said. This provided a sense of student sense-making about their models and, because a number of weeks had elapsed, revealed how much each student remembered from the investigation.

I then re-combined the observations and themes between these data sources in order to construct my own explanations of students' sense-making, and changes in their thinking, while engaged in the practice of modeling and peer review. Although this review was retrospective, the intent was to share the dynamic, personal experiences of this group of students as they participated in the stages of the solar still investigation (Steffe & Ulrich, 2020).

Trustworthiness

No matter our mode of communication, be it written, drawn, or spoken, none of us can ever truly represent our thinking with the imperfect semiotic resources at our disposal (Kress, 2010). The gap between the contents of the mind and the marks on the page will always exist. Be that as it may, I felt an obligation as the researcher and author of this text to represent the sense-making of the students who participated in this study to the best of my abilities. Using students' drawn models and the written feedback from their peers as the primary data source for this study was one technique to ground the findings in students' first-hand responses. I also used triangulation to bring into focus a clear picture of each student's intention: rather than focus solely on the written artifacts, student interviews and classroom videos provided additional insights into what each student intended to communicate.

I admit that I am very close to this work. In addition to my role in the design of the unit, I feel very protective of the students, and their teacher. While this may be seen as a potential source of bias, I also see that as a source of trustworthiness. I feel a sense of obligation to this class for generously allowing me to share in their learning experiences. In exchange for their trust, I owe them my best efforts to honestly report what I observed. My representations are imperfect, but I hope that the months I spent in their classroom allowed me to get to know the students, and their teacher, well enough to deliver a trustworthy account of their learning.

Limitations

Due to the scope and design of this study, it possessed inherent limitations. The scope was limited to a single classroom with one teacher and one group of students. It is easy to imagine different results with the same teacher and a different group of students, the same group of students later in the academic year, a different participating teacher, or if the unit were enacted in another school entirely. Although focusing on this single instance of the Wayfinding Unit limits the generalizability of the study, working closely with these students and their teacher allowed me to provide a close and detailed look as this community engaged in the practice of modeling with peer review. It would be interesting to take a similarly close look at the Wayfinding Unit as it is enacted in other contexts.

In addition, my own presence in the classroom may have influenced both Ms. Davis and the students. Ms. Davis was often honest with me about the various stresses she was under from both the school-level and district-level administration. She was also often forthright with me in her desire to teach the unit to the best of her ability. Like me, Ms. Davis was often too hard on herself. Although I often praised her for her abilities as a teacher, she worried that she was not doing a good job. Similarly, the students clearly reacted to my presence in the classroom. Other than the occasional clowning for the cameras, students would often address me directly or make references to me in classroom conversations. As a former classroom teacher myself, and as someone who has worked in numerous co-teaching situations, I did my best to be a productive and helpful member of the classroom community without being overly obtrusive.

Findings and Discussion

My analyses for this study explored a pair of research questions: (1) What do fifth-grade students communicate through models within a project-based integrated literacy and science unit? and (2) What are ways in which peer feedback influences fifth graders to revise models? First and most importantly, students created meaningful models. Some of these models communicated sophisticated thinking on their own, but most painted a full picture when combined with the writing beneath. While developing their models, both initially and after receiving peer feedback, students addressed three features of the solar still phenomenon. As I present and discuss the findings, I have organized them by these three features. To conclude this section, I offer observations on the project-based context and its importance to the solar still modeling experience.

RQ1: What do fifth-grade students communicate through models within a project-based integrated literacy and science unit?

Fifth graders in this class addressed three features when developing their models: (1) spatial, (2) temporal, and (3) conceptual.

Representing Spatial Features

As a concrete first step in developing their models, students wanted to represent the solar still apparatus. This immediately raised questions of how to represent multiple three-dimensional forms on the two-dimensional surface of a piece of paper. Students recognized that important actions were happening on two planes. As a result, 12 of the 30 students "bent" perspective, so that the top and side of the solar still were in the same picture. This bending led to a blending of perspectives that I call “Dalí-style” for its resemblance to the malleable perspective exhibited by the clocks in the famous Spanish surrealist’s painting *The Persistence of Memory* (1931). For six of the students, the Dalí-style was pronounced, with six more exhibiting a slight bending of planes (Figure 2.7).

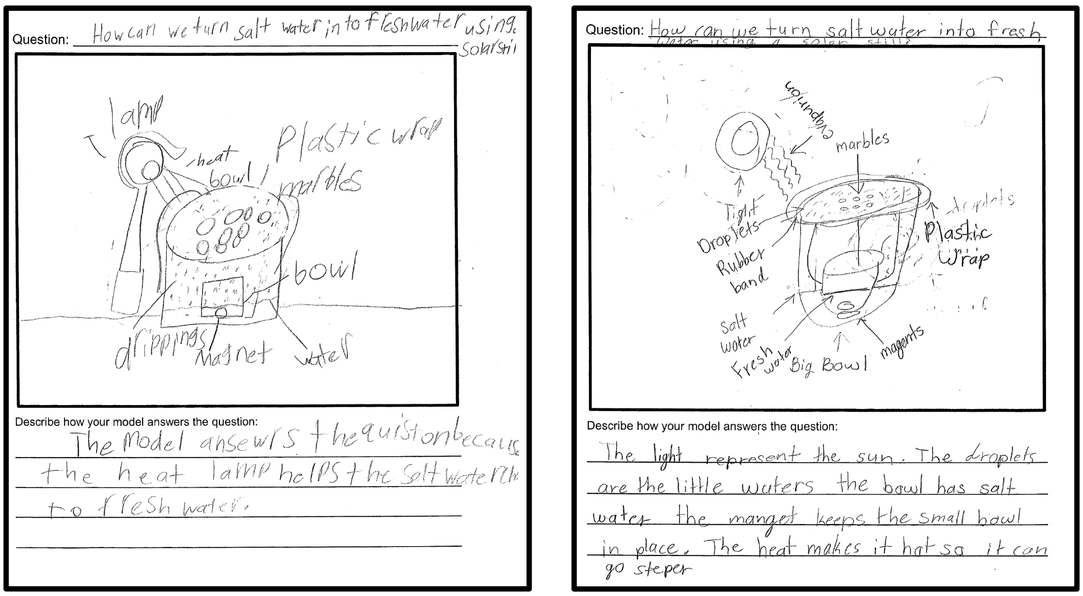

Figure 2.7: Trudi’s model (left) has a pronounced “Dalí-style” perspective, blending the top and side views into a single plane; Florencia’s model (right) has a slight bending of planes.

Even with the physical object in front of them, students created drawings that were not “true to life” (i.e., what you would see if you took a snapshot with a camera). As Manz (2012) argued, no models are actually true to life, as the writer-designer actively makes decisions about what to include and exclude, and how to represent the included components. From the drawings alone, it is difficult to conclude if students used Dalí-style perspective because of their unfamiliarity with techniques for representing 3-D perspective using paper and pencil, or because they were intentionally creating abstracted representations. The former conclusion is consistent with work by Anning (1994, 1997, 1999), who emphasized that specific skills can be taught for representing perspective and occlusion in a two-dimensional drawing. If it was the latter, the top and side of the apparatus appearing in the same plane may have been because students were cued into the important aspects of the solar still. Recognizing that essential activity was happening in multiple locations within the apparatus, they chose to include them all in the same representation. As such, these drawings may represent a first step in abstracting the representation of essential processes, leaving behind a literal depiction in favor of one that focuses on relating components in space based on their functional connections and relationships rather than on their arrangement and appearance in the "real world."

It is important to note that not all students used Dalí-style in their models (Figure 2.8). Eleven students employed a side view. This allowed for representation of nearly all the components, as well as including the key processes occurring within the still. Conversely, three students only used a top view. For an apparatus that included a small bowl nested within a large bowl, with water in each, the top view made it exceedingly difficult to represent what was happening within the still. Four students, either in their initial model or after incorporating suggestions from their peer, included both a top view and a side view. I will discuss more about the use of insets and split-pane perspective in the implications.

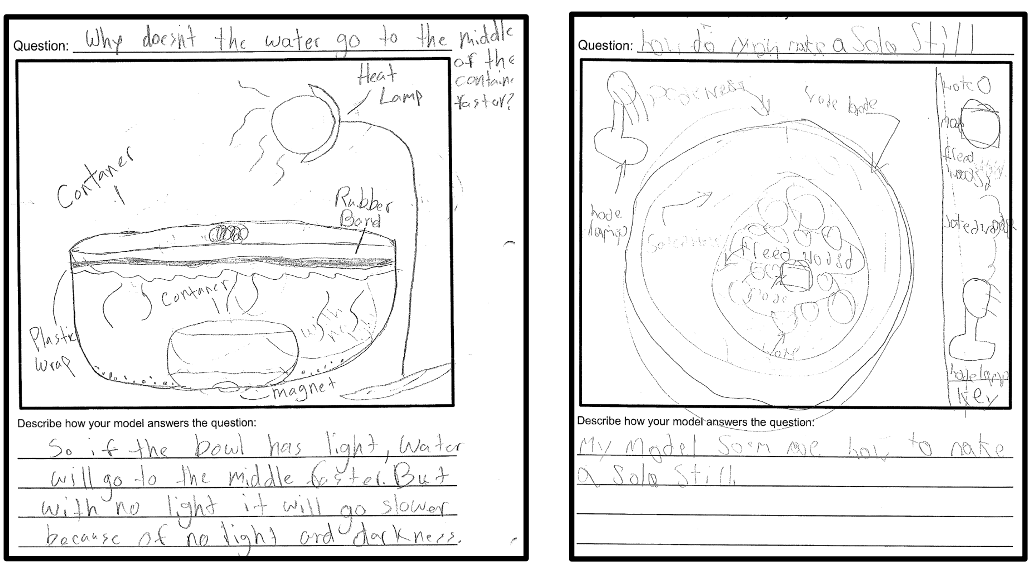

Figure 2.8: Hannah's model (left) utilizes a strict side view; Sam's model (right) uses a top view.

After recording the solar still with a drawing, students clarified the components with written labels. This was the first step in blending drawing and text to create a multimodal representation. Interestingly, only five students included a key, even though a key was specified on the modeling sheet as a requirement. The Wayfinding Unit started one month into the school year. The students had completed a roller coaster project, but that activity had not included the use of key. So, students who decided to include a key were leaning on their prior knowledge of pictorial representation in science.

For the students who included a key, it was clear that the use of this feature was emergent. Four of the five students included labels along with the key, making the key redundant. Only one student, Patrick, relied solely on a key (Figure 2.9). In his model, he attempted to represent a number of round, clear items: water droplets, two bowls, glass beads, and plastic wrap. His example illustrates that, although a key may be helpful in an image with numerous repeating forms (e.g., viral transmission, a food web), a key does not provide clarity when the intended representations are too similar. Lack of clarity is compounded in Patrick's model by his choice to employ a top view. In the case of the solar still, individual labels are more effective than a key. After learning about labels and keys as potential features of a model, students need experience to be able to decide which would be a more valuable addition to assist a viewer in making sense of the model.

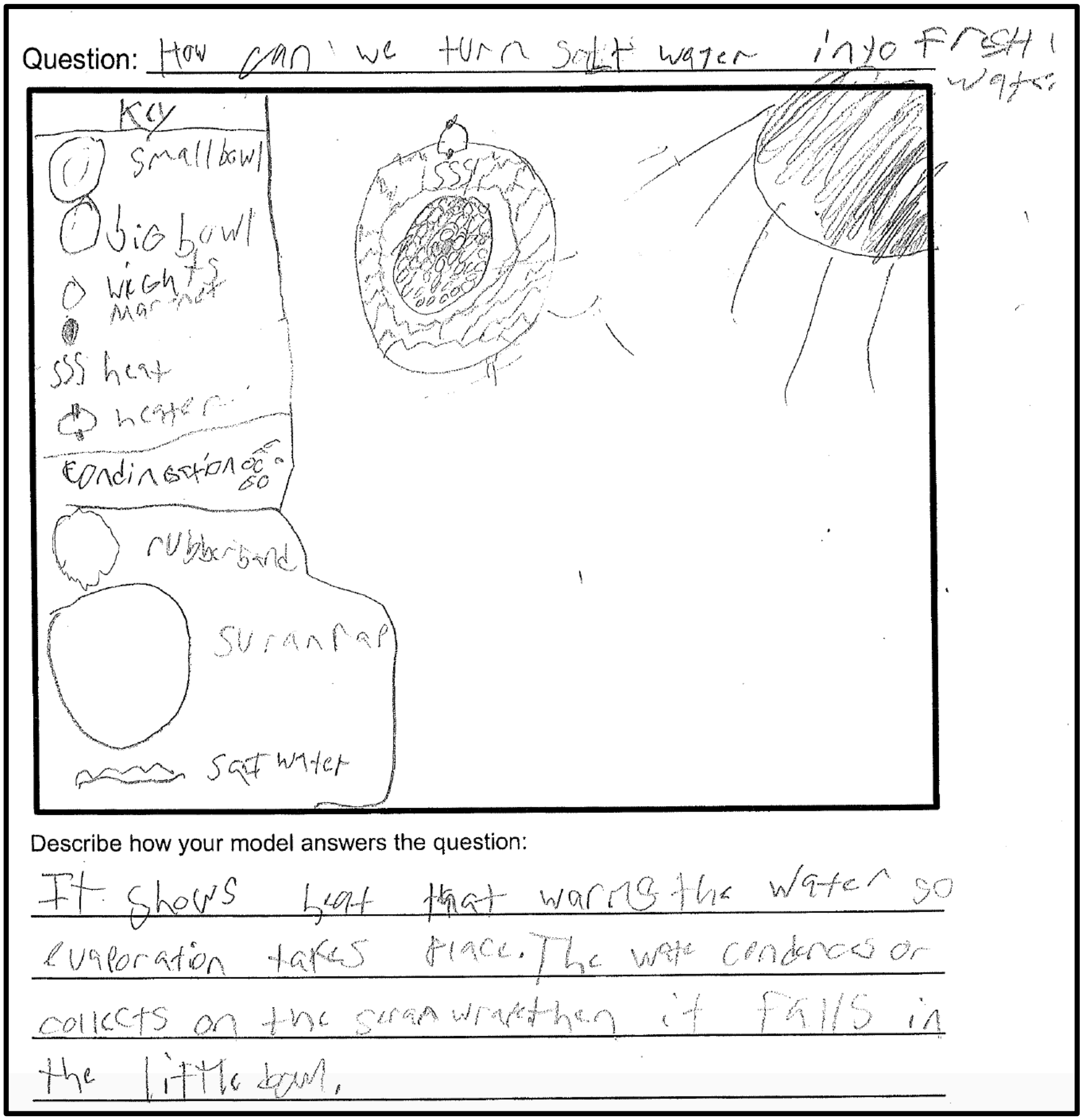

Figure 2.9: Patrick's model includes a key, but no individually labeled components.

I shared how students often employed Dalí-style to bend the notable aspects of the solar still apparatus into a single image. I also shared how the majority of the students in this class used labels to identify the components of their models. Related to a focus on important parts, and also related to labels, students often skipped labeling all of the items in their drawing. This happened rather frequently: 13 students omitted a label for one or more of the components that they had taken the time to draw. Often, the skipped label was for a major component (e.g., the large bowl). In this case, the item may have been so obvious that it was overlooked. Nine of the 13 students omitted at least one label pertaining to the water in the system: the pooled saltwater, the condensed water droplets that collected under the plastic cover, or the freshwater dripping into the center cup. Again, by drawing the water, each of these nine students indicated that they understood it was an essential component of the phenomenon under investigation, but their lack of labels reduced the clarity of their model.

For the initial modeling activity, Ms. Davis left the options open-ended, without providing a teacher example or any suggestions as to how students should approach their representations. Five students deployed both a top view and a side view, either intuitively or at the suggestion of a partner during the peer review process (Figure 2.10). Using multiple viewpoints is a simple technique that, while not immediately apparent to young children, they can take up after they have seen it in use. We will revisit this topic when we discuss peer feedback.

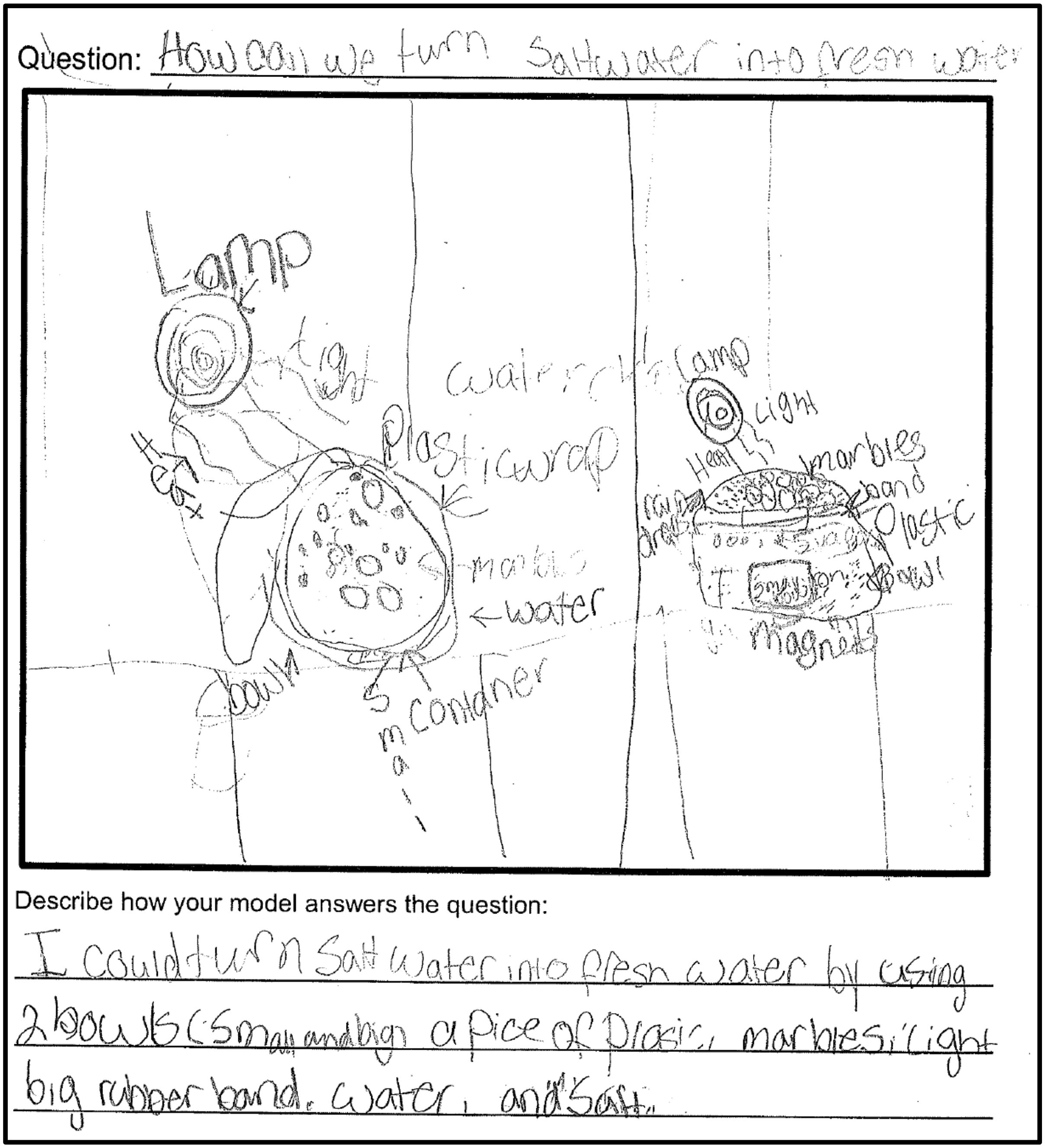

Figure 2.10: Brianna's model incorporates both a top view and side view.

I offer one final observation about how the students addressed spatial features. Each student was presented with the same "canvas," a blank square within which to develop their initial model, and they had to make decisions about the use of space. By the time young people reach fifth grade, they begin to learn about the five-paragraph format when writing essays. During writing instruction, students learn that a well-balanced essay typically allocates an equal amount of space to each paragraph. Allocation in two-dimensional space is equally important to the overall composition of a model. Roughly half of the students made use of the entire space, allowing for visual details and easy-to-read captions, while the other half of the students used one third of the available space or less (Figure 2.11). Students who drew well-spaced representations were able to include more vital information, particularly about the processes occurring inside the solar stills.

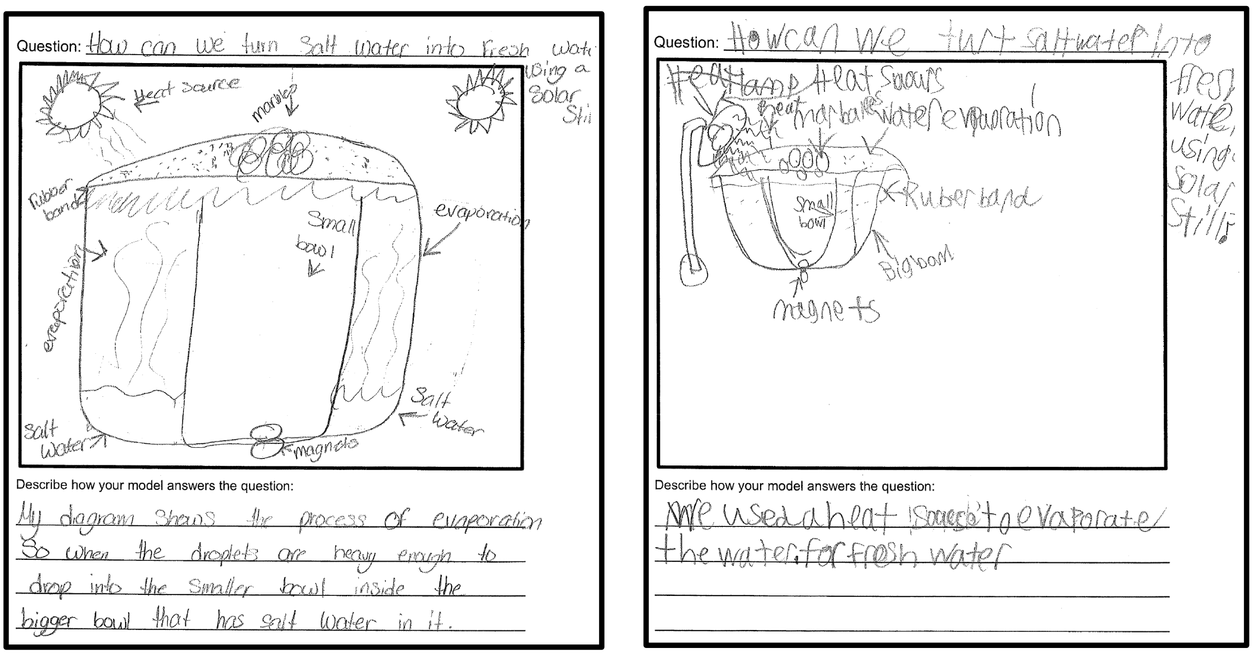

Figure 2.11: Tameika's model (left) is spacious, allowing for visual details and captions that are easy to read; Damon's model (right) is compressed.

Representing Temporal Features

In addition to representing concrete physical forms, students also addressed temporal features of the solar still. Fifth graders are old enough to be aware of time, but the passage of time is still fairly abstract. In this particular investigation, time had a close relationship to the

NGSS cross-cutting concept of *cause and effect*, as the phenomenon under investigation relied on the application of heat over elapsed time. Cause and effect is also a key concept in literacy instruction, and plays a central role in the CCSS.

Time was a critical fourth dimension for understanding the phenomenon. Just as they had tackled representing three-dimensional forms in two-dimensional space, students also had to capture a dynamic and ongoing process with a static drawing. After setting up their solar stills, students made informal observations for an entire week while the stills were exposed to daylight. Then, heat lamps were added to the experimental set-up and they observed for an additional 3 days before developing their initial model. Therefore, students had to make decisions about which time point(s) to represent in their model

Twenty-four students captured the phenomenon as if taking a snapshot, reflecting only a single moment in time. Among these 24 "snapshots," 13 students did not reflect any water movement, while 11 students included dripping and/or evaporating water. Notably, even in the models where water was not changing state, heat energy was depicted as being transferred and was often the only active aspect of the tableau. In a similar way that students addressed spatial features by using split perspective, six students depicted two or more time points in their models (Figure 2.12).

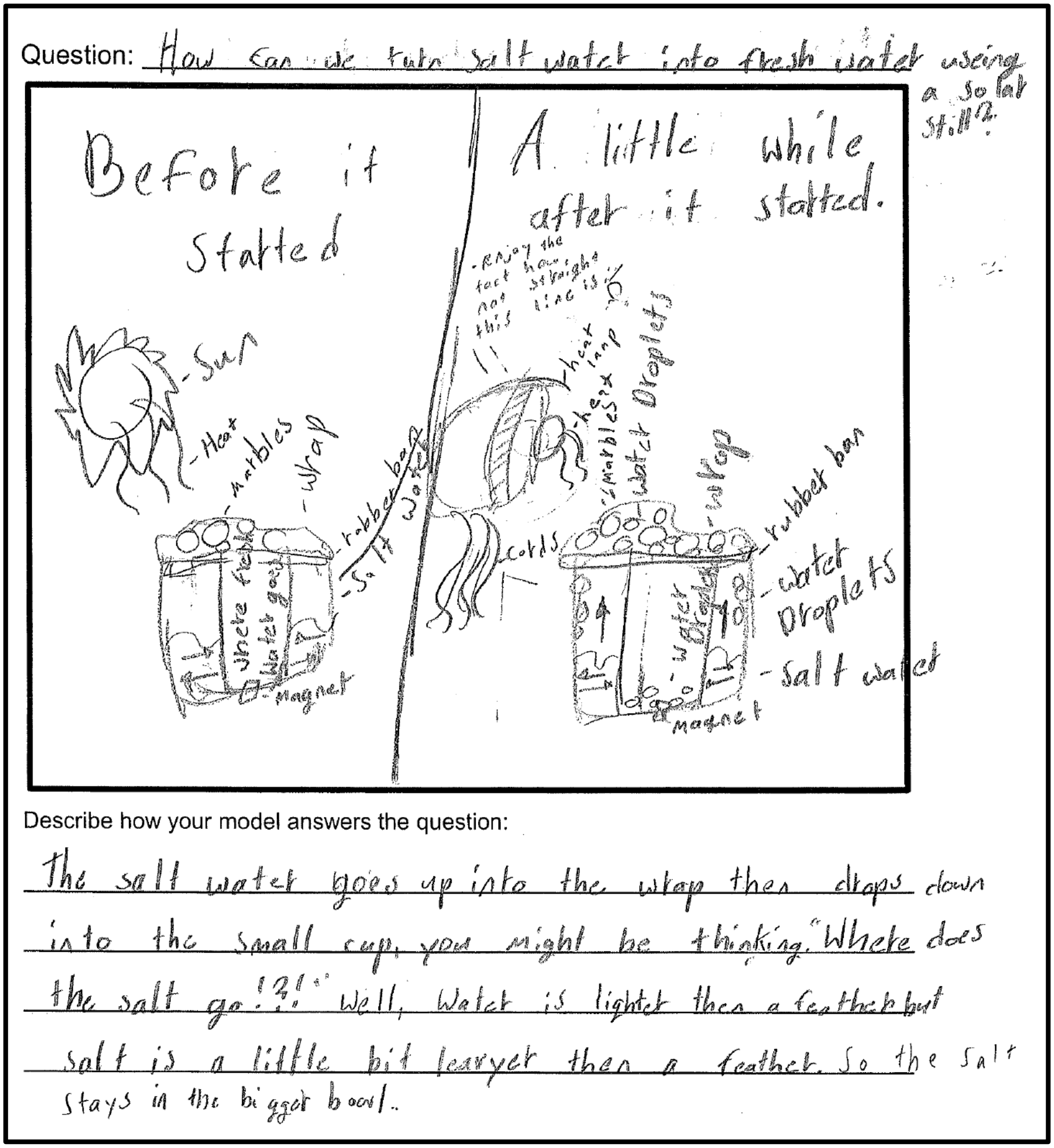

Figure 2.12: Rosie's model reflects the initial set-up and a separate moment after elapsed time.

Of special note, three students (Sawyer initially, as well as Wendy and Sarafina after revisions) used split panels for both spatial and temporal representations. Sawyer included both a top and a side view when representing both the initial set-up and after elapsed time. Wendy, whose initial model included only a single perspective and a single time point, revised her model extensively after being paired with Sawyer for feedback. We will explore their revision process later in this paper (in response to research question 2). Sarafina's model was similar to Sawyer's, incorporating top and side views at each of two time points, but she was reminded by a peer during the feedback process that the initial set-up only included the sun (Figure 2.13). Forced to work within the confines of the static nature of paper, her model uses a series of stills to accurately represent the phases of the investigation. In a similar way to the use of split panels to represent different perspectives, the use of repeating images is another technique that young people may leverage if they are introduced to an example.

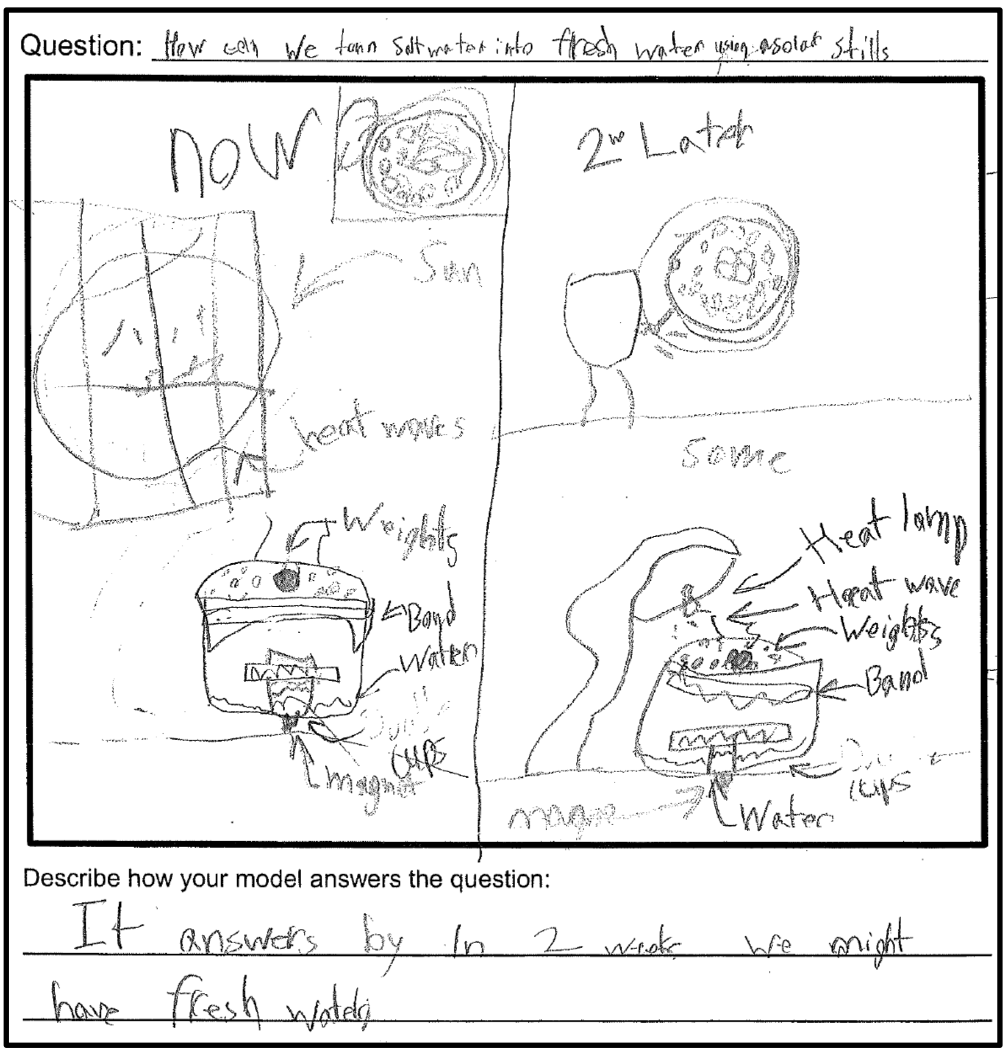

Figure 2.13: Sarafina's model represents spatial and temporal features by utilizing both top and side views at two points in time.

Representing Conceptual Features

Addressing spatial and temporal features set the stage for students to include conceptual aspects. It is here, at the most abstract of the three categories of representational features, where students communicated their understanding of the phenomenon. By successfully representing the invisible processes that underlie why water changes state within the solar still, students transformed a basic labelled illustration of their investigation set-up into a functional model with explanatory and predictive power. Students incorporated steps of the water cycle into their models, but their representations reflected various levels of conceptual understanding. Very few models captured all stages of the phenomenon.

Beginning with the critical component of energy transfer, all but one of the students incorporated heat into their models. Some clearly labeled the transfer of energy as “heat,” although the name for the label, or using a label at all, was not consistent. Especially for students who drew rays emanating from the sun and did not use a label, it was not clear from the drawing alone if they intended to represent heat or light. Not a single student explicitly indicated that heat energy was transferring from a heat source to the solar still, but some students did infer this relationship by drawing heat waves in a directed way (e.g., the models in Figure 2.7).

At this abstract level, it becomes more clear why is it essential to understand the process of modeling as multimodal composing. From their drawings alone, none of the solar still models clearly depicted a relationship between heat and the water within the still. But, when paired with the written description accompanying their labeled drawing, students were able to communicate this connection. Some written explanations established the relationship, like the following description from Trudi (Figure 2.7): "The heat lamp helps the saltwater change to fresh water.[9]" or this blunt statement from Damon: "We used a heat source to evaporate the water for fresh water." Other explanations demonstrated a much more complex understanding, like this description from Patrick (Figure 2.9): "[The model] shows heat that warms the water so evaporation takes place. The water condenses, or collects, on the saran wrap. Then, it falls in the little bowl." In his written description, Shawn indicated why the still works: "The water evaporates, but the salt doesn't. Then, it drips into the smaller bowl. The heat makes the water evaporate." Rosie (Figure 2.12) also focused on the mechanism that allowed for the separation of water and salt: "The salt water goes up into the wrap, then drops down into the small cup. You might be thinking 'Where does the salt go!?!' Well, water is lighter than a feather, but salt is a little bit heavier than a feather, so the salt stays in the bigger bowl."

In some cases, the written descriptions helped to reveal alternate conceptions. Howie was not quite sure what substance was evaporating and what was causing the change: "The light is hitting the wrap, then making the salt evaporate and drop into the cup." Hannah also revealed that she believed it was light, and not heat, that was causing the water to change states: "So, if the bowl has light, water will go to the middle faster. But with no light, it will go slower because of no light and darkness." In most of the other cases, the written description did not add to the conceptual whole, typically listing the components of the solar still without explaining their function or relationship.

One feature that was absent from every drawing was a visual representation relating the amount of heat and the amount of freshwater collected by the solar still. Although some students

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[9] Throughout the document, students' spelling and punctuation have been corrected for readability.

included the switch from the sun to the heat lamp in the experimental set-up, no symbols or labels were included to emphasize the corresponding increase in heat transfer. The only exception was a written description added by Harmony after we had a one-on-one consultation. While walking me through her initial model, it was clear that she thought the process of distillation had to do with light. After having a conversation that helped her recognize that the heat lamp was transferring both light and heat to the solar still, she wrote the following description: “The light brings heat and, like a pot, it will boil and be like way quicker. But, we have a light, so it’s gonna be slow.” In her written description, composed after our consultation, she demonstrates an emerging understanding of the connection between the amount of heat energy transferred and the rate at which freshwater was collected.

Students may have struggled with representing the connection between heat and what was happening to the water in the solar still, but a number of students recognized that some form of invisible process was occurring for the saltwater to get from the bottom of the bowl to the droplets they observed collecting on the plastic wrap. Nine students included the scientific term “evaporation,” with another four students including evaporation in their drawing without a label. Unlike the representation of heat, seven of the students who included evaporation clearly indicated directionality by using upward arrows (e.g., Rosie’s model in Figure 2.12).

The concept of “condensation” was easier to represent, as the students were able to observe water droplets collecting on the underside of the plastic wrap cover over time. All but three students included droplets in their models, labeled or unlabeled. Five students used the label *condensation*, with other students using terms like *droplets*, *drippings*, *raindrops*, or *steam*. As for the third and final step in the water cycle, students never observed the water actually dripping from the plastic cover into the central cup. The only evidence that something had happened were scattered droplets. The word “precipitation” did not appear at all; although, remembering a scientific term from his participation in Science Olympiad, William had a conversation with me and included the label “distillation” in his model. Although it was not labeled, 10 students included a depiction of dripping water, with four of them including downward arrows. Just as with the transfer of heat, some students described the dripping of freshwater into the small cup in their written description.

These examples of students incorporating scientific labels in their models highlight how modeling provides an opportunity for developing technical vocabulary. For their initial models, as the students tried to make sense of the phenomenon, the label used for any given component was less important than communicating an understanding of the role of that particular component. They captured their understanding of the phenomenon through a combination of their drawings, labels that made sense to the writer-designer of that particular model (e.g., students referring to the condensed water variously as *droplets*, *drippings*, *raindrops*, or *steam*), and their written descriptions. But, as students provided feedback to one another, made revisions, and shared their revised models with the class, the teachers and students had opportunities to introduce and use technical terms for the various components, including processes like “evaporation” and “condensation.”

Considering the opportunities provided when comparing and sharing ideas with peers provides a useful segue to findings about the second research question:

RQ2: What are ways in which peer feedback influences fifth graders to revise models?

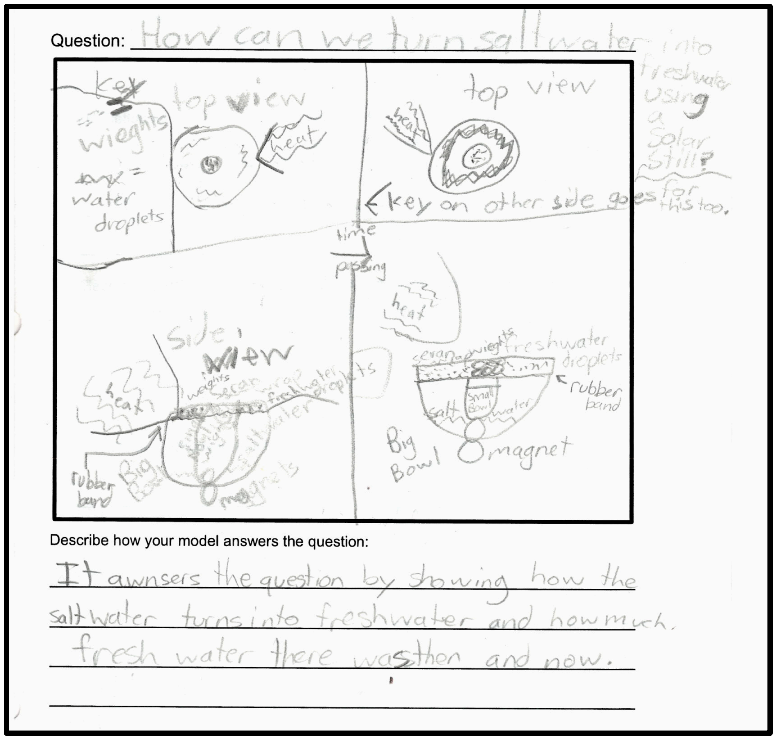
The peer feedback stage brought the social constructivist nature of the solar still modeling activity to the fore. As a recap, the students developed their models individually. As they finished, Ms. Davis matched them with a partner to trade initial models and provide feedback. Responding to an issue raised by the researchers in the MoDeLS project (Schwarz et al., 2009), working one-on-one was intended to provide each student with a guaranteed audience, while also lessening the peer pressure students feel when asked to share with a small group or the whole class. Their peer responded to the 3C prompts (Figure 2.6) that were intended to be part of a recurring protocol for providing feedback throughout the unit. After returning the completed feedback form, the writer-designer of the model was prompted to reflect on the feedback and to make decisions about which suggestions to incorporate through revisions.

In a Vygotskian sense, students leveraged tools, principally written language and drawings, in the creation of their initial models. By inviting students into interaction with one another, the more complex tool that they had developed, namely their multimodal models, were put to the test: did they communicate what the writer-designer intended? Like all written artifacts, the models were something of a time-shifted conversation, with their peers as the first audience. Later on, I served as the second audience, and my review of the feedback sheets became something like eavesdropping on the conversation between each model's writer-designer and their reviewer.

As I mentioned in the methodology section, I recorded my own notes about each model before looking at the peer feedback. What was immediately apparent upon comparing comments from peers to my own notes was the perceptiveness of the student reviewers. Overall, 24 students received a completed feedback form from a classmate. In seven of those cases, the student reviewer noted the same issues that I recorded in my own comments. These ranged from practical composition choices, with a number of students suggesting that the existing drawing was too cramped for details and needed to be expanded, to reminders about missing components, like Savannah reminding Trudi that she had neglected to draw "evaporation on the plastic wrap."

Overall, the one-on-one nature of the feedback session guaranteed each writer-designer an audience, relieving a concern identified by the MoDeLS team about providing a genuine audience for student work (Schwarz et al., 2009). By prompting a manageable number of clear categories for feedback, the 3C sheet seemed to provide enough structure that nearly all students received actionable suggestions. Moreover, the reflection section of the feedback sheet seemed to alleviate the issue raised by the MoDeLS team about ways to motivate students to make revisions (Schwarz et al., 2009). Prompting students to choose only two comments to evaluate seemed to be a manageable number of items for students to consider, especially since the top suggestion provided by each reviewer was usually constructive. Also, students had agency in accepting or rejecting each of the two items, sending the important message that not all proffered advice needs to be followed.

A particularly powerful illustration was provided by the partnership of Sawyer and Wendy. Sawyer, a self-professed science enthusiast and aspiring engineer, already started with the most developed model in the class (Figure 2.14, top). Dividing the canvas into four quadrants, he included top and side views at two time points. Rather than labeling those two moments as “before” and “after,” he acknowledged the ongoing process of change by including an arrow and the phrase “time passing.” Despite the baseline complexity of his model, his partner, Wendy, noticed that he had included heat, but no heat source. Rather than modify his original model, he started from scratch to develop his revised model (Figure 2.14, bottom).



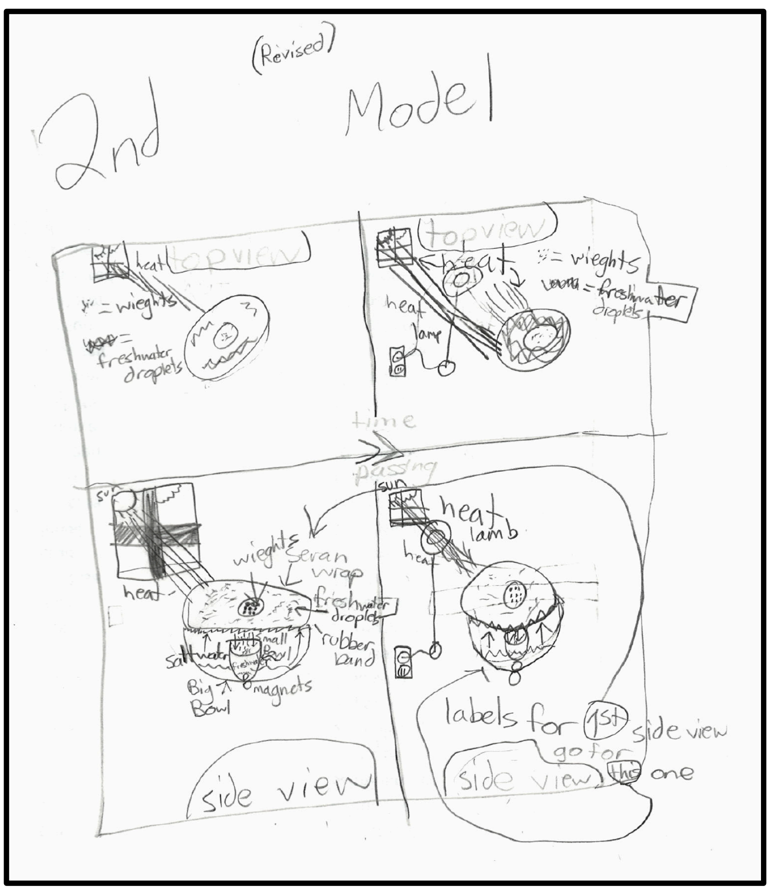
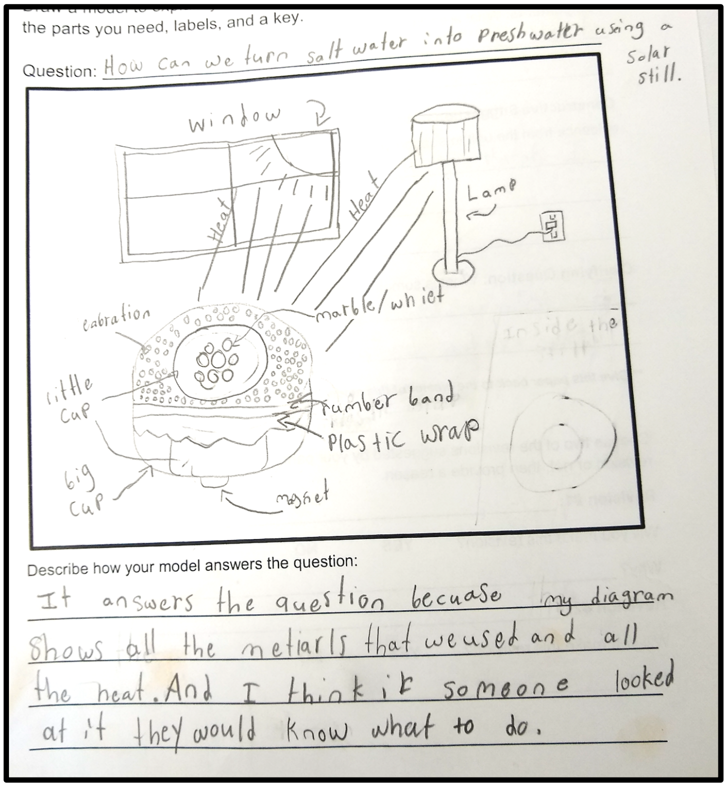


Figure 2.14: Sawyer's initial (top) and revised (bottom) models.

Sawyer’s partner, Wendy, was one of the more gifted artists in the class, but was not as enthusiastic about science. She was exceedingly quiet during both whole-class and small group discussions. I never observed her raising her hand. Wendy’s initial model was similar to her peers’: she chose a single time point, which included both the sun and a lamp as heat sources, and a single perspective (Figure 2.15, top). However, she recognized that both the top and the side of the solar still were important, so she utilized pronounced Dalí-style perspective. Sawyer provided conceptual feedback: that Wendy had not included evaporation or condensation, so he was unable to understand what was making the water droplets. I also served as a peer reviewer for Wendy, as she and I had a one-on-one interview after she received her feedback from Sawyer. We discussed challenges with spatial representation and with including invisible elements. After I asked her about an erased spot on her model, she explained to me that she had tried to draw the inside of the solar still “because you can’t really see it.” She recognized that something important was happening within the device, and had made an attempt at including a second perspective, but she was stymied by how to represent it. I suggested that she use a blank piece of paper to provide the room to show both.

Upon returning to the classroom, Wendy made a first pass at revisions by changing and adding labels (Figure 2.15, bottom). Because they finished their initial models and had their feedback session before their classmates, Sawyer and Wendy had additional time to work on revisions. Wendy used a clean sheet of paper to draw a fully revised model from scratch. Although she did not have quite enough time to complete this version, her elaborate final product looked very similar to her partner’s (Figure 2.16). Through written suggestions and conversation with a peer, as well as a few minutes of guidance from me, Wendy was supported to solve challenges with representing spatial, temporal, and conceptual features.



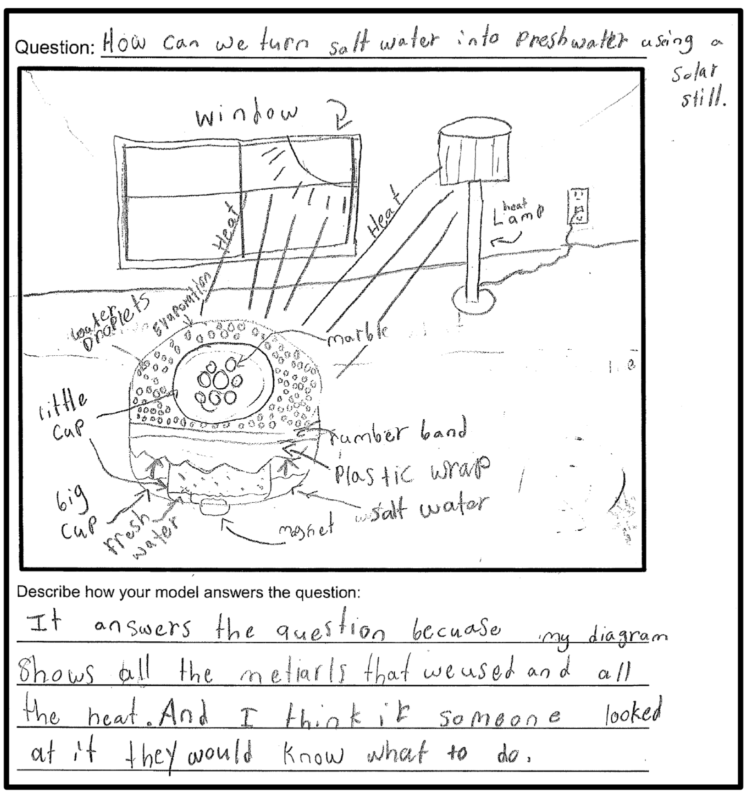


Figure 2.15: Wendy's initial model (top) and first round of revisions that only included additions and changes to labels (bottom).

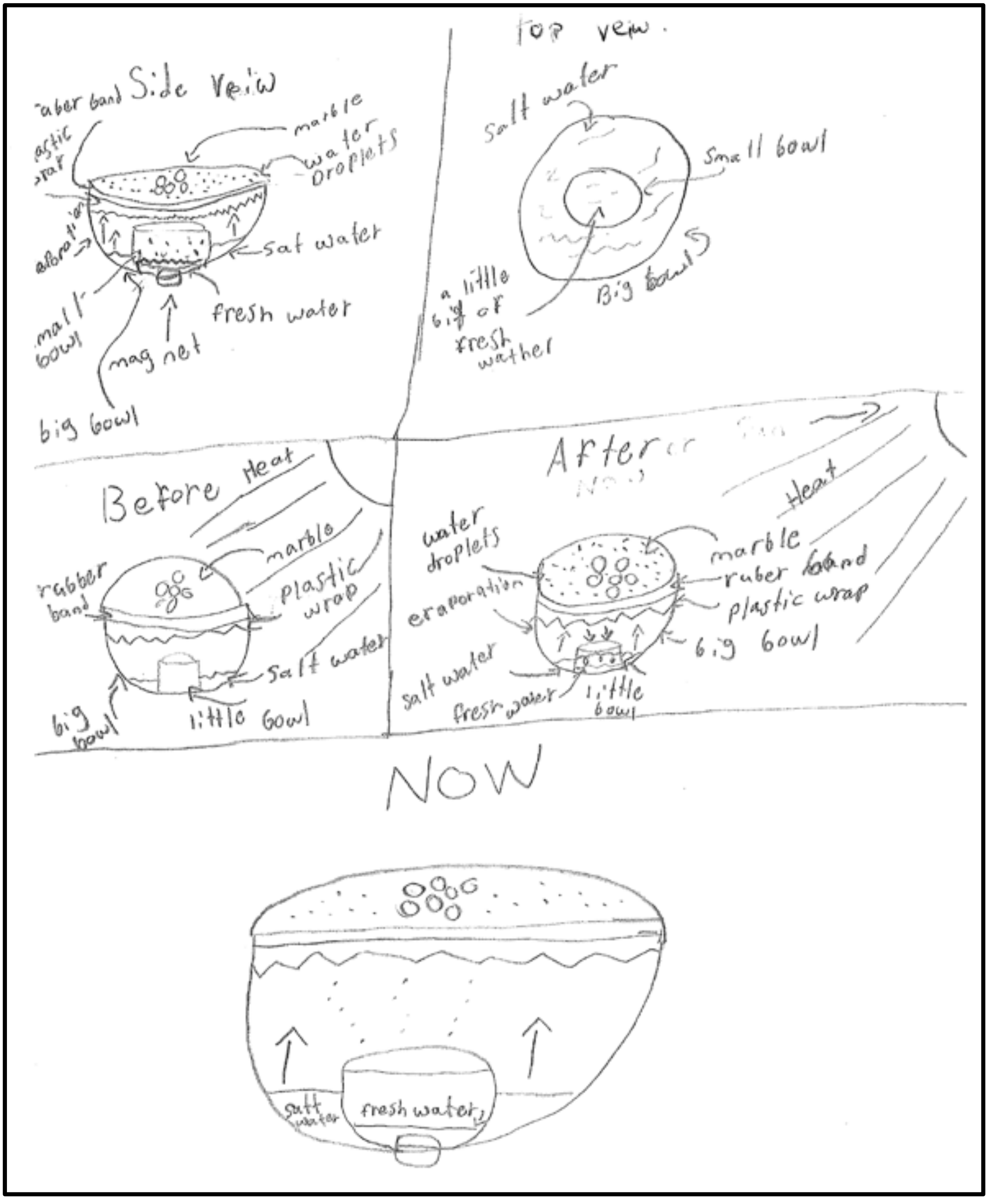


Figure 2.16: Wendy's fully revised model reflecting completely different approaches to representing spatial, temporal, and conceptual features.

Looking across feedback that the students provided to their peers, the overlap between my observations and the suggestions provided by the students to one another highlights that feedback does not always have to come from the teacher. Especially for receiving feedback on an initial draft, simply having a second set of eyes supported many students to notice components of their models that they skipped. This unintentional omission was obvious in the section of the feedback form where students reflected on the suggestions they received. In many cases, the writer-designer of the model immediately recognized that a label was left off or a component was missed. Looking at this process through the lens of Vygotsky's zone of proximal development (1978), the space opened up between two individuals and the task at hand, it was fascinating to see that the suggestions provided for any given student were so often similar whether it was me or a peer as the vertex in the ZPD triangle. In these productive cases, the space between the three vertices (reviewer, reviewee, and the modeling task) were equal. In these cases, the students were well-paired and each member of the dyad received constructive suggestions.

However, in a few cases, the gap in conceptual understanding or facility with the practice of modeling between the reviewer and reviewee was too close together or too far apart. As an example of the former, refer back to Figure 2.8 and the models created by Sam and Hannah. Sam, a good-natured boy who was well-liked by his classmates and seemed to enjoy school, had an IEP for both reading and spelling. His difficulty with spelling made it hard to read his labels. His partner, Hannah, was also popular with her peers, but for very different reasons. The youngest in a family with all boys, Hannah was quick with sarcastic quips and seemed much older than her classmates. She told me in our first conversation that she didn't like anything about school, especially science. In her feedback to Sam, it would have been very easy for

Hannah to have made a cutting comment about Sam's spelling, hurting his feelings. Instead, she focused on the overall model, complimenting Sam's model as being "very detailed" and then suggesting that he could have shown people "how to do it." She declared that she "understand[s] everything. It is done well."

On one hand, Hannah's comments should reassure educators hesitant to pair students for feedback for fear of bullying. Of the 13 pairs who shared models for this activity, only one pair of close buddies made some goofy comments to one another along with their productive notes. So, although Hannah demonstrated considerate disregard for Sam's spelling issues, she also did not provide him with actionable suggestions to improve his model. In his reflection on the feedback, Sam wrote "nothing" in reference to the revisions he would make.

As far as Sam's comments to Hannah, he told her that he liked that she had included the solar still "with light" and "not with light." His other comments mentioned adding labels for the rubber band and plastic wrap. By pointing out her inclusion of light, Sam made no mention or suggestion of the connection of light to heat. He also pointed out components of the solar still that were important for this particular set-up, but not critical for the underlying phenomenon (e.g., the specific use of a rubber band to secure the plastic wrap to the top of the container). Neither student included essential labels about water, including any discussion about evaporation or condensation. Sam's written description "My model shows me how to make a solar still" indicated that he, and perhaps Hannah as well, had difficulty discriminating between a picture to illustrate the parts of an experimental set-up, and a model that explains how those components work together. Sam and Hannah were one of three pairs where both partners seemed to be at the same level of conceptual understanding and, therefore, one or both members struggled to provide constructive feedback.

At the other end of the spectrum, only one pair, Lexi and Molly, were too far apart, both in their sense-making about the phenomenon and their proficiency with the skills involved in drawing representations, to provide each other with effective feedback. Lexi was very engaged throughout the unit. In our end-of-unit interview, Lexi informed me that she didn't have a favorite subject because she liked them all equally. Her hand was constantly raised during whole-class discussions and she consistently focused on conducting investigations even when her group members were not. Molly was not as engaged. She had an IEP that included interventions for reading, writing, and math. As a result, she was often pulled from class to work with specialists, causing her to consistently miss portions of lessons. The two girls developed initial models that looked very different Figure 2.17).

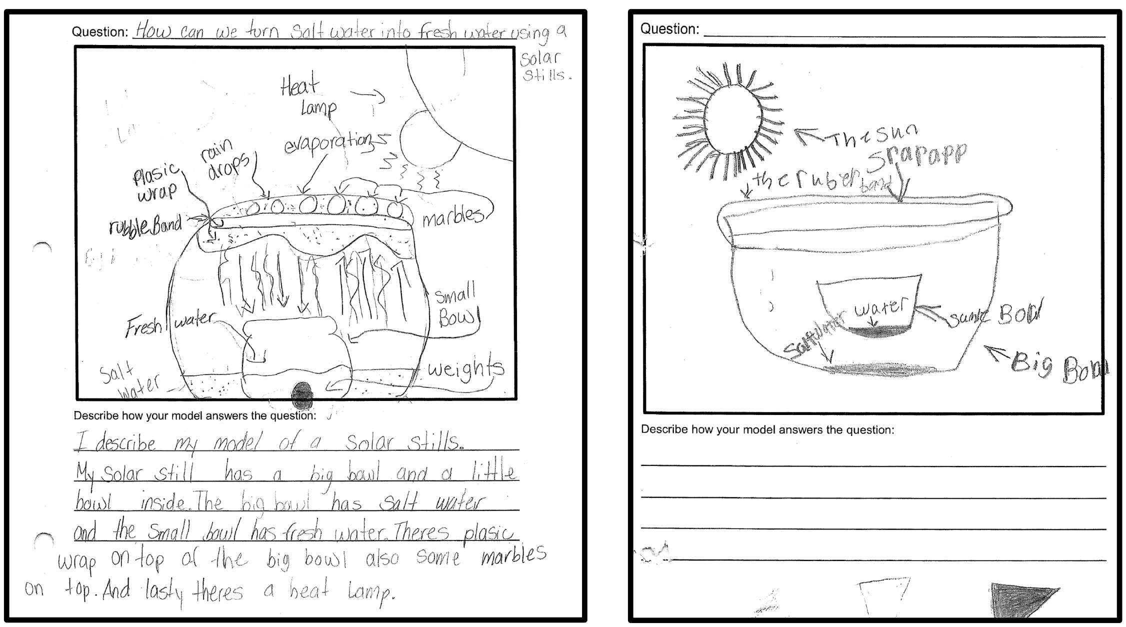


Figure 2.17: Lexi's representation (left) demonstrates conceptual understanding and functions as a model; Molly's representation (right) functions more as an illustration of the apparatus.

Lexi complimented Molly for drawing the sun as the heat source, since her own model only included the heat lamp. She also suggested that Molly could add the marbles as weights "so we can see how the plastic wrap can dip in." Not only did Lexi point out a missing component, but she included the role that it plays in allowing the droplets to roll down and drip into the central cup. Unfortunately, Lexi replied "nothing" as her clarifying question. It is clear from Lexi's model, which included the term *evaporation* as well as arrows indicating the movement of water within the still, that she had a fairly well developed conceptual understanding. Her lack of a clarifying question for Molly was a missed opportunity for the more knowledgeable student to assist her peer. Reflecting on Lexi's feedback, Molly did not even take up Lexi's mild suggestions. She claimed that she "didn't know why" Lexi picked those revisions and decided not to make any changes to her model.

Molly not revising her model after working with Lexi was a missed opportunity. In her own feedback, Molly complimented Lexi for taking her time. She declared that she did not have any constructive suggestions or clarifying questions, but she did state that Lexi "can be good at feedback." As a result, Lexi had nothing to reflect on and made no revisions. From Molly's comment, it sounds as if she recognized that Lexi's model was more developed than her own. Unfortunately, her own conceptual understanding was not developed enough to ask Lexi questions about the functioning of the still (e.g., Was the freshwater already in the small bowl? How did it get there? What is the relationship between the heat lamp and the solar still?). One might wonder if Molly benefited from reviewing Lexi's model, by being presented with an exemplar that might have helped her to recognize components missing from her own work.

Overall, the students provided high-quality feedback to one another. At least half of the students received astute, actionable suggestions that resulted in improvements to their model. Other than one pair of boys including some jokes with their feedback, not a single student included cruel or unnecessarily negative comments. Only three students provided the equivalent of “no comment,” providing no input for their partner. My concern prior to the activity was that “no comment” would be common, and the peer feedback process would not be time well spent. One of these instances was Molly’s lack of comments for Lexi, described above, wherein the model was already well-developed. That being said, even for a student who did not receive actionable feedback, Lexi still liked the peer feedback process and recognized the value in it. When I asked her during our end-of-unit interview if the process was helpful, she replied that it was because “she can tell me what I can change and improve it.” Looking across all of the student interactions, the presence of the features elicited by the 3C scaffold suggests that it supported the students in generating and revising more accurate and complete models.

These encouraging results were the product of practical pairings without Ms. Davis creating a list of partners ahead of time. Instead, students were matched in the order in which they completed their initial models. Ms. Davis recognized that students were finishing their work at different rates, and the practical pairings were to make sure that students weren’t waiting for all of their classmates to finish. Looking at the useful feedback that students received, this solution worked fine. However, it would have been interesting if Ms. Davis had directed students who finished early to work on some other task, and waited until every student had a completed initial model. Then, knowing that all members of the class were ready for feedback, she could have created intentional pairs based on specific observations about her students. This was not necessary for this initial modeling experience, with all students still novice writer-designers, but it would certainly be a strategy to consider to support students in developing various aspects of the practice during future modeling opportunities.

As a final note, I uncovered small hints of the social-emotional challenges of providing peer feedback. One challenge was the vulnerability involved in exposing work to feedback from a peer. Ms. Davis enacted the pilot version of the Wayfinding Unit in the second half of the year, when the students had gotten to know one another. Because of scheduling constraints, the revised version of the Wayfinding Unit described in this paper was enacted only a month into the school year. Although many students had been classmates at Pine Elementary in prior years, it is unknown how well they all knew each other. This lack of familiarity was exacerbated by students feeling self-conscious about their artistic abilities. Two students, Howie and Rosie, literally apologized for their drawing skills. Howie wrote this plainly in the description of his model: “Sorry, I’m really bad at drawing.” Rosie employed self-deprecating humor (Figure 2.12): “Enjoy the fact how not straight this line is!” Although visual art was a special offered at Pine, the students often missed specials when the teachers were pulled to cover classrooms due to persistent substitute shortages. Combined with the lack of explicit instruction in technical drawing, the students knew this was a skill they had rarely practiced.

The other social-emotional challenge in peer feedback was the inverse. As difficult as it may be to offer work for critique, it can be equally challenging to be the one providing the feedback. This challenge was compounded when the reviewer perceived the work under consideration to be better or worse than their own. Ms. Davis did not provide any formal guidance or instruction in how to provide feedback: she relied on the structure of the 3C feedback sheet. Thinking back to the example of Hannah and Sam, for example, it was an open question how much Hannah was self-monitoring to be polite in her feedback to Sam. Uncertainty regarding how to reply may have been the driving factor in the students who provided “no comment.”

The Project-Based Context

Up until this point, I have not spoken about the importance of the project-based context. The direct influence of the context was not directly addressed in the students' models, nor was it expected to be. This only became apparent during the end-of-unit interviews. But first, a reminder of how the solar still activity was situated within the project-based context and how that context motivated the need to engage with modeling (Schwarz et al., 2009). While planning for the journey, students were tasked with calculating how much gear, food, and water to bring. We established that, at 8 pounds per gallon, freshwater was a heavy item to carry on a canoe. With saltwater all around, students set about putting together simple solar stills, observing them under sunlight and then under heat lamps. At the end of the second week of informal observations, the students engaged in the modeling practice. With students imagining themselves on a long journey in the middle of the ocean and in need of water, the intention was to ensure modeling wasn't simply a task to complete by rote, but a method of gaining insight into a life or death situation.

Historically, elementary science "experiments" have often involved recipe-like tasks where the outcome can be guessed (Smith & Smith, 2016). Because of that built-in expectation, students expected that they would build a solar still and it would collect ample freshwater. When it did not, their expectations were upended. My goal when including this investigation in the unit was *not* demonstrating proof-of-concept: the students knew from the outset that freshwater could be distilled from saltwater using such an apparatus. My goal was to demonstrate that such a system would be wildly inefficient, and that human water needs, at a minimum of 1 gallon per person per day, was a very serious limitation when loading their canoes.

What I did not expect was the frustration that was still simmering about the solar still investigation weeks after it concluded. During the end-of-unit interviews, it was clear that the students disliked the activity, not because it was boring, but because it did not produce the result they anticipated. As Trudi said, she didn't like it because "it was so slow and barely any changes." Shawn was even more vocal: "It doesn't work AT ALL. Well, like, it works, but it's just so slow!" His frustration was echoed by William, who didn't like the investigation because "it did not work" and that "you would have died." Unlike Shawn, who only reluctantly agreed that it was useful to see that the solar still would not be a viable way to produce freshwater, William readily agreed that it was useful to learn that it does not work. Harmony was more philosophical about the unexpected outcome and the resulting value of the investigation: "It would take really long, and you need the water right there and now, so you'd probably look for a different solution to get freshwater."

An old adage says that the opposite of love is not hate, it is apathy. Love and hate are both passionate emotions. During the interviews, it was clear that the solar still experience had left an impression: a frustrated impression, but a lasting memory. Of course, we often seek to provide transcendent experiences for our students, fun projects and impressive experiments that will fill our students with wonder. But, the solar still investigation made me think about the power of tapping into passionate emotions by including experiences that run counter to expectations. Including an experience like the solar still investigation, to prove a point by counter-example, is a potential technique to upend the way that school is typically done. Of course, not every investigation should follow this pattern, but the occasional investigation that runs counter to what students predict with their models may help to keep things fresh and highlight that disproving hypotheses in science is an essential process in the scientific endeavor.

Implications and Future Directions

This study has implications for curriculum design and instruction, pre-service teacher education, and in-service teacher professional development.

Curriculum Design and Instruction

In my discussion about RQ1 and what the students communicated through their models, I shared that the students represented three features of the solar stills: spatial, temporal, and conceptual. For RQ2, I highlighted the affordances of peer feedback while developing models. In the following section, I offer suggestions for curriculum design and instruction that may support students as they engage in the practice of modeling and peer feedback.

Supporting the Representation of Spatial Features

One of the major implications of this study, supporting findings that go back decades (Anning, 1994, 1997, 1999; Van Meter & Garner, 2005), is the necessity of teaching young students genres of drawing. The discomfort voiced by two students with their drawing skills made it clear that genres of drawing, including the techniques used within those different genres, are just as important to learn as the genres students learn about with print-only writing. Students do not automatically know the difference between the decorative illustrations found in picture books and 2-D diagrammatic models. It is likely that they have never seen an exploded-view diagram or had a chance to craft a three-dimensional computer-aided design. That being said, the visual arts teacher should not necessarily be the person, or the only person, to instruct students in the genres of technical drawing. Because this is a disciplinary practice, technical drawing belongs in the science classroom.

As students become familiar with genres and features of technical drawings, it will be critical to establish enough familiarity so that they may think flexibly about what is needed for any given drawing. For example, although a key may be a useful feature for a phenomenon with numerous repeating components, a pronouncement such as “all models have a key” may lead to redundancy or confusion. By ensuring that students are supplied with a wide range of visual tools, they will be better positioned to employ a specific genre, or to include a specific feature, which will assist a reader in making sense of their model. Being knowledgeable about technical drawing will also necessitate students being able to reflect and be metacognitive about their representations (Schwarz et al., 2009), asking questions that would guide the drafting of the initial model, such as: Which perspectives are necessary to show essential information? Would an inset help to clarify what is happening in a small area of the model?

Supporting the Representation of Temporal Features

During the course of pandemic-related remote learning, educators across the country were forced to use technology. The emergency transition too often resulted in digital solutions that were inferior to in-person instruction (Lieberman, 2020). Acknowledging the residual hesitancy that many educators may hold, technology really does have affordances not possible on paper. This is especially true when trying to address the static nature of a pencil-and-paper model compared to the dynamic nature of the solar still.

One platform that found widespread adoption during the pandemic was *Seesaw* (https://web.seesaw.me/). As a multimodal digital portfolio that allows for annotations and narration on video, *Seesaw* would be an effective solution for students working on fast-moving models with observable results (e.g., rolling cars across various surfaces to investigate friction). For an investigation like the solar still, where the phenomenon takes place over a number of weeks and where the processes are invisible, a platform like *Seesaw* is less effective. Better to use a purpose-built platform such an *SimSketch* (Bollen & van Joolingen, 2013; Van Joolingen, et al., 2015) that starts with a user-generated drawing that can then be animated.

Less powerful that *SimSketch*, but more flexible, the ML-PBL team developed *Collabrify Flipbook* (https://www.imlc.io/appInfo?flipbook). Just like the old-fashioned method of drawing images on a series of index cards and flipping through them to "animate" a scene, *Flipbook* recreates that experience digitally. The ML-PBL project piloted *Flipbook* as a modeling platform as part of the Grade 4 curriculum (Marcum, 2018). A small group of students in Ms. Davis' class had the opportunity to use *Flipbook* to make a model of moon phases (Figure 2.18). Because of time constraints and many students out of the room for various interventions, only about half of the students were able to start a moon phase model. However, the portions completed showed promise, both in the ability to capture a conceptually abstract phenomenon like the phases of the moon and also to reflect elapsed time for an event that takes multiple weeks. When considering possible modes, including image, writing, layout, music, speech, and moving images (Kress, 2010), it is clear that digital technology offers access to semiotic resources that were not previously available in a classroom setting. Familiarizing students with computer-assisted forms of representation may include their own challenges (Van Meter & Garner, 2005), but the sooner writer-designers have access to these modes, the wider their palette becomes.

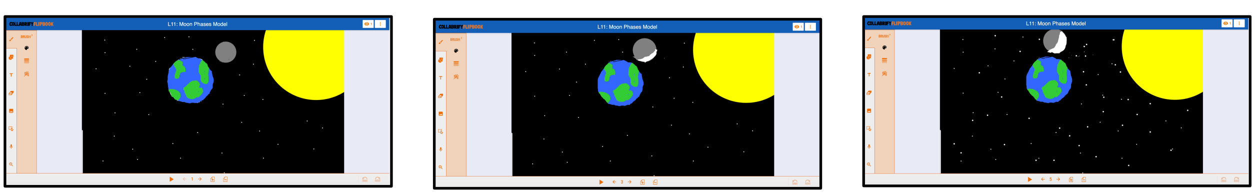


Figure 2.18: Screenshots of slides 1, 3, and 5 from Wendy's moon phases model animated using *Collabrify Flipbook.*

Supporting the Representation of Conceptual Features

Being adequately supplied with the semiotic resources to record a multimodal representation on the page, or screen, is only an initial step. Students still need to do the conceptual work to integrate components into a meaningful whole (Manz, 2012). This work is made more difficult with a model like the solar still, which involves an invisible process (Seah, 2016; Zangori & Forbes, 2014). This added complexity indicates the possibility of a developmental sequence for modeling. Although the MoDeLS project did significant work on learning progressions for modeling intended to gauge levels of progress with metamodeling knowledge and elements of the practice (Schwarz et al., 2009; Schwarz et al., 2012), the findings of this study suggest that the content of the models themselves may offer differing degrees of difficulty. As a result, I suggest a step that would go before assessing levels of progress: creating a more intentional and specific sequencing of modeling opportunities within a curriculum.

In such a hypothetical sequence, students could begin with models based on firsthand investigations. Perhaps students would begin by modeling a phenomenon where both the cause and the effect are visible (e.g., rolling a ball down a ramp of varying slopes to see how far it moves a target object after a collision). Then, they could move on to a modeling experience like the solar still, where some of the steps are invisible. After gaining experience with modeling firsthand investigations, students could try a secondhand model. This was the case in the Wayfinding Unit. During Week 4, the students developed a model about the "lifecycle of plastic" after reading a number of texts and watching a series of videos. For the students who participated in ML-PBL in Grade 3, they created a Food Web model using evidence from texts. Only at this point, after multiple experiences with "realistic" models, could students start to use more abstract symbols, as models that share a resemblance to the target phenomenon are more accessible than models that are more abstract (Lehrer & Schauble, 2012).

Recognizing how difficult it is to transfer the practice of modeling between these levels of difficulty was the mistake we made on the pre- and post-assessment. Near the end of the Wayfinding Unit, students investigate the relationship between the depth of water and the speed of waves. In order to create a physical microcosm of waves reaching the shore, the students use an aluminum pan filled with increasing amounts of water. The assessment question asked the students to develop a model based on that investigation. The students did not know what to do and, as a result, the pre- and post-models looked essentially the same. The mistake was not recognizing that wave investigation itself was already very abstracted from the phenomenon of waves washing on the shore, and involved more complicated invisible processes. As an instructive example, after modeling evaporation and condensation in solar stills, the assessment for the MoDeLS project asked students to explain what would happen to a colored marker with the cap left off, a real-world example that also involves evaporation (Kenyon et al., 2008). A more appropriate near-transfer assessment question for the Wayfinding Unit would have asked the students to develop a model of the solar still to predict the effect on freshwater production if they had switched to stronger heat lamps.

Taking into consideration these levels of complexity may result in an intentional sequencing of modeling activities that takes into account frequency and vertical alignment. When we first started designing the ML-PBL curriculum, one of our aspirations was to include regularly occurring modeling experiences, perhaps one or two per unit. With four units per year, that would provide students with between four and eight modeling opportunities per year. If that plan had come to fruition, and if the students had participated in ML-PBL in both Grade 3 and

Grade 4, the solar still model would have been their ninth, or even their seventeenth, modeling experience rather than their first. With all of that additional practice, it is easy to imagine how different their models would have looked.

That repeated exposure is especially important to allow students to see connections between different modeling experiences (Schwarz et al., 2012) and to develop meta-modeling knowledge (Schwarz & White, 2005). During my end-of-unit interviews, the students I spoke to were initially unable to separate the practice of modeling from the solar still investigation itself. Upon further questioning, they identified models as a way to demonstrate a phenomenon, with comments like Trudi's "so people know what it looks like and how it does its stuff," Shawn's "to show people what happened," and Lexi's "if there's people wondering how it turns into freshwater, they can look at it and they can get an easier idea of it." Without examples for comparison, they could not yet see all of the uses of modeling or modeling as a practice that could be applied in other situations. One unanswered question is how frequently students need to engage in modeling to be able to recognize, identify, and apply the conventions of modeling across contexts.

Sequencing modeling instruction in a systemic and ongoing way also provides an opportunity to link this practice to the development of scientific explanations (Baumfalk et al., 2019; Forbes, Zangori, & Schwarz, 2015; Zangori et al., 2017). As another practice new to elementary instruction, marshalling evidence and reasoning to answer a scientific question is challenging for young students (Zembal-Saul et al., 2013). Because scientific explanations are often written in complete sentences in paragraph form, they can be intimidating for students who struggle with writing. In my end-of-unit interviews, a number of students indicated that they prefer modeling to explanation writing, because drawing pictures allows them to share information more easily than with words. As Brianna said in her quote that began this article, "When I draw I think I can get everything I'm trying to say, but just not in words. In words, sometimes there won't be enough space to do it. Or I try to write something, but it doesn't sound right. So, in pictures, they can understand what I'm trying to say." Rather than teaching them as two separate practices, more work needs to build on the studies of Zangori, Forbes, and colleagues to explore combinations of drawn models and written scientific explanations, with the drawn representation supporting the writing of the explanation and vice versa.

Affordances of Peer Feedback

The peer feedback process supported the majority of students to improve their models. This has a number of implications. First, the students did not receive explicit instruction in providing, and receiving, constructive feedback. Their participation in the feedback process was guided by their instinctive politeness and graciousness (as well as the 3C framework). With more formal guidance from the teacher, and/or listening to the feedback provided by other pairs, students may develop a wider repertoire of constructive comments and suggestions. Second, just as students stand to benefit from repeated and regular modeling experiences, so too should they benefit from recurring use of the 3C peer feedback protocol. During the Wayfinding Unit, the students used the protocol twice, for the solar still model and a later lifecycle of plastic model. With regular use over the course of a year, or ideally, multiple years, students would become increasingly facile in peer review situations.

Most importantly, the general perceptiveness of the students in providing feedback to one another should assuage the concerns of educators who worry about the quality of peer comments. The classroom teacher does not need to feel burdened to provide feedback, at least initially, to all students. Peer feedback provided enough grist for students to make an initial round of revisions.

Although we did not have time, providing time for revisions after whole-group sharing, a different forum for giving and receiving peer feedback, would likely lead to additional improvements.

As a potential caveat, the “no comment” cases raised an important issue. In all three instances where a reviewer failed to provide suggestions, it was a female student not providing revisions to a male student. While this may have been a coincidence, feeling able, or unable, to provide feedback to a peer is a vital reminder about power relations in the classroom. What is said, or not said, depends on power, as much as it does on the linguistic and representational repertoire of the student (Kress, 2010). Supports like the 3C feedback sheet helped guide students to be polite to one another, but such tools do not remove the gender, racial, and other interpersonal dynamics at play when students interact with one another. Social interactions are not neutral: they always involve power. That being said, the positive and constructive comments that the majority of students provided to one another during the modeling process do provide evidence that peer feedback is a worthwhile activity.

Incorporating these implications is perhaps asking too much of individual teachers. In order to facilitate more widespread reforms, this study has implications for teacher learning, both pre-service and in-service.

Pre-Service Teacher Education

Modeling is still a new enough phenomenon that the majority of students in pre-service education programs likely did not encounter modeling in their own K-12 science education (Ke & Schwarz, 2021). As a result, the majority of future educators will experience modeling for the first time in their university coursework (Hug et al., 2008; Windschitl & Thompson, 2006). As their science preparation may include only a single methods course, that does not provide much opportunity for undergraduates to get a firm understanding of modeling before they are expected to teach it (Schwarz & Gwekwerere, 2006). Similarly to how subjects are often siloed in elementary instruction, too often these silos are mirrored in preservice methods classes. Just as science methods classes had to adapt to the NGSS, so too should literacy methods courses. As a disciplinary literacy practice, it would be just as appropriate to cover modeling in a literacy methods class. By leveraging natural overlaps in methods classes incorporating interdisciplinary approaches, preservice teaching candidates would have more opportunities to hone their personal familiarity with science and literacy practices without the need for additional courses.

In-Service Teacher Professional Development

The decentralized nature of the educational system in the United States makes it particularly difficult to institute reforms all at once. One way of supporting in-service teachers is the use of educative curriculum materials (Arias et al., 2015; Beyer & Davis, 2009; Davis & Krajcik, 2005; Davis et al., 2017), which has been used to augment teachers' understanding of science content. What would it look like to include educative curriculum materials to support teachers with science practices? The MoDeLS project team reported promising initial results from assigning preservice teachers to read a specific expository text which explained the purpose and use of models and modeling along with suggested instructional strategies, supplemented by narrative examples from a fictional teacher (Davis, Kenyon, et al., 2008; Davis, Nelson, & Bayer, 2008; Hug et al., 2008). In the Wayfinding Unit, we included a "Guide to Writing Scientific Explanations" that was included as a text for the students to read, but was also intended to support the teacher. A future iteration of the unit might be well-served by including a similar guide for modeling.

Beyond curricular supports, in the same way that pre-service coursework is often siloed into methods courses for individual subjects, so too are professional development sessions. Especially in larger districts, where different subjects areas fall under the purview of different curriculum specialists at the administrative level, interdisciplinary learning can often fall by the wayside. Although it is often logistically challenging for individuals at the administrative level to find time to work together, the curriculum lead for English language arts may still choose to integrate the NGSS as much as the CCSS into professional learning opportunities. The reverse is also true: as many districts are still implementing NGSS-aligned curricula, they have a prime opportunity to provide examples of how science instruction can be connected with other subject areas.

Conclusion

This study adds to the body of literature demonstrating that the practice of modeling is possible with elementary-aged students. Furthermore, it hints at potential improvements for curriculum design and instruction regarding modeling, with implications for teacher preparation. Working closely with this group of students highlighted that models are not an item to be completed and handed in. Their utility, consistent with Vygotsky's notion of tools (Wertsch, 1991), was in how they were used to communicate understanding with others. The initial model was merely the first pass at sense-making, with peer feedback playing a meaningful role in revising those initial ideas.

As a main takeaway, this study highlights the need to teach multimodal composition, especially the genres and features of technical drawing. Students, and teachers, need to learn that, while expressive art certainly occupies a necessary place in human society, drawing can convey scientific ideas as well. Multimodal composition is both a science practice and a literacy practice.

It may be necessary to make the connections to literacy clear for students, including the intentional introduction of science terms, and also as a way to reinforce literacy practices from the CCSS, such as cause and effect.

Another main takeaway from this study is the need for students to have extended experiences with modeling, throughout an academic year and then over multiple years. I suggest a potential method of sequencing those modeling experiences, in the hopes that those regular and ongoing experiences with the practice help students to separate the practice from the individual investigations. This regular and ongoing practice also applies to providing peer feedback, potentially in the form of an open-ended yet flexible protocol like the 3C sheet shared in this work. Over time, students will become used to receiving and providing feedback in ways that are considerate of their peers emotionally in addition to improving their skills with providing constructive suggestions.

Overall, the findings of this study provide ideas that may assist curriculum developers, educators, and others who are interested in interdisciplinary instruction in project-based contexts to support students to communicate their ideas in powerful and novel ways.

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Chapter 3: Designing Models of Long-Distance Voyaging Canoes: Imagining the *Framework for P-12 Engineering Learning* in Action in Elementary Schools

Introduction

Engineering, as a formally-defined subject, has historically been unknown at the elementary level in the United States (Cunningham, 2018; Sneider & Purzer, 2014), a state of affairs that changed rapidly after the release of the *Next Generation Science Standards* (NGSS, NGSS Lead States, 2013). The adoption of the new standards, in whole or adapted form, triggered a sea change wherein, in less than a decade, it is no longer unusual to find engineering taught in elementary schools alongside language arts, math, science, and social studies. Because the United States does not have federal curricular mandates like other countries, this sort of large-scale uptake is remarkable and represents an opportunity for the development of a complete P-20 trajectory for engineering education. Without the introduction of the NGSS, such widespread adoption of engineering instruction for young children would have been unlikely.

However, the characterization of engineering in the NGSS is incomplete. The NGSS define three dimensions: *cross-cutting concepts* (CCCs), *science and engineering practices* (SEPs), and *disciplinary core ideas* (DCIs, NGSS Lead States, 2013). Engineering is explicitly referenced in two of these dimensions: the SEPs and the DCIs; i.e., the practices and knowledge necessary to engage in engineering. Taking a closer look at the SEPs, the NGSS identifies eight practices: (a) defining problems; (b) developing and using models; (c) planning and carrying out investigations; (d) analyzing and interpreting data; (e) using mathematics and computational thinking; (f) designing solutions; (g) engaging in argument from evidence; and (h) obtaining, evaluating, and communication information (NGSS Lead States, 2013). Regarding DCIs, the NGSS offer three at the upper elementary level, all under the heading of *Engineering Design*: (a) defining a problem with criteria and constraints; (b) generating and comparing solutions, and (c) planning and carrying out fair tests (NGSS Lead States, 2013). However, as Cunningham (2018) observed, this arrangement conflates engineering knowledge and practices, while making no distinction among the various fields of engineering. As a result, the NGSS falls short when identifying and defining the knowledge, practices, and habits of mind specific to engineering.

These shortcomings have been on the radar of the engineering education community for some time. In 2018, the Advancing Excellence in P-12 Engineering Education (AE3) research collaborative was founded to support the explosive growth in pre-college engineering education. Working in collaboration with the American Society for Engineering Education (ASEE), the two organizations released the *Framework for P-12 Engineering Learning* in late 2020. This document was produced to provide practical guidance for educators and curriculum designers. While not explicitly stated, the *Framework* functions as a corrective to the conceptualization of engineering in the NGSS. Rather than viewing engineering as an addendum to science education, the *Framework* centers engineering as its own discipline and provides the coherence and structure afforded the other elementary school subjects.

Upon its release, the *Framework* was accompanied by Performance Expectations and Performance Matrices for high school instruction. This makes good sense, as engineering is more likely to be taught as a stand-alone subject at the secondary level. I have high hopes that the eventual Performance Expectations and Matrices developed by the AE3/ASEE partnership for the younger grades will be developed with input from elementary experts and will be developmentally appropriate. In the meantime, the elementary materials are not yet available and the timeline for releasing them is unknown. That being said, as the research undergirding the *Framework* has been circulating in the engineering education community for some time, I offer that the field does not have to wait for the official release of Performance Expectations and Matrices tailored to the elementary grades in order to get a closer look at how the ideas in the *Framework* play out with younger learners.

This paper was constructed around a rare opportunity: I designed and collected data on a Grade 5 project-based engineering unit prior to the release of the *Framework*, but I started the data analysis after. Because the design of the unit was informed by the same set of engineering education literature that guided the development of the *Framework*, many of the ideas overlapped. Therefore, I was able to use the *Framework* components as lenses for my analysis, as described below. By doing so, we may imagine the *Framework* in action at the elementary level.

Taking a closer look, the *Framework for P-12 Engineering Learning*, like the NGSS, is divided into three dimensions. Two out of the three dimensions are analogous: the NGSS SEPs appear in the *Framework* as *Engineering Practices*, while the content knowledge that the NGSS refer to as DCIs are labeled *Engineering Knowledge.* Instead of the NGSS CCCs, the *Framework* introduces a dimension called *Engineering Habits of Mind*, centering the types of social and emotional considerations that mainly appear in the NGSS as appendices. The three dimensions of the *Framework* are divided into main components (Table 3.1).

Table 3.1

Taxonomy for the AE3/ASEE Framework for P-12 Engineering Learning (2020)

Dimension of Engineering Learning	Main Components
Engineering Practices	**Engineering Design**
	Material Processing
	Quantitative Analysis
	Professionalism
Engineering Habits of Mind	**Collaboration**
	Optimism
	Persistence
	Creativity
	Conscientiousness
	Systems Thinking
Engineering Knowledge	Engineering Sciences
	Engineering Mathematics
	Engineering Technical Applications

In addition to illuminating the *Framework* in action at the elementary level, the engineering unit featured in this paper included two supports. The first support was grounded in ongoing conversations about how young students plan, and how/if they leverage written/drawn plans. Because of this, the unit included a written design planner with embedded guiding questions, as well as a structured data collection sheet. Exploring the use of these documents lines up well with the *Framework's* Engineering Practice of *Engineering Design*. As Engineering Design is categorized in the NGSS as a disciplinary core idea with three components, and is not conceptualized as a set of practices, the lens and language of the *Framework*, with the added clarity of nine sub-components (Table 3.2), provided a detailed view not possible with the NGSS.

Table 3.2

Sub-Components of the Practice of Engineering Design in the AE3/ASEE Framework

Main Component	Sub-Components
Engineering Design	Project Management
	Design Methods
	Problem Framing
	Engineering Graphics
	Information Gathering
	Ideation
	Prototyping
	Decision-Making
	Design Communication

The second support was grounded in a commitment to the social nature of learning. I was curious both about the affordances of working with peers, as well as the potential influence of working with more experienced others. In the unit under investigation, students worked in trios under the supervision of mentors from a university engineering department. Peer supports align with the Engineering Habit of Mind of *Collaboration*. Because the NGSS does not explicitly include social and emotional dimensions, using this lens revealed wide-ranging experiences that may have otherwise remained unseen.

To summarize, I used selected components of the *Framework for P-12 Engineering Learning* to explore the enactment of a final engineering project for an interdisciplinary unit in Grade 5. In particular, I asked a pair of research questions:

RQ1. How do the features of an iteratively designed engineering project provide opportunities for enacting the practice of engineering design in an elementary school classroom?

RQ2. How do the features of an iteratively designed engineering project provide opportunities for collaboration, with peers and university mentors, in an elementary school classroom?

Literature Review

The following literature provides a brief overview of the push for standards in pre-college engineering education, clarification about the definition of "engineering literacy," and selected research, from elementary contexts, about engineering design.

The Push for Standards in Pre-College Engineering Education

A small, but vocal, contingent of scholars and educators have been calling for P-12 engineering education for decades (for a thorough history of this movement, see Sneider & Purzer, 2014). This movement picked up steam around the turn of the millennium. Centered in Tufts University and the Boston Museum of Science, Massachusetts became one of the first states to institute engineering standards. Also around that time, Cunningham, Lachapelle, and colleagues began developing *Engineering is Elementary* the most widespread and widely studied curriculum for the elementary years (Cunningham et al., 2020). Engineering did not become widespread for the younger grades until the release of the NGSS in 2013. Although the adoption of the NGSS helped spread engineering education to elementary schools nationwide, the representation of engineering is incomplete. Based on her extensive work in elementary schools, Cunningham and colleagues (2018) developed an expanded list of 16 Engineering Habits of Mind. The newly released *Framework for P-12 Engineering Learning* (AE3/ASEE, 2020) further refines the taxonomy for engineering education (Table 3.1).

“Engineering Literacy” or Literacy in Engineering?

One of the stated goals of the *Framework for P-12 Engineering Learning* is to help students develop “engineering literacy.” I would like to clarify that definition. In my mind, the way the authors of the *Framework* use that term, it is more akin to “engineering competency” or “engineering proficiency.” Literacy has its own distinct definition. I offer a comprehensive view of literacy, one that is applicable to engineering, by combining definitions from Frankel et al. (2016) and Alvermann (2004): *the process of using oral, aural, visual, tactile, and digital modes of learning to extract, construct, integrate, and critique meaning through creation, interaction, and involvement with multimodal texts in the context of socially situated practices to communicate and collaborate with others*

Engineering Design

As defined by Dym et al. (2005), engineering design is “a systematic, intelligent process in which designers generate, evaluate, and specify concepts for devices, systems, or processes” (p. 104) to meet a need within constraints. Therefore, the engineering design process is the ability to break a problem down into steps, which can be engaged with repeatedly or in a non-linear fashion, in order to arrive at a solution. But what does this process look like for young children: how do they learn design and what do they do when designing (Kelley et al., 2015)?

A logical place to begin examining the engineering design process, and how it may or may not be the same for younger learners, is to look more closely at the steps in the process itself. While the field of engineering is not in agreement as to the particular steps of the design process (Dym et al., 2005; Portsmore, 2009), Wilson-Lopez, Gregory, and Larsen (2016) proposed a simplified three-step version for elementary students: *project scoping*, *developing solutions*, and *realizing solutions* (p. 27). Because I am interested in exploring connections between engineering and literacy, my focus in this paper will be primarily on the first two stages, examining students' writing, drawing, and speaking as they planned physical models of canoes in conjunction with their teammates and an undergraduate engineering mentor.

Project Scoping

Concerning the first stage, project scoping, students need explicit instruction in framing design problems and organizing their thinking while brainstorming (Kelley et al., 2015). A common misconception about open-ended design problems is that students are simply turned loose to tinker with little oversight or structure (Hmelo-Silver, Duncan, & Chinn, 2007; Mayer, 2004). Not only do young children need support because of the unfamiliarity of the design process (Cunningham, 2018), their cognitive development may influence them to approach problems in a manner qualitatively different than adults. From a social constructivist viewpoint (Palincsar, 1998), looking at engineering tasks as situated in, and mediated by, the co-creation of knowledge in a social context, the ability to plan is not solely dependent on students' biological maturation, but on interactions with more knowledgeable others (Vygotsky, 1978, p.86).

The influence of an experienced other on why students use, or do not use, a systematic approach to defining a problem can be seen in a study by Kelley et al. (2015). Observing students in Grades 5 and 6, the authors found that, in a classroom with a teacher who had over five years of experience with design-based teaching, students spent 23% more time planning and 27% less time enacting their solutions than students in classrooms with teachers who had only received two weeks of summer professional development. In the classroom with the experienced teacher, and only in that classroom, the students used a strategy of writing their problem definitions individually, then consulting with their group members to combine their individual definitions into a consensus definition. By front-loading their work in the planning stage prior to proceeding, the group needed less time during the other stages of the design process.

Even with older students, similar results were found by Atman et al. (2007) when comparing freshman and senior engineering undergraduates engaged in a design task. The seniors spent almost twice as much time as the less-experienced freshmen working on project scoping. Consistent with findings also reported by Cunningham and Lachappelle (2014), novice designers are often tempted to skip brainstorming and planning in a rush to build and test their prototypes (p. 127). While helping students to focus on project scoping may improve the utility of initial brainstorming, questions remain as to the most effective ways to support them to do so.

Developing Solutions

Concerning the second stage of the design process, developing solutions, a small, but growing, body of work takes an up-close look at elementary-age children as they plan. Two studies, while conducted in the lab and not in the classroom or specifically in the context of engineering, hint at developmental differences in planning during the elementary years. Gardner and Rogoff (1990) compared the maze-solving strategies of children aged 4.5 to 7 years with children aged 7 to 9.5 years when asked to privilege accuracy or speed. They found that the older children planned more often when accuracy was a requirement. The authors concluded that older children may plan more than their younger peers, but only when provided with a compelling reason. Absent a consequential benefit for spending time planning, older students will skip it in favor of improvisation.

Similar results were found in a study by Gauvain and Rogoff (1989) comparing 5-year-olds and 9-year-olds using lists to collect groceries from a model store. The authors found that, overall, the older children spent more time looking at potential routes than the younger children, and that a longer time dedicated to scanning routes resulted in more efficient shopping trips. These studies support the idea that children are capable of planning a solution, but that this practice increases with age. The studies also indicate that advance planning is beneficial when the plans are used, but that planning is neither automatic nor universal in young children.

An alternative conception of the “developing solutions” stage was offered by Smith and Smith (2016), inspired by the “do it yourself” Maker Movement. Rather than preparing written plans, they recommended that students engage in *fabrication* and *tinkering*. Fabrication is the step-by-step process of constructing an object, more in line with the recipe-like way that schools often teach science (p. 33). They argued that this formalized process is useful for familiarization with tools or the properties of materials. Having gained that knowledge, students can then spend time tinkering, the “unstructured process of testing ideas” (p. 31). This lends support to Portsmore’s notion (2009) that it may make more sense to ask young children to record drawings of their prototypes after building them, rather than before, transforming the process of drawing a prototype from one of outlining future action to one of recording what has already been done.

These studies highlight that design does not simply result in a *product*, but that it is also a *process* (Cross, 1982). Like all disciplinary processes, students need explicit guidance in the ways that professional engineers think and act (Baynes, 2010). Importantly, young students need to have a compelling reason to plan, otherwise they will immediately skip to enacting solutions (Cunningham & Lachappelle, 2014). Design challenges need to be carefully constructed to provide incentives to plan, like the condition in the Gardner and Rogoff study that valued accuracy over speed. Moreover, it is still unclear whether asking young students to plan is needed at all. Because of their unfamiliarity with the characteristics of materials, perhaps it is more meaningful for students to iterate versions of their prototypes through tinkering, then asking them to record their prototypes after they are constructed.

The existing literature about the engineering design process raises almost as many questions as it answers. First and foremost, a host of questions remain about how elementary-age students can effectively represent and record their ideas as they plan. It may be premature to ask *how* young students plan, if the answer to one of the most basic questions still remains unanswered: *do* young students use written plans when building prototypes? If the answer is no, then perhaps the engineering design process needs to be completely reimagined for young children. If the answer is yes, which the existing research seems to support, what could effective scaffolding look like that would help students successfully communicate their thinking while engaged in engineering design?

Theoretical Framework

The design of the unit was informed by a social constructivist perspective (Palincsar, 1998). Rather than conceptualizing learning as something "out there" that can be collected, sense-making is an active and internal process of constructing an understanding of the world. Although this may give the impression of being an individual act, learning is inherently social. The cognitive tools that we leverage to make sense of the world, principally language, but also visuals, gestures, and other semiotic resources, are imbued with meaning through interactions with others in a particular time and place. Specifically, the unit design was guided by Vygotsky's (1978) notions of cognitive tools, social interactions, and the zone of proximal development.

Regarding Vygotsky's concept of *cognitive tools*, scholars such as Wertsch (1991) and Yore and colleagues (2003) have discussed the ways in which humans use symbols and signs as representations imbued with meaning to mediate interactions. Engineering design requires young students to leverage semiotic resources in ways that are novel to elementary instruction. As just a few examples, the vocabulary may be unfamiliar, methods of drawing may be challenging, and these representational modes may be combined in multimodal ensembles that are unfamiliar to teachers. Furthermore, students working on an engineering project may be asked to shift back and forth between written/drawn representations and physical models, and vice versa. Thoughtful scaffolding is required to assist young learners in navigating these challenges.

Regarding the notion of *social interactions*, collaboration is the heart of the engineering endeavor. Long gone are the days of a Leonardo da Vinci sitting alone at a drafting table imagining human flight. As just one example, the recent landing of the Perseverance rover on Mars was the culmination of the efforts of thousands of individuals. From the teams that designed the optics to the groups that fabricated the heat shield to the group calculating telemetries, such a monumental feat of engineering is only possible through combined efforts. Although the project under consideration in this paper is on a much smaller scale, the same dedication to discussion, compromise, and communication holds true.

Finally, the unit development was predicated on Vygotsky's notion of the *zone of proximal development* (ZPD, Vygotsky, 1978). In this view, opportunities for learning open up in the spaces created between two or more individuals and the task at hand. While working collaboratively, one learner may offer prior experiences with adhesives while another contributes knowledge about the overall design from a family trip. In this unit, students were grouped as trios, so that they could learn from one another. Then, the trios were each guided by a mentor from a university engineering department, who contributed specialized knowledge.

However, a "curriculum as written" and a "curriculum as enacted" are not the same. As Engeström reminds us with his notion of Cultural-Historical Activity Theory (CHAT, 2005), the enactment of a curriculum takes place in a particular place at a particular time. Looking more closely, even at the same moment in the same place, the "same" activity is actually an overlay and interaction between multiple perspectives. The goals of the individuals involved in the activity are not necessarily the same. In fact, they may not view themselves as being involved in the same activity. For instance, the designer of the unit may have included a number of written prompts with the intended outcome of a well-reasoned set of decisions about materials. During the enactment, a university mentor might decide to skip some or all of the prompts, because their desired outcome is to support the students to finish their projects on-time. Simultaneously, a student might ask the mentor a series of unrelated questions rather than answer the prompts, because her intended outcome is to gain more knowledge about topics of interest to her personally. In a design-based system, therefore, a goal is to acknowledge that disparate outcomes, or *contradictions* (Engeström, 2005, p. 165), are an inherent quality of activity systems. When reviewing a design-based unit, it is instructive to look at a given enactment to identify where the intended outcomes and the observed outcomes were more consistent and places where they were less consistent. Analyzing and reflecting upon these instances of lesser and greater contradiction helps to guide future iterations of the curriculum.

Method

The unit under consideration in this paper was one part of the larger *Multiple Literacies in Project-Based Learning* (ML-PBL) project. Our charge was to develop NGSS-aligned science curricula for upper elementary schools, with four units each for Grades 3-5. As the project followed the principles of design-based research (Brown, 1992; Collins, 1992), each potential unit was enacted, analyzed, and revised over the course of multiple years. I collected data during two enactments of a single unit developed for Grade 5: a pilot year in 2018-19 and a revised version in 2019-20. The experiences I share in this paper were from the second enactment.

Within the context of the broader ML-PBL project, I asked two questions to guide this study: (1) How do the features of an iteratively designed engineering project provide opportunities for enacting the practice of engineering design in an elementary school classroom? (2) How do the features of an iteratively designed engineering project provide opportunities for collaboration, with peers and university mentors, in an elementary school classroom? To explore these questions, I used an instrumental case study design (Stake, 1995). Because collaboration is essential to this work, and because activity systems within complex organizations like schools are best understood as nested and overlapping (Blackler et al., 2000), I used variable units of analysis. Although the case under consideration is the enactment of the a single curriculum unit, I will focus on two Black girls, Tameika and Sarafina[10], both fifth graders in the same classroom. At times, I will expand the unit of analysis to relay the experiences of the other two members of her group and/or their university mentor (Figure 3.1). In the following section, I will further describe the participants and context, along with the curricular unit, data sources, data analysis, and trustworthiness for this work.

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[10] Names of places and people are pseudonyms

Figure 3.1: Centered on Tameika and Sarafina, I use varying units of analysis while exploring the enactment of the unit under consideration in this study.

Context and Participants

The context for this study was a Grade 5 classroom in Pine Elementary School, a public K-5 school in a semi-rural Midwestern town. Through my other responsibilities with the ML-PBL project, I spent two years working in the school prior to the start of this study. During my third year with the ML-PBL project, with units already developed for Grades 3 and 4, I transitioned to working with Grade 5. I was introduced to Ms. Davis, a White woman, who had more than 20 years of experience with elementary teaching, with roughly a quarter of those years teaching fifth grade. She enacted both the pilot version and a revised version of our initial unit for Grade 5. Her participation during the pilot in 2018-19 was her first experience with project-based learning.

During the 2019-20 enactment of the revised unit, the focus of this study, Ms. Davis had 30 students: 12 females and 18 males. Nine students were Black, one was multiracial, and 20 were White. Six students has Individualized Education Plans (IEPs), one was being evaluated for special education services, and one student from the school's high-needs resource classroom spent inclusion time with Ms. Davis and her students. All of the students were native speakers of English. Schoolwide, 62% of students qualified for free or reduced-price lunch (Michigan's Center for Educational Performance and Information, 2018). Parents/guardians granted informed consent for the overall study. I received verbal assent from students prior to individual interviews.

Focal Students

My data collection in Ms. Davis' room included filming the whole class and collecting artifacts from all of the students. However, I have dedicated the space of this paper to celebrate two Black females, Tameika and Sarafina. I decided to tell the story of the enactment of this unit by focusing on their experiences for a number of reasons. First and foremost, my intention was to highlight the brilliance of these two individuals. The literature, and our society, benefits from stories of Black excellence. Second, women and people of color remain underrepresented in engineering (Wright, Wendell, & Paugh, 2018). While each of those identities individually face sexism and racism that create barriers to success, Black females are multiply marginalized based on their intersectional identity, resulting in persistent silencing (Annamma & Morrison, 2018). Putting a spotlight on the experiences of Black females was my way of amplifying stories that may not otherwise be heard. Finally, scholarship around STEM subjects often feels rational and cold. This dispassionate stance leans into patriarchal stereotypes and perpetuates "masculine" norms. Letting these two Black girls lead us through the unit was a way to humanize and personalize the work of engineering education, hopefully fostering a more compassionate approach to curriculum design and educational research. During my time in the classroom, I was lucky enough to get to know these girls, and I am excited to share their stories. In the sections below, I provide brief profiles of the girls. Before I do so, it is important that I am very clear about my positionality.

I am the first to admit that I'm not the ideal person to write this paper. As a White male, as an adult, as a doctoral candidate at a well-known university, I possessed power over the students when I was in their classroom. The power and privilege associated with those identities carried over to the writing of this manuscript. As such, my good intentions are fraught with the possibility of oppression. Acknowledging that, I am motivated by the words of scholar and abolitionist educator Bettina Love (2020) on the subject of privilege: "You didn't earn it, so spend it for somebody else." In composing this work, I had a choice of focus, and I decided to focus on the stories of Tameika and Sarafina. At some point in the future, I am certain they will accomplish great things and they will be able to share their own stories. Until that day, it is my great honor to make space for these young Black girls here and now.

Introducing Tameika. Fifth grade is a transitional time, with some students who still act like little kids and others who can't seem to wait to become teenagers. Tameika was older than most of the students in the class, celebrating her 11th birthday during this unit. Sometimes, when her classmates were bouncing off the walls and she was laser-focused on her work, Tameika looked like a college student trying to study in a preschool. Helpful, calm, and polite with adults, she could be goofy and tough with her peers, rotating through various silly voices and tossing off playful warnings. Although not identified as such among the classroom community, Tameika saw herself as an inventor. In an interview at the beginning of the unit, I asked her if she liked to write. She told me "I have a journal at home and I write in it, like stuff that I do on a daily basis, and my ideas, because I have like… me and my brothers, all three of us have a hoverboard, and I try to build like cars and stuff with it, because I like to build stuff." She proceeded to go into great detail about her tinkering with toys in the house and funny stories about times that her "inventions [went] crazy."

The more I visited the classroom, the more I was struck by the power of Tameika's wardrobe. While her classmates sported the typical elementary assortment of brand logos, video game images, and generic pictures of basketballs or hearts, Tameika's clothes often made a statement. Her shirts were emblazoned with messages like *The Future* or *Fearless*, four different outfits that declared *QUEEN*, and one that stated *Girls can be SMART, Girls can be STRONG, Girls can be FIERCE*. I never asked Tameika if she selected her own clothing or if it was the choice of a family member, but I was struck how often she arrived at school wrapped in messages of Black excellence and female empowerment.

Because she was self-motivated, Ms. Davis often assigned Tameika to a desk in the back of the classroom, close to where I would sit. About a week into the unit, Tameika called me over to her desk. During the last hour of the day, about half of the class would attend various interventions. Unable to proceed with core instruction, Ms. Davis would often have the students conduct individual research. She had encouraged the students to write biographies about well-known explorers, and I would occasionally lend a hand. Uncomfortable with the legacy of violence connected to most of those figures, I was glad to introduce students to "explorers" like Neil Armstrong and Jacques Cousteau. Tameika called me over and told me that she was interested in Malcolm X. As someone who is often too controversial to be discussed in the classrooms of White elementary teachers, I was surprised by Tameika's request and I was only too happy to lead her to a website where she could learn more about him.

Introducing Sarafina. Whereas Tameika was older than most of the students in the class, Sarafina was much younger. She was only 9 years old, two months shy of her 10^{th} birthday during this unit. So, although they were in the same grade, Sarafina was more than one year younger than Tameika. Sarafina was new to Pine Elementary, having left a small charter school. When I interviewed her at the beginning of the unit, she was very clear that transferring to Pine was not her choice. By the end of the unit, she had formed her own trio of friends, with Daylah and Trudi, and admitted to me that public school wasn't as bad as she had feared.

Despite being young for fifth grade, Sarafina was an excellent reader, with an expressive voice and an expansive vocabulary. More than once, she had to be urged to put down a book to join the line-up for lunch. Because of her love for reading, Ms. Davis would frequently ask her to read passages out loud. Sarafina also loved to draw, and told me that her attempts to compose illustrated books had always been foiled when she would "only write one or two words and end up only drawing." She admitted to me that one of the reasons she liked the engineering unit was that it gave her permission to draw, something that typically would get her in trouble.

Sarafina had her own t-shirt with a message of female empowerment: *Girls Run the World*. However, Sarafina's clothing was more likely to reflect her whimsical imagination, with sayings like *I Speak Unicorn* and *Hoptimist* (accompanied by a picture of a bunny). In general, Sarafina was protective of animals. Her engagement in the unit noticeably increased during the week that we discussed plastic pollution in the ocean. On the day the class studied microplastics, she approached me at dismissal time to ask me for the name of the plastic ingredient in consumer products, to be on the lookout when shopping with her mom. At the end of the unit, she admitted to me that she had thrown away her sister's toothpaste after discovering that it contained a plastic compound. I sensed an environmental activist in the making.

A Snapshot of the Wayfinding Unit

The Grade 5 unit enacted at Pine Elementary was about Polynesian wayfinding: navigating across the oceans using clues from nature like the direction of winds, patterns in the waves, and the movement of stars. Like all of the ML-PBL units, the Wayfinding Unit was organized around a driving question (Krajcik & Czerniak, 2014): *How can we find our way in the world by using only clues in our environment?* The unit was enacted over a period of 9 weeks, divided into two distinct sections. The first 5 weeks were designed around 20 interdisciplinary lessons, intended to be taught for 90 minutes each, that included engineering, literacy, science, social studies, and math components. The following 4 weeks were dedicated to a pair of final projects: 1) planning, building, and testing models of Polynesian-style double-hulled canoes, and 2) creating videos identifying a problem facing the environment and proposing potential solutions (see Appendix A for the Table of Contents).

The unit was intended to feel like a journey: deciding why to go, planning the trip, gathering knowledge and skills, then finding a way to the destination. Along the way, students read a wide range of texts, watched videos, and made observations using an online planetarium. Investigations included collecting freshwater from saltwater using a solar still, observing the speed of waves at various depths, and creating a video to demonstrate why the sun looks larger and brighter than other stars. With a major focus on the oceans, the students spent a week exploring the impact of plastic pollution, including conducting an investigation to identify microplastics added to everyday household items.

The Polynesian Voyaging Society (PVS) served as the inspiration and the through-line for the unit. Based in Hawaii, their organization has been working since the 1970s to bring attention to the achievements of Polynesian ancestors and to pass that legacy to future generations. In a feat of human ingenuity, the PVS crew successfully circumnavigated the globe in their flagship canoe, the Hokule'a, during a 4-year journey from 2014-2017. The two final projects reflected the dual mission of the PVS: (a) to demonstrate the possibility of sailing long distances using only traditional methods and (b) to send a message that all people around the globe are stewards of the Earth.

The Final Canoe Project

The canoe project unfolded in distinct stages, with broad phases of the design cycle built into the "theme" of each day: Planning Day, Building Day, Testing Day, and Sharing Day. Ms. Davis assigned students to groups of three. On the Planning Day, the marine engineering mentors visited Pine Elementary. I had asked the university students to bring some sort of artifact to share with the students: textbooks, photos on phones, CAD designs on laptops. As the mentors got to know the kids, I slowly brought groups to the empty classroom we were using as our construction space. In advance, I had laid out and labeled all of the materials (Figure 3.2). Once in the construction space, the students and their mentors were encouraged to walk around and touch the materials. When they had a good idea of what was available, each group had an assigned work spot somewhere in the room (Figure 3.3).

The groups sat with their mentor to complete a structured design planner (see Appendix F). The planner served multiple purposes, both practically and conceptually. First, the planner was intended to guide student thinking. By breaking the design task into a specific number of required criteria and optional elements, it cued students to consider the essential elements of the canoe, as well as outlining specific constraints (e.g., maximum dimensions, material choices, etc.). Second, the planner was intended to guide the university mentors. Knowing that I would likely have less than 10 minutes of orientation before introducing the mentors to the students, I crafted the planner to be a sort of questionnaire. At the same time that it did so for the fifth graders, the planner cued the mentors to the criteria for success and the constraints of the project. Third, because the university students were all volunteers, and had various prior commitments, I was certain that at least some groups would work with more than one mentor. Therefore, students were able to use their planners to bring a replacement mentor up to speed. Finally, the planners helped to provide some uniformity to the engineering problems being discussed and to the resulting models. This allowed for easier comparisons when the students came together at the end to share their results.

As students worked in their groups to complete their plans, they were encouraged to return to the materials tables as often as necessary to check out the properties of the materials. However, in order to prevent students from rushing through the planner, and to keep the day's work in a conceptual space, I informed students and mentors that no construction would happen during the session.

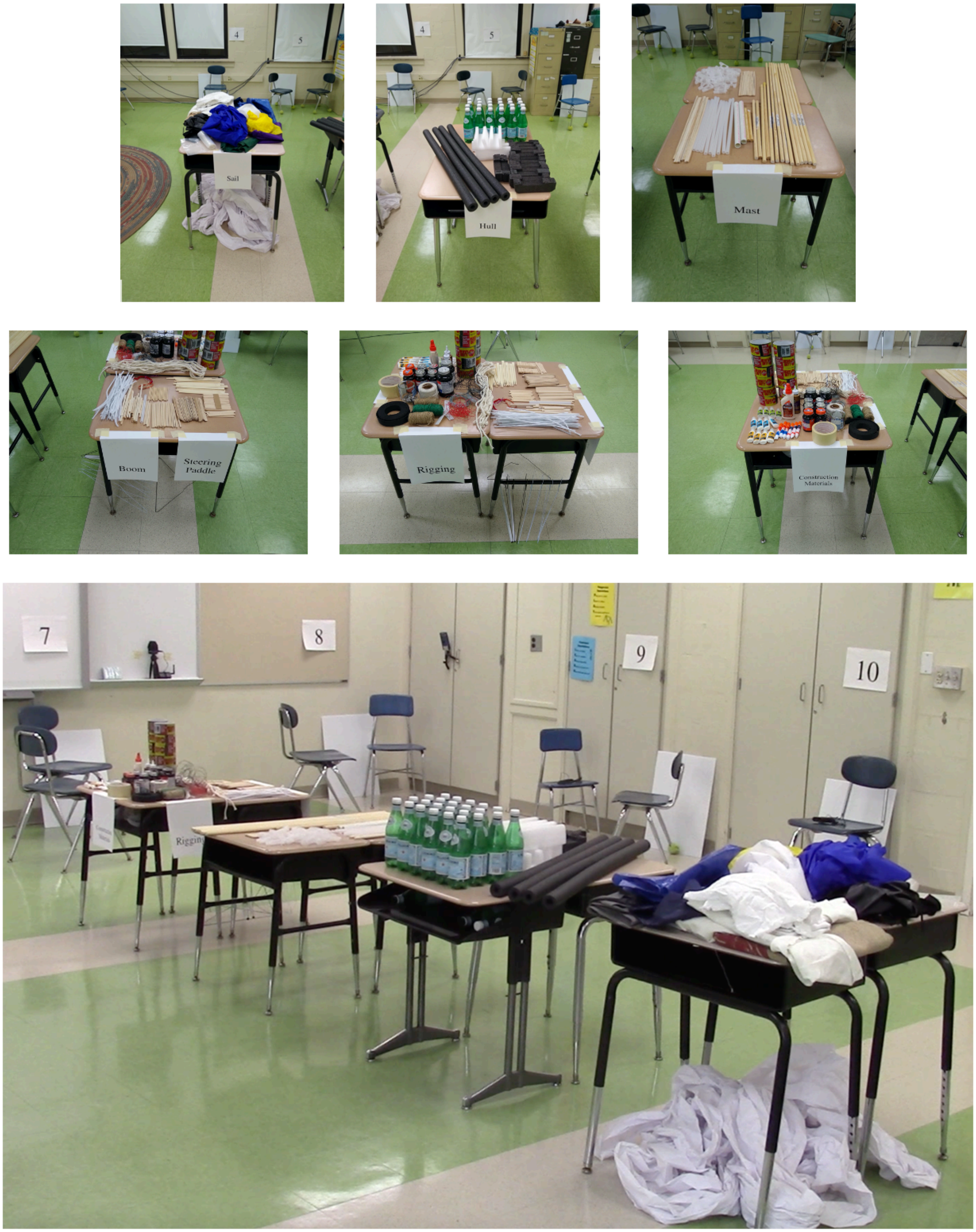


Figure 3.2: Materials displayed prior to the start of the Planning Day.

Figure 3.3: Sarafina's group (left) and Tameika's group (right) discussing their designs during the Planning Day.

Next was the Building Day, also hosted at Pine. Again, the university mentors met with the students in their classroom. For students with a returning mentor, it was a chance to review any changes they had made. For groups with a new mentor, they had time to share their planners. When they were ready, I slowly brought groups to the construction space (Figure 3.4). Other than the communal materials, each group was provided with scissors, a roll of duct tape, and a large piece of corrugated plastic board to use as the deck. For safety reasons, an adult was assigned to a "cutting station" equipped with saws, box cutters, and drills. The expectation was that each group would have a complete canoe model by the end of the session. In the days that followed, I acted as the mentor to assist groups with wrapping up their models.

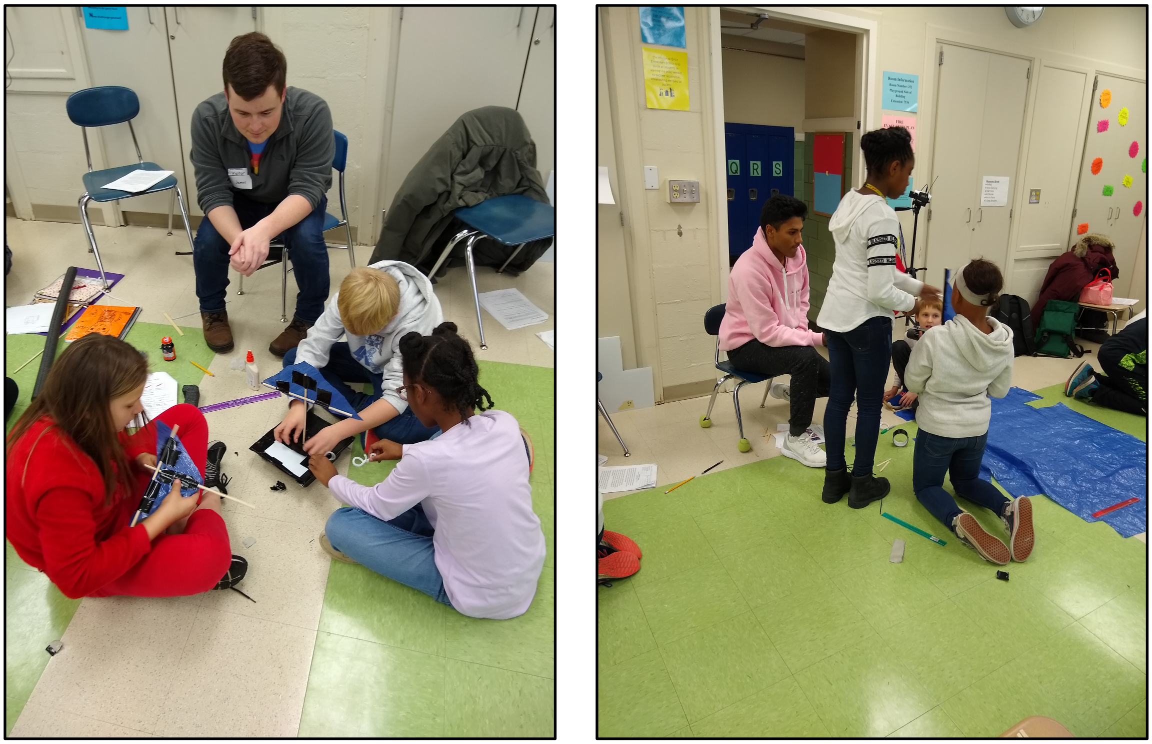


Figure 3.4: Sarafina's group (left) and Tameika's group (right) constructing their model canoes during the Building Day.

On the Testing Day, the students brought their completed models on a field trip to the university Marine Hydrodynamics Lab. Instead of a planner, the students had a data collection packet for recording trial times, revisions, and sketches of their canoes (see Appendix G). While half of the groups toured the lab, the other groups tested their canoes. The Wind/Wave Interaction Tank was staffed with four engineering students. Two were inside the tank itself to release and catch the models. The other two volunteers were outside the tank, to assist with getting the models into and out of the tank, and to discuss observations with the fifth graders. Students observed two trials per test, recording times and observations (Figure 3.5). Another group of volunteers staffed a “revise and rethink” room. Stocked with tools and excess materials, students were encouraged to return to this room after their test to repair and improve their models. Groups were encouraged to iterate and re-test their models as often as time allowed.

Figure 3.5: Sarafina and Weston observing their canoe model inside the Wind/Wave Interaction Tank during the Testing Day.

On the Sharing Day, students communicated their results to their peers (Figure 3.6). Immersed in their own designs, students had not yet had the opportunity to see what other groups had created. One by one, groups went to the front of the room. They were asked to describe their initial design, the results of their various tests, and the changes they made to their models. Each group then took questions from their peers. As a final task, students were asked to draw sketches of their final model in their data collection packet.

Figure 3.6: Tameika's group communicating their results during the Sharing Day.

Data Sources

To document the dynamic and multimodal nature of the canoe project, I constructed this case study from multiple data sources: observations, student artifacts, interviews, and surveys.

Observations

I approached the filmed aspect of observations with a cinematic approach, attempting to provide as much coverage of these very active spaces as possible. For the lessons leading up to the final canoe project, I always had two cameras rolling: one in the back connected to a wireless microphone worn by Ms. Davis, and a second camera in the front connected to a wireless microphone that I wore. For the classroom lessons, I recorded fieldnotes.

My video set-up for the days of the canoe project involved more cameras. I used small cameras deployed throughout the room, focused on each group. I also had a camera in the corner to record a wide view. These cameras were mostly small and placed in unobtrusive places like windowsills and on top of filing cabinets. I asked the mentors to wear wireless microphones, which recorded their comments, as well as the speaking of the students in their group. During the Planning and Building Days, I supplemented the video recordings with plentiful still photos. For the Testing Day, I was assisted by a professional photographer. Because I was moving around during the days of the canoe project, I did not record fieldnotes in real-time. Instead, I composed a memo after each session to capture my observations and impressions.

Student Artifacts

I collected the design planners and data collection packets from all of the students in the classroom. Also, because the canoe models themselves were the focus of this unit, I documented them with still photos. I took a few photos of each model at the end of the Building Day to record what each group was able to accomplish in a single session. Over the following days, as each group completed the initial version of their model, I more fully documented each canoe, taking photos of the top, front, rear, and both sides.

Interviews

I conducted two sets of interviews with Tameika and Sarafina. I spoke with each of them after the second day of the unit, to get their early thoughts on the unit and to learn a bit more about each of them. I conducted much longer interviews at the end of the unit. Using their written materials for stimulated recall and a semi-structured format, we discussed individual activities, as well as broader questions about the unit as a whole.

Surveys

In order to hear more from the students and the volunteer mentors, I administered brief surveys. At the end of the unit, the students completed a 2-sided Attitude Survey. The front of the survey consisted of nine multiple choice items, gathering student feedback on how they felt and how much value they found in the major activities in the unit. On the back of the survey, students voted for their two favorite activities and to explain their choices. Finally, they were asked who they would like to work with on a future project.

For the mentors, I sent a 4-question Google Form at the end of the Planning Day, Building Day, and Testing Day. I asked them what went well, what was challenging, any suggested changes, and to share any notable moments. The response rate was high for the Planning Day (7 out of 8 mentors responded) and the Building Day (5 out of 9 responses), but low for the Testing Day (2 out of 11 volunteers responded).

Data Analysis

As Spiro and colleagues (2007) noted about the use of video in research, the goals are both to present complexity as it naturally occurred and to share that complexity with others so that they may learn from it. Although they cautioned that presenting the full complexity of a learning experience is not possible, a fuller presentation of complexity may be approximated by using multiple camera angles, supplementing with auxiliary material (e.g., student artifacts), and including commentaries from multiple participants.

Therefore, the task for data analysis was to bring these various sources together to present a cohesive presentation of the multiple activity systems at play during the canoe project. I started with data sources specific to Tameika and Sarafina: beginning with their initial interviews, I reviewed video footage in order, often watching the same moments from various angles. As I did so, I prepared an overview document for each girl that functioned as a timeline of their experiences within the unit, including descriptions of actions, as well as transcriptions of conversations. As I did so, I made extensive notes and engaged in some initial coding using an inductive approach (Charmaz, 2014). These overview documents served as the inspiration for the narratives that comprise the first part of the Findings section.

I then transitioned to a deductive approach to coding, using selected items from the *Framework for P-12 Engineering Learning* (AE3/ASEE, 2020) as a heuristic for examining the ways in which the canoe projects provided opportunities for the students to engage in engineering design and collaboration. In particular, I used the nine sub-components of Engineering Design, found in Table 3.2, to organize the material I had coded from the videos. To provide additional insights to those moments observed on video, I supplemented with student work, still photos, and comments from surveys.

As I mentioned earlier in this paper, although I look at the enactment of the canoe project primarily through the experiences of Tameika and Sarafina, the unit of analysis does shift (Figure 3.1). At times, I turn attention to another member of the group. Other times, the activity is focused on the interaction with the group, or the students interacting with a mentor. Because the engineering volunteers wore microphones, sometimes they discussed their insights with one another when the students were not in the room, or they shared insights with me through the written surveys. These comments provided valuable insights that often corroborated, or upended, my observations. By reviewing, coding, and combining these data sources, my intent was to re-present the enactment of the canoe project.

Trustworthiness

Acknowledging that it is impossible to capture events in all of their complexity, or to touch on even a fraction of the activity systems operating during the days under consideration, my goal was to share the dynamic nature of the canoe project (Steffe & Ulrich, 2020). Using the advice of Spiro and colleagues (2007), I tried to approximate the enactment of this particular engineering design task in this place and time by reviewing footage and audio from multiple cameras, combined with insights from the students and mentors in their own words from interviews and surveys. I would like to be clear that, as much as video footage seems like a "true" document of reality, it is not. The findings reported in this paper, even when I quote the participants, are my interpretation of events.

That being said, as an educator, I am protective of students. I feel a great sense of obligation to conduct this work with great care and to be as honest as possible in my writing. This means not only advancing aspects of the project that were successful, but admitting where it fell short. My re-presentation of the canoe project could never be perfect, but I hope that the time I spent with these students, and my careful review of what happened during this engineering design experience, has resulted in a trustworthy account of this enactment.

Limitations

Due to the scope and design of this study, there were inherent limitations. The scope was limited to one classroom, focusing on a small subset of students. The results would likely have been different if I had selected a different subset of students, or if I had worked with a different teacher. I am curious what the Wayfinding Unit would look like if it were enacted in different contexts. As it stands, the generalizability of this study is limited. Another limitation of the work is my role as both principle curriculum designer, participant-observer, and the sole researcher. As I shared when I discussed Trustworthiness, I hope that my use of multiple data sources has allowed me to present an approximation of the complexity of this experience. Finally, my own presence in the classroom may have affected outcomes in unexpected ways.

Findings and Discussion

My analyses for this study explored a pair of research questions: (1) How do the features of an iteratively designed engineering project provide opportunities for enacting the practice of engineering design in an elementary school classroom? (2) How do the features of an iteratively designed engineering project provide opportunities for collaboration, with peers and university mentors, in an elementary school classroom?

The findings are organized into two parts. First, I have composed an overview of each girl's journey. This linear narrative is intended to provide context and a holistic representation. Second, I use components of the *Framework for P-12 Engineering Learning* (AE3/ASEE, 2020) to provide finer grained detail about the Engineering Practice of *Engineering Design* and the Engineering Habit of Mind of *Collaboration*.

Narrative Descriptions of the Canoe Project

I begin this section by sharing overviews of Tameika, Sarafina, and their respective teammates and mentors as they engaged in the canoe project. I intend for these linear narratives to provide a useful map and context for the subsequent part of the findings, when I look at specific moments from throughout the project through the lens of the *Framework for P-12 Engineering Learning.*

Tameika Working With Brianna, Mark, and Their Mentor Arif

Tameika was partnered with Brianna, a Black girl, and Mark, a White boy. Like Sarafina, Brianna was new to Pine Elementary in 2019-20. Unlike Sarafina, Brianna had “begged her mom” to let her switch schools and felt that Pine was “better than the school I was going to.” Although she was new to the school, Brianna had already become fast friends with Tameika and Tameika’s best friend, Florencia. At two different points during the unit, I surveyed the students about who they would like to work with in the future. At both points, Tameika, Brianna, and Florencia all mutually selected each other, the only trio in the class to do so.

Mark was an easy-going kid who liked to make the class laugh. He had an IEP that specified supports for math, reading, writing, and speech, which meant he was often pulled from class to receive services. When he was in the classroom, he was engaged, and he seemed to enjoy both engineering and science. For some students, working as the third member with a pair of girls who were good friends might have been a challenge, but Mark did well. They were matched with Arif, an undergraduate junior in the marine engineering program. Arif was the only South Asian American mentor, and one of three students of color out of the 16 university volunteers who participated in the canoe project.

From the Planning Day on, Tameika and her group approached the project with determination and focus. Upon entering the construction space, they spent a sold 8 minutes inspecting the materials before they sat down. Arif followed my advice, and led the students systematically through their planners. As they made their way through the questions, Tameika and her partners made six additional visits to the materials tables. In this way, this group made choices grounded in the physical properties of the materials they selected. Tameika usually had her packet in her hands, looking at the photos while having candidate items in her hands (Figure 3.7).

Figure 3.7: Tameika and her group inspecting the materials (left); Tameika referencing her design planner (right).

Unfortunately, the group hit a bump early on. While discussing the very first component, the material for the hull, Brianna disagreed with her teammates. Although they were friends, and although they were both big sisters in their own families, Tameika often treated Brianna like a wayward younger sibling. During this first disagreement, which we will revisit in the Collaboration section, Arif helped the students to vote and move on. However, after losing the vote, Brianna partially disengaged from the process. From that point on, it was clear that

Tameika was determining the direction for the group, with Mark as her assistant, and Brianna increasingly detached from the project.

Tameika's group, with Arif's steady guidance, answered all of the key questions and make material choices during the Planning Day. I had intentionally scheduled a day between Planning and Building to give students a chance to finish their planners. Tameika's group worked on their multiple view drawings. Tameika was reluctant and told me, "I don't want to draw." I let the group know that the drawings didn't need to look exactly like the boat, they just had to show how the parts go together. Tameika, who also had extremely neat handwriting, was not one to do something partway, so she used the edge of her pencil case to ensure she drew straight lines (see Appendix H for Tameika's completed design planner).

Arif returned as their mentor for the Building Day. Returning to the construction space, Tameika had a clear vision of the boat that she wanted and quickly abandoned her design planner. Working with Mark as her assistant, and with Brianna rarely touching the model, Tameika took the lead in constructing their canoe. Interestingly, she rarely spoke or gave direct commands; her leadership of the group was accomplished almost solely through gestures and looks, especially in Arif's presence. Although the students did not often refer to their planners, Arif had his and guided the students through the various sections. The group put together a boat that was noticeably smaller and simpler than their peers. Tameika's attention to detail was evident in the clean lines of tape and sharp angles. Unlike nearly all of the other groups, Tameika and her partners had a generally completed model by the end of the session (Figure 3.8). When I brought them back to the construction space the following day, Tameika added a steering paddle and I helped them adjust the angle of their sail. Their additional building time was less than 10 minutes.

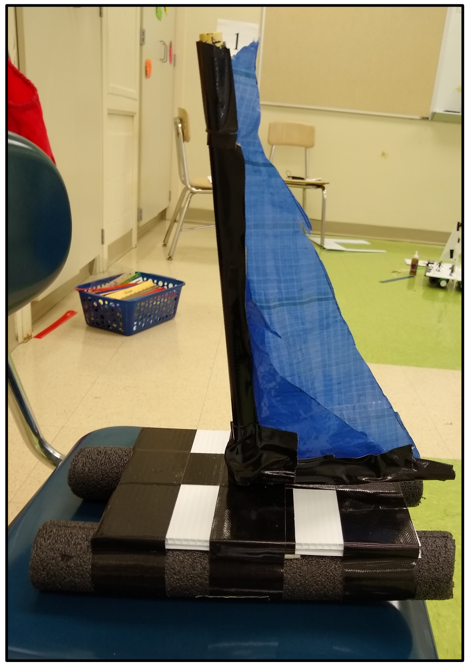


Figure 3.8: Progress at the end of the Building Day on the canoe model constructed by Tameika and her group.

During the Testing Day, Tameika and her team were among the last to test. Mark was impatient to get to the Wind/Wave Interaction Tank, but Tameika was dissatisfied with their steering paddle. As she taped and retaped it, she did not ask her group members for help. When they finally tested their boat, it stayed upright, but it "rode the wall" and the friction made it go very slow. It took nearly a minute to cross the finish line, when most groups were averaging 10 seconds. Their sail had twisted, pushing the boat into the wall. The steering paddle that Tameika had fussed over was sticking straight back like a tail and was not touching the water.

By the time they returned to the "revise and rethink" room, most of the marine engineering volunteers had left. No one checked with them or assisted as they repaired their boat. Again, Tameika made all of the changes and did not let her partners touch the boat. During their second visit to the tank, their boat sailed straight for longer and they crossed the finish line in 9 seconds. This time, the volunteers at the tank discussed how their sail - while it resembled the images of long-distance canoes that they had seen - was actually imbalanced. Because the wind pushed on one side of the boat and not the other, it drove their boat into the side of the tank. The group agreed to add a matching sail to the other side of their mast, but, despite some half-hearted discussion back in the "revise and rethink" room, they did not make any further revisions (see Appendix I for Tameika's completed data collection packet).

During the Sharing Day, after taking the lead for the entirety of the project, Tameika allowed Mark to be the spokesperson when they communicated their results with the class. Although Mark did most of the talking, Tameika contributed their major decisions and findings: that the steering paddle needed to be adjusted, that they used a double deck to make their canoe sturdy, and that they had to adjust the angle of their sail. When questioned by a classmate about why their sail only had "one side," Tameika admitted that they "were going to add another sail, but we didn't have enough time." She reiterated this when another student asked about the change that they would make if they had more time: to "put another sail."

Sarafina Working With Molly, Weston, and Their Mentor Andrew

Sarafina was also partnered with one female and one male: Molly, a White girl, and Weston, a White boy. Molly, like Mark, had an IEP with supports for math, reading, and writing. Because of this, Molly and Mark were often out of the classroom at the same time when receiving services. Weston described Molly as a "bully," and while she often yelled at Weston when he disagreed with her, Molly tended to ignore Sarafina. Molly's engagement with the project varied widely. She barely spoke during the Planning Day, worked steadily during the Building Day, and recorded data for the group during the Testing Day.

Weston was a curious case who exemplified the in-between nature of being in Grade 5. On one hand, Weston often presented a "jock" persona, and he associated with the popular football players in an area obsessed with football. On the other hand, he often supported Sarafina's more whimsical suggestions, or joined her when she was decorating the canoe. In those moments, his tough exterior fell away and he revealed himself to be the little boy that he still was. Weston tended to make decisions on behalf of the group. He did not seem to prevent Sarafina's participation, and more than once suggested a task for her, but he did not go out of his way to make sure she was included. Sarafina's group was matched with Andrew, a White male, one of the few graduate students from the marine engineering department.

At the beginning of the Planning Day, Sarafina was extremely enthusiastic, so much so that Andrew pointed it out when the group's attention was flagging at the end of the session. Sarafina's group only spent about 4 minutes inspecting materials when they first entered the construction space, about half the time of Tameika's group. Sarafina made a few short visits to the materials tables on her own after their initial inventory, making notes about the materials in a tiny jack-o-lantern notepad, but for the most part, her group remained seated for the remainder of the planning session (Figure 3.9). Once her group started planning, her imagination was firing: she was imagining sleeping quarters and showers, and what would happen to the crew if it rained. Weston was equally concerned with these human elements, but Andrew did not see the point. As her suggestions were repeatedly rebuffed, Sarafina slowly lost interest. Their group also lost momentum by the haphazard way they completed their packet. They started with sketches before considering any of the questions, then went back and started looking at the pages one-by-one.

Figure 3.9: Sarafina and her group inspecting the materials (left); Sarafina taking notes in her jack-o-lantern notepad (right).

Like Tameika's group, Sarafina's group had the same mentor for the Building Day, as Andrew was able to return. Any enthusiasm for the project that Sarafina had felt for the project seemed sapped. She did not cut, glue, tape, or in any way contribute to the canoe itself. It was unclear if she was unwilling or unable to contribute more. Early in the session, she told Andrew "I'm bad at cutting." She may not have had confidence in her ability to cut. She followed up that statement by declaring "I just want to draw" and spending the majority of the build time sitting in a chair next to Andrew and drawing in a notebook. But, it didn't seem as if she was checking out on purpose: she asked Andrew six times if there was anything she could do to help. Andrew, Weston, and Molly all suggested various tasks each time she asked, but she did not follow through on any of them. It was as if she were frozen. She did chat with the team, and she asked Andrew lots of questions, so she was definitely paying attention to what was going on. Finally, about 40 minutes into the 1-hour building session, Andrew showed Sarafina how to make a stick figure sailor out of a pipe cleaner. She was very enthusiastic about this, and spent the remainder of the time making little sailors. At one point, Sarafina, Weston, and Andrew were all working on pipe cleaner sailors. With the clock ticking and their actual boat not finished, Molly yelled at all of them "Guys, we don't need to be worrying about stupid sailors!" Even with the time spent on adding decorations, Sarafina's group was nearly finished by the end of the session (Figure 3.10). Like Tameika's group, they only needed an additional 10 minutes in the construction space to complete their initial canoe model and used the time to add a steering paddle.

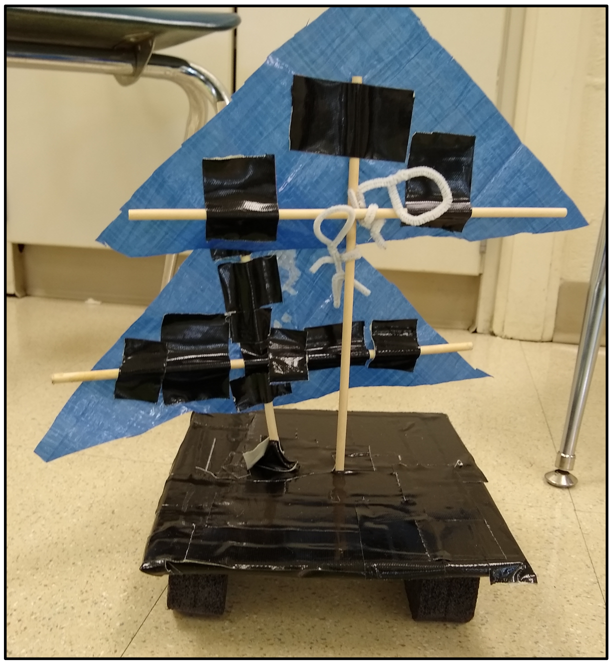


Figure 3.10: Progress at the end of the Building Day on the canoe model constructed by Sarafina and her group (note the two pipe cleaner sailors clinging to the sail).

Sarafina was very excited during the Testing Day. Although she still did not touch the boat, she eagerly answered any questions asked about their model and she focused her attention on the trials and revisions. Sarafina and her group made five trips to the Wind/Wave Interaction Tank. Their initial model tipped forward and the mentors told them to record an "F" for failed test. After a discussion with the volunteers, they decided to remove the lower sail and leave the taller one. However, this made their model top-heavy, and it again toppled over. Removing the tall sail and replacing the lower one, they managed to complete a run, but their model rode the wall. Somehow, between their second and third test, they had lost their steering paddle. They replaced it and their boat went fairly straight, earning times between 9 and 12 seconds. Although Andrew was the only mentor left in the "revise and rethink" room, he did not offer any assistance to the group until their after they returned from their fourth test. He noticed that they were trying to add two additional steering paddles, so he helped them saw some notches into their canoe. On their fifth and final visit to the testing tank, with the single short sail and three steering paddles, their canoe sailed super straight and earned a time of 7 seconds, one of the fastest of the day. Sarafina had her data collection sheet with her during the first two tests, but abandoned it after that, as did Weston (see Appendix K for Sarafina's completed data collection packet). Even after they gave up on their data collection sheets, both Sarafina and Weston still enjoyed using the stopwatches. Molly, who seemed reluctant to stand to close to the testing tank, stood at a good distance and recorded the times on behalf of the group.

After stepping back during the Testing Day, Molly took the lead when communicating their results with the class during Sharing Day. Sarafina was also uncharacteristically talkative, providing information about their various revisions and fielding questions from her classmates. She explained that they had to change their number of sails and to lower them to better catch the wind. She also justified their unusual choice of hull material, because they were worried that the other options were too light. Finally, she was proud to point out the little sailors that she had made.

Having provided a broad overview regarding the experiences of Tameika, Sarafina, and their respective teammates during the different phases of the canoe project, I turn to the *Framework for P-12 Engineering Learning* (AE3/ASEE, 2020) for a closer look at particular moments throughout the experience.

Engineering Practice: Engineering Design

The first component I will explore is the *Framework*'s definition of Engineering Design. Unlike the NGSS, which classifies Engineering Design as a disciplinary core idea, the *Framework* rightfully identifies Engineering Design as a set of practices. Providing further clarity, whereas the NGSS breaks Engineering Design into three components, the *Framework* identifies nine subcomponents (Table 3.2). I will use moments from throughout the canoe project to provide illustrative examples of what those practices could look like at the elementary level.

Project Management & Design Methods

I have combined the first two sub-components, *project management* and *design methods,* as they are both meta-strategies for managing a project as a whole. These practices have to do with personnel management, time management, and design strategies. Although these tasks are appropriate at the high school level, they likely place unnecessary demands on elementary students. As novice designers, the attention of young children is better invested in the problem at hand. During the canoe project, these sorts of managerial considerations were off-loaded onto the schedule and with the use of the design planner.

As one of the mentors shared after the Planning Day: "The packet was a good guide for the students and it helped them structure their thinking about each part individually." That being said, a tool is only as effective as how it is used. Tameika's group and Sarafina's group used their planners in very different ways. Arif led Tamekia and her partners systematically through the design planner on both the Planning Day and the Building Day. He used the prompts and asked the students for their thinking for each choice. So, when the Building Day arrived, even when the students weren't looking at their planners, Arif grounded their choices in what they had previously discussed. For instance, less than 5 minutes into the Building day, as the students were looking at mast materials, Arif reminded them of a project constraint: “Something to keep in mind is that your ships are technically supposed to be less than one foot.” Later in the session, as they moved on to constructing the deck, Arif again referred to his planner before they even marked the board: “So, I think if you go to the page with the deck, you guys said you wanted it to be 8 inches by 6 inches. Do you still think that length is good?” As the Building Day wore on, Arif himself started to drift away from the packet. By the time they got to the sail, Arif asked them what size and shape they wanted it to be, even though the students had already recorded the information in their planners. Also, Tameika was in line at the cutting station at the time, and was not there to remind Arif and her teammates that they had already decided and recorded that information. Even with that small oversight, Tameika, Brianna, and Mark proceeded efficiently through the planning and building of their model canoe by sticking closely to the design planner.

This was not the case for Andrew and his work with Sarafina and her team. As he wrote to me in his survey after the Planning Day:

> Keeping them on track and focused on what they were doing was difficult towards the end of the class when they felt they had done enough. The majority of the packet, while a helpful reference, was mostly ignored in favor of the last page where they could draw their design.

From the video, I did not see evidence that Andrew attempted to guide the students through the design planner. He seems to be the one who started with sketching, before the group had discussed the individual components of the canoe. Without a firm grasp of the components, the discussion around the sketch was more abstract. He began to use the prompts during the latter part of the session, but since the students had already created their sketches, they did not see the point in answering the questions after the fact. During the Building Day, Andrew did not refer to the design planner. Since they had not decided on firm measurements, he may have felt that their overall decisions about number of sails, hull material, etc. was enough to guide construction. However, by not following the plan, and especially by not deciding on roles, Molly and Weston essentially worked in parallel while Sarafina removed herself from the project entirely. They still managed to construct a model, in nearly the same amount of time as Tameika's group, but the experience likely felt very different from the students' perspective.

Problem Framing

Problem framing is the process of defining a problem statement, taking into account the goals of various stakeholders and evaluating various sets of criteria and constraints. For the canoe project, the problem was already scoped for the students, with the criteria for success and constraints stated in the design planner. This was a choice for this particular project, but problem framing is well within the abilities of elementary students. In the other final project for the Wayfinding Unit, student groups had to define a problem in the environment and propose possible solutions. If elementary students are provided with a number of engineering tasks over the course of a year, it is easy to imagine them moving from projects where the problem is already defined to increasingly open-ended scenarios.

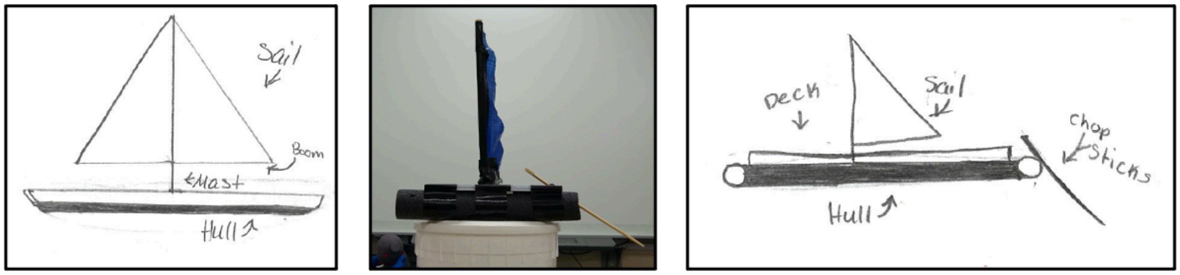
Engineering Graphics

According to the *Framework,* the practice of *engineering graphics* entails "interpreting, analyzing, and creating graphical representations of a design idea following commonly accepted conventions" (p. 31). One of the key unsettled questions with elementary-age designers has to do with drawn plans (Portsmore, 2013): do the drawn plans inform the model building, or do they need to build something first and then draw to record what they have created?

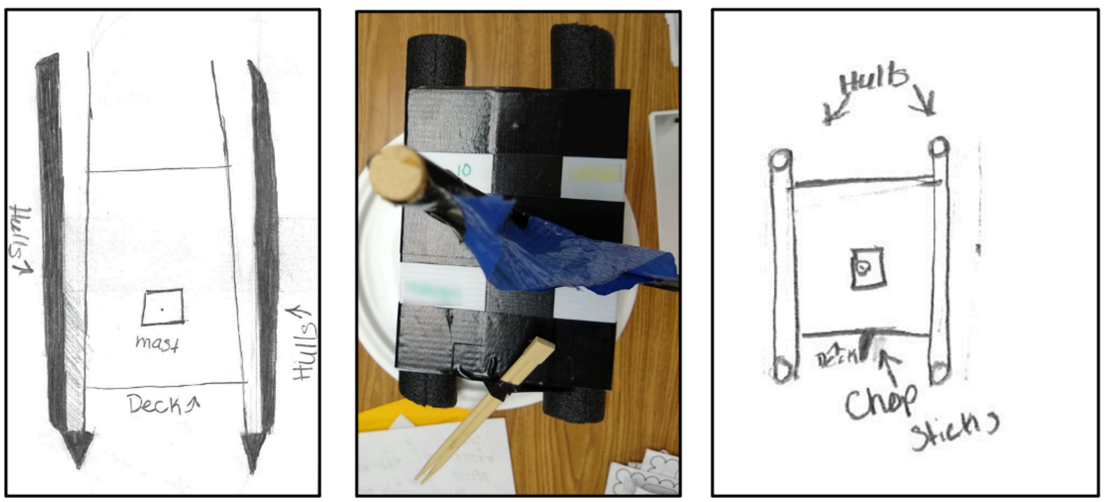
I decided to embed a test for these competing ideas within the canoe project. First, inspired by Benenson and colleagues and their *City Technology* project (2012), I requested that students practice drawing multiple view of their canoe at the end of their design planners. It is very important to note that the students drew these sketches when their canoes were still just an idea, which required mentally rotating the model. One of the arguments against students sketching ahead of time is that they are not well-versed enough in the properties of materials to understand how components will interact with one another. So, I added a second drawing step. After the students constructed their initial canoe models, I asked them to create another set of multiple view drawings in their data collection packets. This task was the equivalent of drawing a still life: the realized, physical model was in front of them and they were able to move the model to observe it from various angles.

In Figure 3.11 (Tameika) and Figure 3.12 (Sarafina), I present the results of this exploration of students and their drawings. For each row, the first image is the sketch from the design planner, when the canoe was an abstract idea. The second image is a photo of each group's boat at the end of the Building Day. If they had followed their design planners, the idea was that the photo would look similar to the plan. The third image in each set is from the data collection packet, in which the students made drawings of their physical models. Here, the idea is that the drawing would be easier to compete with an actual object to use as reference.

Side View



Top View



Front View

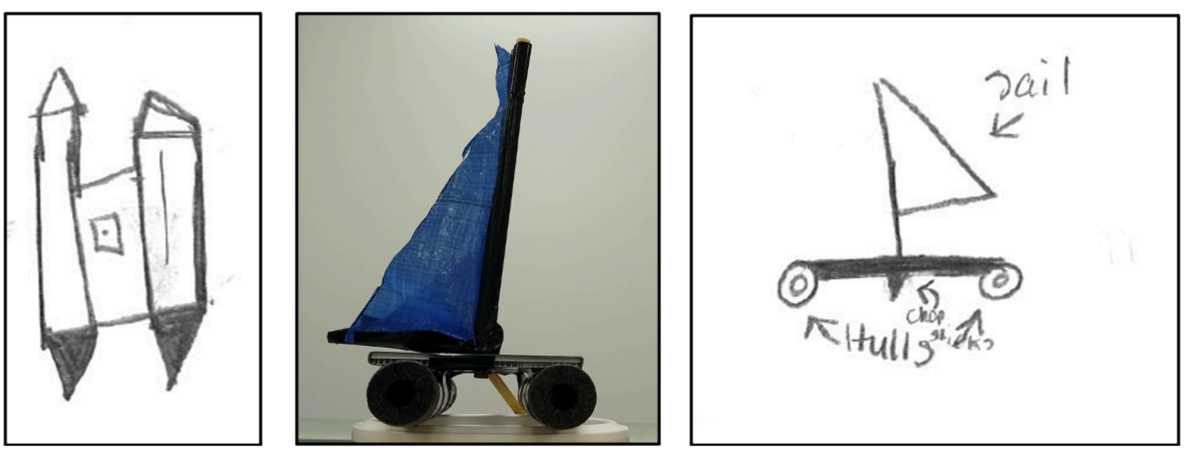
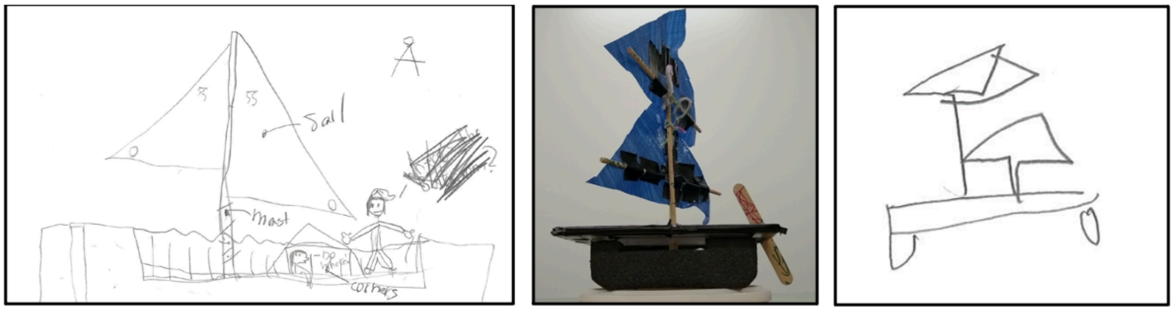
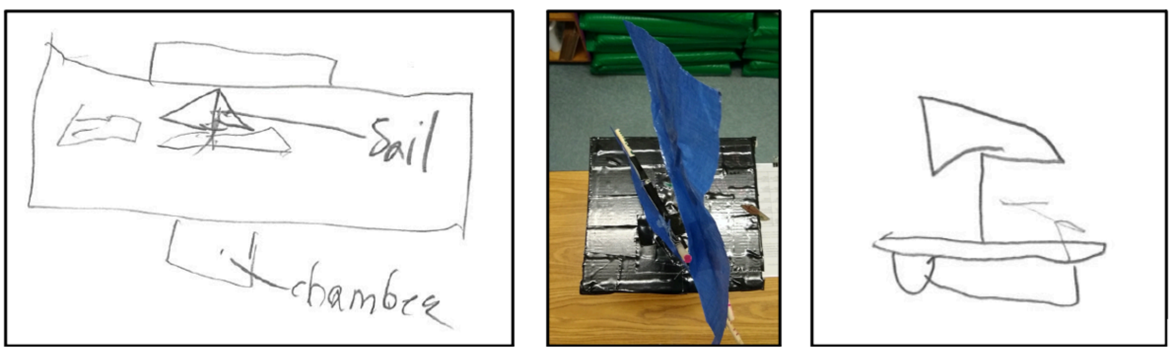


Figure 3.11: Multiple views of the stages of Tameika's design: sketches from design planner (left), photos of initial physical model (middle), and sketches of initial physical model (right).

Side View



Top View



Front View

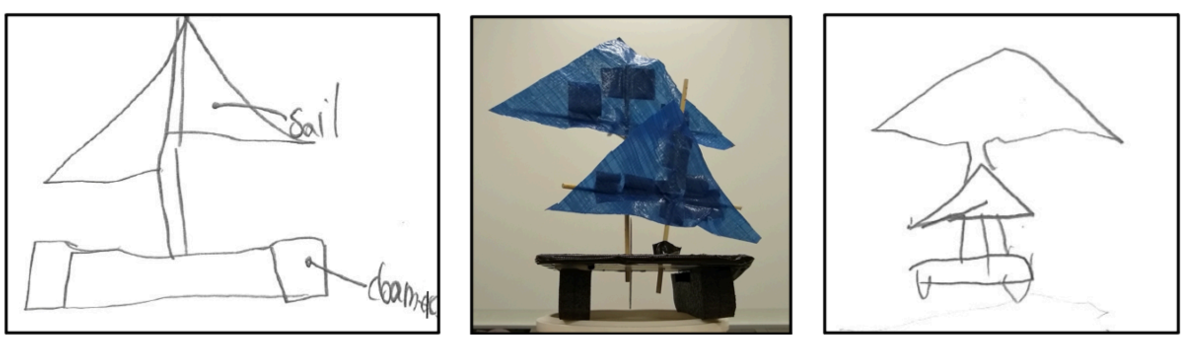


Figure 3.12: Multiple views of the stages of Sarafina's design: sketches from design planner (left), photos of initial physical model (middle), and sketches of initial physical model (right).

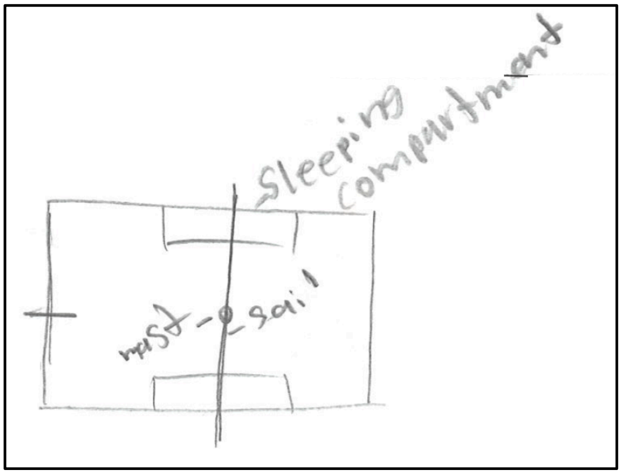
One of the first observations is Tameika's (Figure 3.11) neatness and the simplicity of what was, essentially, her design. Although all of the students had access to rulers, or to any straightedge nearby, Tameika was the only student who I observed using a tool to make straight lines. Conceptually, her initial side view is interesting, in that it looks like a "classic" sailboat, the kind you might see stenciled on a child's bedroom wall. What is also interesting is her difficulty in drawing a front view, which looks like the top view. When I worked with Tameika's group to finish their model on the day after the Building Day, I asked them which end was the front of their boat. None of the three students could identify the "front." It follows that, if Tameika and her partners were unclear about which part of their boat was the front, they would be unable to draw it.

The connection between their sketches and their initial physical model is easy to see. Even though some of the small details have changed, the overall structure of the boat is clear. In this case, it seems that the sketches have provided a useful guide for construction. Even if the planner itself was not heavily used during the Building Day, the conversations and decisions around the planner seem to have provided Tameika with a clear enough mental model that she knew exactly what to build.

The connection between Tameika's initial boat and the sketches from her data collection packet is even more clear. Everything from the shape of the sail to the shape of the hulls is easier to see. Also, our discussion about which end of the boat was the front has had an impact on Tameika's ability to draw a front view. Interestingly enough, the sail is missing from the top view in both drawings: it is tough to translate something thin like a sail into a line when viewed from above. In Tameika's case, drawing both before construction and after construction seems to have provided benefits.

The results for Sarafina are a bit more muddled (Figure 3.12). In her initial side view, she is clearly imagining the Hokule'a. Rather than a model, she has drawn something that looks like it would illustrate a story. From the perspective of CHAT, her drawing provides an example of a mismatch between the goal of the activity and the outcome. The goal was to support students in deciding on the materials and dimensions for their soon-to-be-constructed canoe models. However, Sarafina was always more clearly interested in the human aspect of the canoes. She has decided to respond to the human problems of living on a canoe for an extended period of time. The storyline that animated the entire unit was compelling for Sarafina. Nearly all of her questions and comments during the Planning Day revolved around the needs of the humans. She was consistently focused on people who sailed on the canoe, not on structure of the canoe itself – except for amenities like sleeping compartments and showers that would make the journey more comfortable for the sailors.

At first glance, the other two pictures that Sarafina drew during the Planning Day seem to be more aligned with the goal of the activity. However, Sarafina may have included these out of a sense of obligation, rather than the passion that guided her side-view drawing. At the end of the Planning Day, Andrew had left his planner with the students. He had sketched his own version of a top view and a front view (Figure 3.13). All three members of the group ended up copying his drawings. On one level, following Andrew's example was an opportunity for the students to practice multiple views. But, it also means that those drawings do not represent Sarafina's own skills.



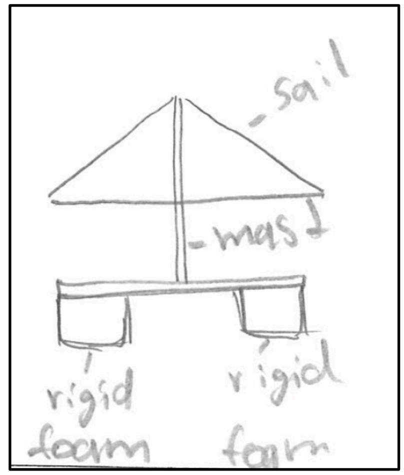


Figure 3.13: Top view and front view sketches by mentor Andrew that Sarafina used in preparing her own sketches (Figure 3.12).

It is also difficult to draw conclusions about the drawing that Sarafina at the beginning of her data collection packet. The two hulls are there, as are the two sails with their varying heights, but the drawings have been completed hastily and they are not labeled. That is why the final page of Sarafina's data collection packet is something of a revelation (Figure 3.14). Perhaps because she felt success at the lab, or because she was in more of a mood to draw, Sarafina's final set of drawings are a leap in quality from anything she completed previously for the project. Changed components, like the lowered sail and the triple rudder, are clearly visible. She has successfully represented all three views. Most impressive of all, she has picked up a "commonly accepted convention" of technical drawing; in one of his sketches, Andrew had labeled the bottom of the mast with an "A" and wrote a corresponding "A" for the spot on the deck where the mast would connect. Sarafina had mistaken the letter for a drawing, and had asked Andrew why he had put a small human on the deck. Andrew had explained the convention to her, and pointed out that it allowed him to draw a part in more detail elsewhere on the page. Sarafina was evidently paying attention, as she adopted this convention for her top view.

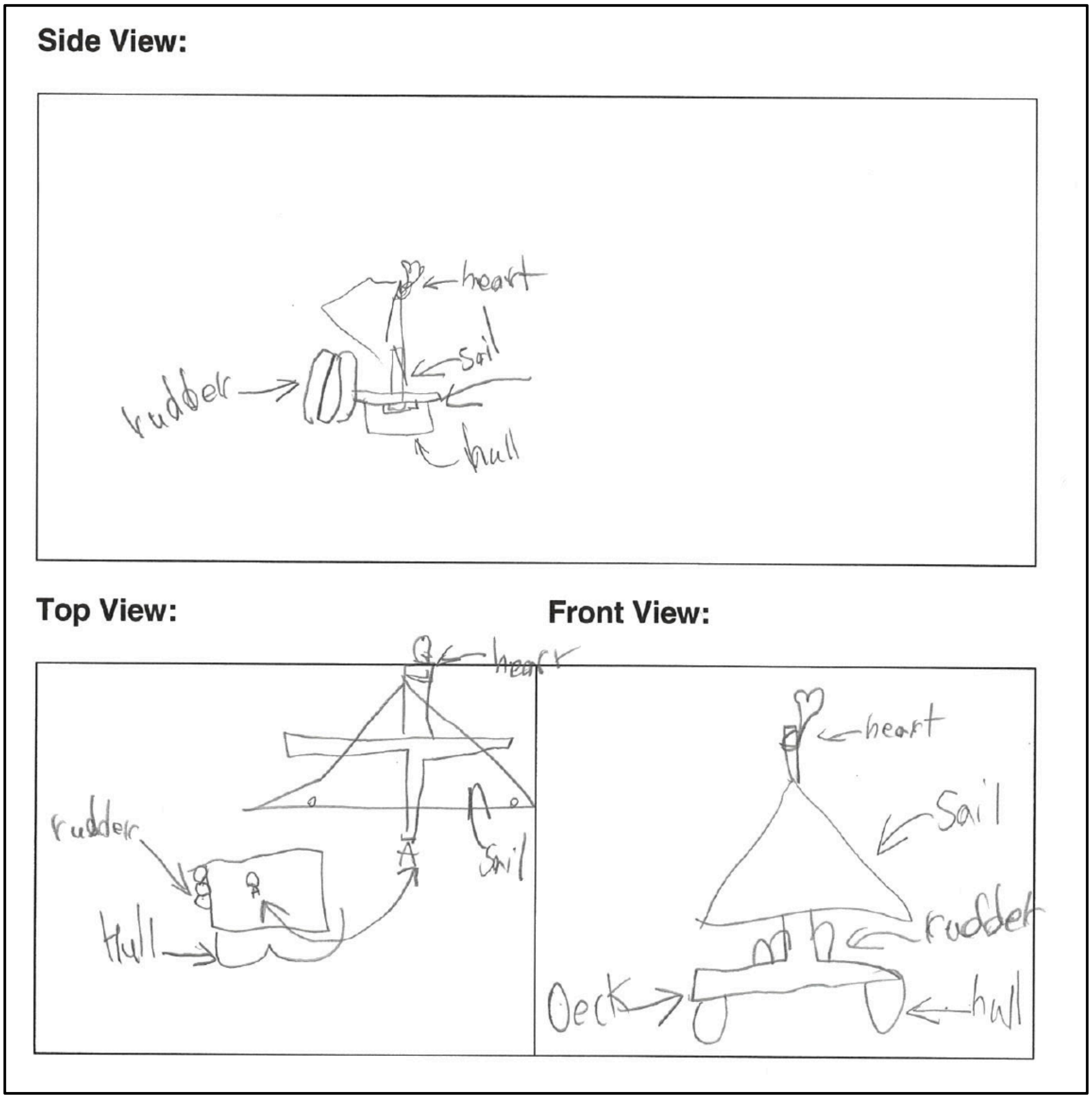


Figure 3.14: Sarafina's sketches of her group's final design.

Information Gathering

According to the *Framework, information gathering* is “collecting, evaluating, and synthesizing data and knowledge from a variety of sources to inform their design process” (p. 31). For the canoe project, the engineering task was the culmination of the entire Wayfinding Unit. For five weeks, the students were immersed in the story of the Polynesian Voyaging Society and their flagship canoe, the Hokule’a. Students had read a wide array of texts and watched a number of videos, so even if we didn't discuss all of the relevant physics, they had been observing and discussing long-distance voyaging canoes for weeks before they tried their hand at building one.

This resulted in an unexpected clash of background knowledge. When I first developed the Wayfinding Unit, I was concerned that the students would be heavily influenced by the animated Disney film *Moana*, which also focuses on Polynesian wayfinding. This was not the case. Even with a student like Sarafina, who told Andrew that she had watched *Moana* "more than 300 times," the film was rarely discussed in class. But, the university mentors assumed that *Moana* was the primary influence on the students.

This resulted in an ongoing series of conversations between humanity and efficiency, with students and mentors having different outcomes in mind for the canoe. More than one mentor expressed confusion as to why students wanted to include safety railings, sleeping quarters, and wide decks for storage. As one mentor shared via the feedback survey:

> I thought it was interesting that when my students were talking about the dimensions of the deck, they were much more interested in the amount of cargo they could carry and how easy it would be for them to get around the deck rather than thinking about how the size would affect the boat's ability to sail.

Some of the mentors assumed that this was childish thinking related to *Moana*, when it was really the students drawing on their knowledge of the Polynesian Voyaging Society and the needs of the Hokule'a crew. Indeed, the students had several lessons dedicated to planning for the voyage, including learning about provisions and how they would be stored on the canoe. Therefore, students like Sarafina may have felt that their concerns for the sailors were not being heard, while the engineering students were focused on creating the fastest design.

Take this conversation between Andrew and Sarafina as an example:

Sarafina: I had an idea. To keep people safe, we could put a tarp under the sail, under here. To protect people from rain and their clothes and stuff. and with a little window.

Andrew: I don't think we'll be getting any rain in the wind tank.

Sarafina: I'm pretending.

Andrew: You would have the tarp on deck, just over everything?

Sarafina: Not over everything, over the sleeping chambers.

Andrew: The sleeping chambers? Where are the sleeping chambers going to be?

As Andrew shared in his feedback, "Their imagination, while helpful in bringing ideas to the table, limited their ability to actually design the boat. They focused on things that didn't really matter for the project (e.g. sleeping arrangements and protection from rain) but they had fun with it and that matters too." The students were grabbed by the human element, which animated and motivated the project. To the kids, this was an epic adventure, whether they were thinking of the fictional story of *Moana* and/or the very real accomplishments of the Polynesian Voyaging Society. To the university students, this imagination was more something to be humored, but that "didn't really matter for the project."

Andrew recognized that students were thinking about their prior learning. Later in his feedback, he wrote:

> I think that some of the things they talked about in class before they designed the boats definitely influenced their designs. I'm not sure that they realized where the testing would actually take place and what the wind tank looks like. Showing them what their boat would be doing might help.

I am glad to know the project-based context so clearly animated what could have been a mundane taping-together of plastic bottles and transformed the activity into something alive and human. I am sorry that I did not do a better job of informing the university volunteers about what the students had been studying prior to their visit. Andrew's suggestion warrants consideration: I had intentionally withheld images of the lab from the students to maintain an element of surprise, but perhaps a sketch of the testing tank and procedure prior to the Planning Day would have helped students with their design choices.

Ideation

As defined in the *Framework, ideation* means "generating multiple innovative ideas through both divergent- and convergent- thinking processes while communicating and recording ideas in two- and three-dimensional sketches using visual spatial techniques" (p. 31). As discussed above, students created a number of sketches in their design planners and data collection packets. Because Polynesian canoes were made out of natural materials, no one knows exactly what they looked like. The Hokule'a itself is a best guess. The design planner contained a number of imagined sketches and a pair of diagrams. I did not see the students refer to those images at all, nor did Arif or Andrew cue their groups to look at them.

Instead, both mentors made extensive use of a pair of models that were fabricated by the staff at the Marine Hydrodynamics Lab (Figure 3.15). Arif was particularly good at highlighting the analogous components between the Lab-built models and the students' project: "So, this is a design just for you guys to look at to keep in mind. So the hulls that we picked up, that's like the foam that you chose. Now we're looking at the deck, which is here. So, what size do you want to make your deck? That's the material we're going to use for the deck."

Figure 3.15: Two models fabricated by staff at the Marine Hydrodynamics Lab.

As "cool" as the Lab-built boats were, I was hesitant to let the students see them. I was worried about design fixation (Bartholomew & Ruesch, 2018; Luo, 2015): how can you provide an example without stymying creativity? This revealed itself with both Tameika and Sarafina. As the Building Day was wrapping up, a number of the volunteers commented to Arif about the quality of his team's boat. Andrew even declared that it was "the" boat. Arif explained to Andrew, "They really heavily used the example as a resource" [i.e., the Lab-built model]. Looking at the image of the boat with the blue decoration on the sail, the influence on the canoe that Tameika and her group constructed is clear.

Sarafina saw the Lab-built models as a way to build the "right" canoe (Figure 3.16):

Sarafina: Can we make something like this? Can we keep it and copy it or something?

Andrew: No (with a laugh)

Sarafina: Why not?

Andrew: Because you have your own design.

Sarafina: Not like *copy it* copy it… we can add our own little stuff to it, we can copy this part (pointing at the hulls).

Andrew points out that they don't have any drills or screws or metal.

Sarafina: We're going to do it our way, but copy this.

Figure 3.16: Sarafina suggesting that they "copy" the Lab-built model.

It would have been interesting to see if the students had only used photos and videos for reference. That would have kept the design process in a purely conceptual space until the students themselves constructed their models. In the end, the presence of the Lab-built models did not influence the designs all that much: Tameika's group seemed to be the most heavily inspired, with a great diversity of designs among the remaining groups.

Prototyping

At its heart, the canoe project was a *prototyping* task: selecting materials and tools to build an initial prototype that could be tested and improved. Because the prototyping process was so key, I will have Tameika explain her group's process in her own words:

> OK, so, when I was planning it, we had some difficulties because everybody wasn't on the same page. And then, Arif, he helped us and he was like… I said we should use rubber cement, and he brung it to my attention that if we did that, it would be hard to,

> like, redo it… like, to take parts off of it. So, then, we went with tape, because tape is easier to get off. We went with the pool noodles because they were light. Our deck was thick with two bases, kind of… Our mast was one of the longer wooden ones, instead of the short ones (gesturing) because we wanted a long vessel to catch… if it was short, we thought it wouldn't catch as much air, so we made it tall. But our steering paddle was in the wrong way, it was like this (gesture) instead of straight. So we had to turn it straight, so it wouldn't stay up against the wall (gesture), like this against the wall. And it took a long time, so we turned the steering paddle a different way. We didn't have one of those things at the bottom. (t-shape gesture [rudder]). The steering paddle was made out of chopsticks, the boom was made out of those little wooden ones. The sail: tarp. Aaand… that's it.

One of the bottlenecks in engineering with young students is their unfamiliarity with materials. This was the most frequent comment reported in the mentor surveys: "Students did not have a clear grasp of how adhesives worked. I wonder if there might be a benefit to having a day where students could try out the different adhesives with the different materials before planning?," Reported another: "I think one thing that was challenging was the kids not really understanding how to use the materials. Glue seemed like a foreign concept. The kids were also mesmerized by the drill. Exposure to these materials earlier on is awesome but it was hard to teach them how everything connects together."

As researchers like Cunningham (2018) and Smith and Smith (2016) have encouraged, it is essential to provide students with opportunities to interact with materials, to learn their properties and limitations. During both years of the project, I was struck by how many fifth graders had never used rubber cement. Seeing the name on the bottle, they all thought that it would dry like cement. Adhesives in general were unfamiliar to the students, and they rarely took into consideration the time it takes glue to cure. As highlighted in Tameika's retelling, many mentors had to convince students to use tape rather than glue. Letting students get hands-on with the materials was beneficial. As another mentor reported, "The kids learned best when the material was right in front of them. Having them go up to the tables and grab the material to show me their designs allowed them to clarify what they meant." This repeated exposure to materials in the real world is the only way they can develop an intuitive grasp of their different properties. That is part of why it was so important that Tameika's group visited the materials tables so often, and why it was concerning when Sarafina's group did not (Figure 3.17).

Figure 3.17: Tameika and her group on one of their repeated visits to the materials tables (left); Sarafina explaining a potential material using a photo from her design planner (right).

Repeated exposure is also necessary to practice how to manipulate materials. For example, Arif had to demonstrate some "obvious" techniques, like using the edge of a sheet as one side of a shape rather than cutting the entire shape from the center, or tracing an item that you want to duplicate rather than re-measuring it. Both Andrew and Arif had to help their group members with the use of rulers. Watching a fifth grader struggle with a ruler or with glue is a statement on how infrequently students are provided with opportunities to practice these "basic" skills.

Decision-Making

The *Framework* specifies that *decision-making* means "informed (data/evidence/logic-driven) choices" (p. 31) made collaboratively. As discussed earlier, the design planner was developed to help guide these types of conversations. In Tameika's group, Arif frequently asked the group to provide their reasoning according to the prompts included in the planner. Even after a decision was made, he would often verify their choice. Also, when presenting options or advice, Arif often explicitly provided the reasoning or the next logical step. For instance, "You guys have your hull (points to the two pieces). So, what you want to do, probably next, is get the deck cut out, *since you're going to attach your mast to the deck*." Instead of issuing an order, like "Next, cut out the deck," he provides a suggestion accompanied by *why*: "since you're going to attach your mast to the deck."

As another example, when Mark was cutting the sail, "I'd say try to measure from here, so you're not measuring from the middle. *That way you're maximizing the amount of deck and you're not wasting*." He did not issue commands, but rather provided suggestions that students could weigh to see their logic. It is much easier to agree with a suggestion when it is backed up by reasoning. Also, he helped to model the sort of logical, step-by-step thinking necessary for an engineering task: start at the bottom and work your way up, rather than building whatever, whenever.

That being said, Tameika and her group rarely reached consensus before they moved on to the next component of the canoe. In response to the prompts, Tameika, Mark, and Brianna all contributed ideas. However, their answers were often directed at Arif, rather than at one another. Tameika and Mark were typically in closer agreement, with Brianna in dissent. For the very first choice, regarding the material for the hull, Brianna held her ground regarding her choice. She even called for a vote, raising her own hand for her selection. Mark then had the rest of the group vote, and Brianna was overruled. From that point forward, Brianna contributed a little less to the discussion about each subsequent component. By the end of the Planning Day, she was saying very little. So, while the group appeared to be in agreement, much of this had to do with Brianna abstaining from the process. We will discuss this dynamic, and the complications for reaching consensus, later in the section on collaboration.

Along with the challenges of reaching consensus while planning, a missed opportunity was the use of the data collection packets to inform revisions when the students were testing in the lab (Appendix G). I was hoping that the groups would run two trials with each iteration of their model. I was hoping that they would return to the "revise and rethink" room, note their times, write down observations about what worked, and note their changes. I also informed the marine engineering volunteers about the intended process and what students were recording. Unfortunately, by the time Tameika and Sarafina's groups started testing, many of the volunteers had to leave for other obligations. Tameika's group only made one change, so their data would not have looked very different. But Sarafina's group made five trips. Molly recorded some of the data, but the students kept most of it in their heads. Finding a way to have students keep more accurate records is necessary to support them to make truly data-driven decisions.

Design Communication

As the final sub-component of Engineering Design, the *Framework* calls for the sharing of information throughout and at the end of a project through a variety of verbal and visual means. Because of time constraints, the groups did not prepare formal presentations. Instead, each group stood at the front of the room with their improved canoe, told the story of their initial ideas and revisions, then took questions from the audience. Each group summarized and articulated the journeys of their particular models. The students asked excellent questions, mostly focused on materials decisions, why they had included (or omitted) certain components, things they would still like to improve. A future iteration of the Wayfinding Unit could certainly include a more formal data presentation.

Engineering Habit of Mind: Collaboration

For the final part of the findings, we turn our attention from the Engineering Practice of Engineering Design to the Engineering Habit of Mind of Collaboration. Of course, this habit of mind overlaps with decision-making, design communication, and many of the other sub-components already discussed. However, because peer and mentor interactions were so essential to the canoe project, I have a selected two moments, one positive and one more cautionary, that I would like to address here.

On the positive side of collaboration, working with the university mentors made this entire project possible. Logistically, one or two teachers would not have been able to manage that many kids and materials on such a tight timeline. Over and above that practical consideration, it made a huge difference that the volunteers were specifically from the marine engineering department. They were familiar with the terms, and they introduced new vocabulary to the students. They described complex physics in easy-to-understand ways. This often took the form of spontaneous "tests," such as Andrew's demonstration of why a mast is attached to the length of a sail (Figure 3.18), Spencer's demonstration of why a low sail is more stable than a tall one (Figure 3.19), and Andrew's illustration of why boats typically have the same components on each side (Figure 3.20).

Figure 3.18: Andrew asking Molly to blow on a sail to demonstrate why a mast is attached along its entire length.

Figure 3.19: Spencer pushing at the top and the bottom of a sail to demonstrate why a low sail is more stable than a tall one.

Figure 3.20: Andrew using a bottle and a dowel as a "seesaw" to demonstrate why boats typically have the same components on each side.

Although the collaboration with the university mentors was a success, Engineering Design possesses a certain tension when it comes to collaboration among peers. As Wright (2020) has highlighted, in regards to the engineering components of the NGSS, there is a disconnect between a message of sharing and respecting all ideas, but then charging students to eliminate other ideas to converge on a single decision. To illustrate this tension, I offer a simmering disagreement that arose between Tameika and Brianna early in the project and carried through to the end. As I established earlier, Tameika had definite ideas. So did Brianna, but Tameika had Mark to back her up.

At the very beginning of the Planning Day, the group could not agree on a material for their hull. Tameika and Mark were in agreement, but Brianna wanted a different type of foam. She tried to take a vote, raised her own hand, and laughed. She was then outvoted by her teammates. Arif tried to mediate: “Are you OK with using the pipe foam if the rest of the team wants to?” Brianna said yes, but she was clearly annoyed by the situation. She disengaged from the rest of the Planning Day, and fooled around so much during the Building Day that Tameika had to reprimand her repeatedly. During the Testing Day, over a week later, Tameika and Brianna were sitting together. Out of nowhere, Brianna brought up the disagreement:

Brianna: That means half of this… half of this wouldn’t be done, because I know I didn’t agree to half of it.

Tameika: Yes. You did.

Brianna: No, I got forced into it.

Tameika: No, you didn’t. Arif was like “Do you agree to this?” and you were like “Oh, yeah!”

Brianna: I said no. No.

Tameika: You was like "No" and then he was like "Are you guys sure you want it?" and then you was like "Yeah." So, you agreed. Period.

Brianna: No, I didn't. I said no the whole time…

Tameika: Stop lying.

Brianna: …and you guys were like "Are you willing?" and I was like "Yeah," but that doesn't mean I want to!

Mark: C'mon!

Tameika: OK, well you said "yeah" because you wanted to co.op.er.ate.

As suddenly as it had started, the conversation abruptly ended. Brianna was still obviously hurt that her voice was not heard. Something as "fair" as voting still comes with power dynamics. As educators, we need to be cautious and compassionate about such situations and the undercurrents of frustration or anger that students feel after being placed into certain "collaborative" situations (Webb et al., 2009).

The same argument came up again in my end of unit interviews with both Tameika and Brianna. Tameika let me know that Arif was good at helping the group to compromise when they were disagreeing. Brianna said something similar, and it seemed to be a settled matter:

> The canoe project? I think that was my favorite activity out of all of them because I like building stuff, I basically like arts and crafts. Basically. That makes it easier for me to do. And I just like the part where we builded it. The time when we were trying to get everything together was kind of difficult 'cause people wanted different things. But, instead, we just voted and we actually got the boat that we made. I like when we had mentors to help us because, if we had did it by ourself, we would have sat there the whole time arguing over which one.

Brianna's initial enthusiasm for the project cooled as soon as she was outvoted by her peers. A similar pattern played out with Sarafina, who started the Planning Day as the most enthusiastic member of her group, and ended up being sidelined for most of it. Upon reflection, the design planner guided the mentors to query the students for the reasoning behind their decisions. In this regard, the planner, when used by a mentor like Arif, seemed to fulfill its goal. However, the design planner provided less structure in supporting the group to reach *consensus*. That is, the students voiced their reasons behind their choices, but they often acted as if Arif was their audience rather than the other members of their group. Because of this, their ideas were presented sequentially, rather than in interplay with the other ideas already voiced. Decisions about any given component seemed to proceed when "general consensus" was reached (i.e., no member of the group continuing to voice a disagreement) rather than a true consensus that the choice under consideration was the one most likely to meet a given criteria for success.

In that respect, I placed the mentors in a difficult position. On one hand, they likely knew that best practice in engineering is to reach consensus. On the other hand, I had very little time for orientation, they had little time to get to know their students, and the entire process was under a very tight timeline. Within these limitations, the mentors did the best they could to negotiate disagreements and to move the projects forward. To reduce the number of competing ideas, rather than groups of three, I wondered if it would have been better to have had each mentor supervise two sets of pairs. I also wondered about other ways that roles could be more specifically assigned to prevent students from being excluded from a project that was supposed to be a highlight of their Grade 5 experience.

Implications

Overall, the two supports I explored in the Wayfinding Unit - the use of a design planner and collaborating with university engineering students - both showed great promise in supporting students logistically and conceptually as they engaged in engineering design. In particular, the design planner served to off-load certain aspects of the practice that may still be too difficult for elementary-age students to navigate on their own.

One of the major implications of this study is the need to change the “drawing diet” of elementary school children. Young students need to be introduced to drawing as a technical tool, not only as a form of decoration. This also means that drawing needs to be taught regularly. Ms. Davis informed me that, due to persistent shortages of substitutes, the visual arts teacher at Pine Elementary is often pulled to cover classes. When that happens, the students miss their visual arts class for that week. Pine Elementary is lucky to have a visual arts teacher; budget cuts have eliminated those positions in many schools. Also, while the visual arts teacher can provide instruction in techniques like vanishing point perspective, the classroom teacher is also able to introduce students to genres of technical drawing, and to provide opportunities for students to practice.

Another major implication of this study is the power of project-based learning to bring lessons to life. After spending five weeks learning about life on a long-distance voyaging canoe, the canoe project was no longer only about engineering. It was about people too. That is as it should be. Engineering is the human-built world. Design tasks are intended to solve problems for people, and those potential solutions have consequences. In the case of the Wayfinding Unit, using the frame of project-based learning kept the work grounded in the lives of people. If that means some level of peak efficiency has to be sacrificed to accommodate the needs of people, that is an essential engineering lesson to learn as well.

A student-centered task like the canoe project also provided opportunities for Tameika and Sarafina. Tameika was positioned as the leader of her group, placing her in a role with responsibility. Although Sarafina was somewhat sidelined in her group, it is unclear how much of this was her own choosing. She still asked many questions, and she was excited to visit the Marine Hydrodynamics Lab. Hopefully, both girls will remember this project as an exciting and unusual capstone to their elementary school experience, especially since the last portion of their fifth grade year was interrupted by the pandemic.

Finally, including the university students has implications for their own professional lives. Most of the volunteers were undergraduates, who likely do not see themselves as experts. However, in this project, their knowledge was highly valued. One of the mentors told me about his surprise when sharing his work with the students. To him, it was just a bunch of homework assignments. To the fifth graders, it was a glimpse into a different world.

Another volunteer shared with me that he had attended a summer camp after he himself was in fifth grade. During that camp, they had built handmade boats similar to the canoe project. He had enjoyed it so much, he had decided to major in marine engineering. Although I don’t expect all of the students in this class to apply to university engineering programs, his story reminds us of the long-range, and often unexpected, outcomes of our educational interventions. I hope that Tameika, Sarafina, or one of their classmates found some form of inspiration in the canoe project. Who know? Maybe one day one of them will sail around the world.

Conclusion

This study adds to the emergent body of literature about engineering design with students at the elementary level. It hints at the promise of using written scaffolds, like design planners and data collection tools, to assist students with developing engineering practices. The study also highlights the affordances of recruiting university engineering students to assist with an engineering design task in a classroom setting. The type of project-based task described in this paper does not have to be reserved for out-of-school experiences.

As a main takeaway, this study highlights the ongoing and self-reflective work necessary to ensure that we hear the voices of all students in our classroom. Whether that is through an increase in the amount of pair/group work, bringing in outside mentors, providing engaging and student-centered tasks, or combinations thereof, we need to work diligently and thoughtfully to ensure equity in our classrooms.

Another main takeaway is the utility of the *Framework for P-12 Engineering Learning.* With its greater detail, the *Framework* provides a much needed lens to consider how engineering education is enacted in schools. As the *Framework* begins to be adopted, I have three hopes. One, I hope that the materials developed for the elementary level are developmentally appropriate for young children. The work described in this paper may provide some examples as to what that may look like. Second, I hope that the developers of the *Framework* find areas of overlap at the elementary level with the NGSS and standards for English language arts, mathematics, and social studies. Finding ways to reduce the overall number of standards that elementary teachers need to juggle will increase the likelihood that the *Framework* will be viewed as a useful tool rather than a burden. Finally, I hope that the *Framework* does not become a checklist. Like with the Wayfinding Unit, I hope that future curriculum designers remember to lead with intriguing phenomena and meaningful activities.

Overall, the findings of this study provide a “preview” of a project-based engineering experience for elementary students that leverages written supports and collaboration with peers and mentors to engage in a meaningful engineering design experience.

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Chapter 4: Conclusion

I present this final chapter in two parts. In the first part, I review findings from the two studies. In the second part, I look across the dissertation to highlight common themes, suggest considerations for pedagogy and curriculum design, and indicate areas for future research. By doing so, I hope to inspire the creation of learning experiences for elementary students that are engaging, empowering, and educative.

Modeling as a Literacy Practice and a Science Practice

Chapter 2 explored a pair of research questions: (1) What do fifth-grade students communicate through models within a project-based integrated literacy and science unit? and (2) What are ways in which peer feedback influences fifth graders to revise models? Through a conceptual analysis (Steffe & Ulrich, 2020; von Glaserfeld, 1995) of student artifacts, classroom videos and field notes, and student interviews, I constructed explanations of students' sense-making, and changes in their thinking, while engaged in the practice of modeling and peer review. My goal was to share the dynamic, personal experiences of students in one fifth-grade classroom as they investigated the phenomenon of collecting freshwater from saltwater in solar stills.

For RQ1, regarding the development of their initial drawn models, students created models that indicated emergent conceptual understandings of the phenomenon. Nearly all of the students represented the key components of the investigation set-up and at least some invisible elements (e.g., heat, evaporation, etc.). A few students indicated relationships among the components and invisible elements within the drawn portion of their models, but more often, these relationships were included in a prose description. The use of visuals and text in concert supports the notion of modeling as an act of multimodal composition (Kress, 2010), and that students play roles as *writer-designers* when engaging in the practice of modeling.

Students addressed three features of the solar stills when making decisions as writer-designers: (1) spatial, (2) temporal, and (3) conceptual. As novice writer-designers, the students wanted to draw realistic representations of the solar still. They made decisions about perspective and with the allocation of space on the page. Some students recognized that they could more accurately represent the phenomenon by using multiple views (e.g., a top view and a side view). Students also had to represent a time-dependent process in a static drawing. The majority of students only included a single moment depicting a nonspecific time while the phenomenon was in-progress. Similar to the usage of multiple views, a few students depicted the solar still at two different points in time. In addition to the practical task of representing a 3-D, dynamic phenomenon using paper-and-pencil, the students also had the conceptual task of communicating their understanding of what was actually occurring inside the solar still. Students included invisible elements, like heat and evaporation, but it was uncommon to find visual depictions of the direction, amount, or relationship among the components and invisible elements. Students were more successful at describing these variables and their relationships through prose.

For RQ2, regarding the use of peer feedback, student sense-making and the accuracy of their models benefitted from one-on-one consultations supported by a “3C” protocol (i.e., compliments, constructive suggestions, and clarifying questions). In general, students provided suggestions about the same aspects of their peer’s models that I would have. Typically, these involved comments about compositional choices and/or missing components. The one-on-one setting provided each student with an authentic audience for their work (Schwarz et al, 2009), and the reviewer could not rely on someone else to "do the work," as sometimes happens when feedback is provided in small groups. Importantly, students were empowered to improve their own models, rather than converge on a single "consensus" model, allowing for multiple, equally valid representations. In some cases, students received no actionable items during the feedback session; a situation that seemed to arise when the gap in conceptual understanding or the metamodeling knowledge (Schwarz & White, 2005) between the peers in the dyad was exceptionally close or exceptionally wide. That being said, in general, the process of one-on-one feedback, supported by the 3C protocol, supported students to improve their models.

In summary, findings from this study add to the growing body of literature about the possibilities of elementary-age students engaging in the practice of modeling. In particular, additional instruction in genres and techniques of technical drawing, as well as providing regular and systematic opportunities to develop models, would likely support students to address the immediate decisions faced by a writer-designer. Furthermore, receiving feedback in pairs, using a consistent feedback protocol, shows promise for supporting students to improve their models.

Designing Models of Long-Distance Voyaging Canoes

In Study 1, I looked at how students observed a *physical microcosm* (Lehrer & Shauble, 2012) and transformed it into a drawn/written model. In Study 2, I examined the inverse: observing students' drawn/written plans and how those plans manifested as physical models. Because Studies 1 and 2 are connected, I asked a related pair of questions: (1) How do the features of an iteratively designed engineering project provide opportunities for enacting the practice of engineering design in an elementary school classroom? (2) How do the features of an iteratively designed engineering project provide opportunities for collaboration, with peers and university mentors, in an elementary school classroom? Through a careful review of recordings from multiple cameras, supplemented with student artifacts, interviews, and surveys, I presented the enactment of a project to plan, build, and test physical models of long-distance voyaging canoes by focusing on the stories of two Black girls, Tameika and Sarafina, along with their teammates and university mentors. By doing so, I intended to illustrate specific aspects of the *Framework for P-12 Engineering Learning* (AE3/ASEE, 2020) – namely, the Engineering Practice of *Engineering Design* and the Engineering Habit of Mind of *Collaboration* – in action at the elementary level.

For RQ1, regarding the features of the project that provided opportunities for the practice of engineering design, I found that the use of a design planner with embedded guiding questions supported students with many of the sub-components outlined in the *Framework*. When combined with a clearly-defined schedule, the design planner "off-loaded" tasks like *project management* and *design methods*, providing students with exposure to these concepts while relieving them of the responsibility of managing such meta-considerations on their own. In turn, this provided students with more time to focus on the problem at hand, which was to construct their canoe models. Similar to the modeling study, I found that students struggled with representing their ideas using multiple views. This challenge was partly relieved by asking students to draw sketches of their physical models after they were constructed. The design planner also focused student attention on the properties of materials. Consistent with findings reported by other scholars (e.g., Anning, 1997; Cunningham, 2018), students were limited in their understanding of the affordances and limitations of various materials, particularly adhesives. The embedded questions in the design planner cued students to discuss and provide reasoning for their decisions about materials for a constrained and manageable set of components for their models.

For RQ2, regarding collaboration, students worked in groups with two other peers and a mentor from a university marine engineering program. In addition to the support that the design planner provided to the students, the design planners supported mentors with criteria and constraints, as well as suggesting questions to elicit student decision-making and reasoning. Working with university mentors allowed many more students to receive focused attention from adults who had specific engineering knowledge for the problem under consideration. This disciplinary knowledge often manifested in the use of technical vocabulary, as well as spontaneous demonstrations of relevant physics principles. While working with the university mentors was clearly a success, the benefits of working in peer groups were more mixed. Although the students were working in relatively small groups, only three students per team rather than the 4-6 common in school contexts, one student in each trio was consistently excluded from being directly involved in the work. The participation of mentors was key in mediating disputes between team members and doing their best to include all students in the process. Future iterations of this project may benefit from including defined roles for group members to support equitable participation.

In summary, the findings from this study provide needed examples of what engineering design and collaboration look like at the elementary level. More specifically, the use of written design planners and the participation of university mentors from the specific engineering field addressed in the project combined to support students in successfully constructing canoe models and in deepening their conceptual understandings of the physics concepts related to sailing. In addition to findings about the project itself, this study hints at promising methodological techniques, involving the deployment of multiple cameras and audio recorders, for collecting nuanced data about a large number of participants working in very active spaces with significant levels of background noise.

Looking Across the Papers and to the Future

This work illuminates a selection of issues that have animated my life as an educator: from my experiences as a classroom teacher to my doctoral coursework and research assignments to my concerns as a curriculum designer and learning scientist. To conclude this dissertation, I discuss themes that run from my prior professional life through my doctoral work and this dissertation with connections to destinations in the future.

The Meaning of "Meaningful"

As an educator and curriculum designer dedicated to project-based learning, I often make reference to "meaningful" learning. As I conducted the various literature searches for these papers, I found other scholars invoking "meaningful" experiences as well. But, the more I read, the more I realized that we were not using the term in the same way. This realization came into sharp focus as I read a piece by Berland and colleagues (2016) titled "Epistemologies in Practice: Making Scientific Practices Meaningful for Students." Since the article serves as a capstone for the MoDeLS project that figures heavily in Chapter 2, and because both of my papers are focused on students' learning practices, I had high hopes that reading the piece would dovetail with my work and the findings of my study.

However, as I read the piece, I was crestfallen. The article describes a continuum of "meaningful" scientific practices. One end includes activities "meaningful" to the scientific community: generating models to explain how and why the natural world works. The other end of the continuum includes activities "meaningful" to the classroom community: enabling students to explain why they are engaged in a particular practice and how that practice contributes to sense-making. The authors are explicit that "meaningful" does not mean that "all students find the same knowledge construction goal compelling at all times" (Berland et al., 2016, p. 1087). As I finished that sentence, I realized we were speaking a different language.

Of course, as a researcher, I value the construction of new knowledge, and as an educator, I hope that my students, at all times, can explain why they are doing what they have been asked to do. But, why *shouldn't* students find their learning pursuits compelling at all times? For an article written in this decade, discussing current concerns with epistemologies and their connection to practices, a statement such as that, made by esteemed researchers, sends a message of "take your medicine because it is good for you." With apologies to the researchers, it feels like a lack of imagination.

Now, I am not arguing that learning should always be fun and games, and that some students will not become bored. I would agree with Berland et al. that it is impossible to guarantee that all learners will find all lessons compelling all of the time. But, I push back on the limitations of their continuum and I ask a *why* that is one level higher. I turn to the solar still investigation to explain what I mean. Yes, I hoped the students would develop models that explained the phenomenon of collecting freshwater from saltwater. Yes, I hoped the students would be able to explain why a model is a useful tool for predicting the rate with which freshwater would collect in the small bowl. But, then I ask the *why* that a 10-year-old would likely ask: when a child asks "Why are we doing this?," they are not looking for an answer that provides the epistemic considerations. They want to know the *application*.

When Berland and colleagues, and other scholars, discuss "meaningful," they are using the word in terms of "making meaning" – they are talking epistemology. That is a valid line of inquiry and I am glad for their contributions. However, when I discuss "meaningful" in my work, I mean *purpose* and *significance*. How is the activity meaningful to a student as an individual? As a community member? As a living being on this very small planet? To me, the solar still model was meaningful because it was figuring out how to source water in the middle of the ocean, a matter of life or death. Later in the unit, the students constructed a model about the life cycle of plastic, as part of a sequence of lessons on plastic pollution and recycling. That model, apart from its immediate epistemic meaning, had power because it was directly connected to a critical problem of our time. Creating the physical canoe models, while useful for learning about physics, was *meaningful* because the students associated it with trying to make it 26,000 miles around the world crammed together with a dozen people on a deck 62 feet long by 20 feet wide.

To me, “meaningful” as Berland and colleagues use it, and “meaningful” as I conceptualize it, are not mutually exclusive. Making learning meaningful is to create lessons that are engaging. Making learning meaningful is to design experiences that are memorable, not just for the academic year, but perhaps for life. Making school meaningful means thinking about how to bring practices to life. The experiences described in these two papers was my way of illustrating what “meaningful” learning can look like.

Looking to the future, I find myself wondering about pushing the envelope on research examining project-based learning. In large part because of funding structures that have prioritized large-scale randomized control trials, the existing research on project-based learning, even with the focus on *projects*, tends to report on the results of traditional pre- and post-tests. This leads to comparisons with “business as usual” classrooms, and often leads to comparisons with gains in scores on standardized tests, often to make the claim that students engaged in project-based learning can still get “good scores” on such measurements. Why take an expansive and open-ended experience and channel it through a traditional test to show effectiveness? What if research can demonstrate that a project - measured through a rubric for the final artifact, or perhaps through interviews with the students directly - can demonstrate students' proficiency with state standards as effectively as a traditional test?

Even more radically, what if we reimagine the expected outcomes of project-based learning entirely? What if we skip test scores as the measure of "success" in favor of looking at ways in which students demonstrate that the learning has been meaningful? What if we survey students about shifts in perception after engaging in a project-based learning experience: Has it changed their level of concern about a particular issue? Has it spurred them to action? Ms. Davis reported to me that recycling rates went up in her classroom after the Wayfinding Unit. Sarafina told me about throwing away her sister's toothpaste when she discovered that it contained a plastic compound. To me, those are both examples demonstrating the success of a project-based learning experience connected to critical issues with real-world impacts. What would education, and education research, look like if we started looking at outcomes like increases in compassion, engagement in the world, and activism, rather than increases in test scores?

Letting Kids Be Kids

This theme goes hand-in-hand with the concerns I have voiced above. The United States is at the beginning of its third decade of standards-based reforms. Some of those reforms have been fantastic, such as how the NGSS fostered the explicit inclusion of practices and the introduction of engineering education at the elementary school level. However, concurrent with standards-based reform has been the rise of accountability measures, typically in the form of high-stakes standardized testing. This has resulted in an unfortunate fixation on test scores and a worrisome focus on outcomes over process. It also means that students, even at the youngest grades, are forced to sit through an ever-expanding number of tests. As I questioned in the previous section, *why*?

In addition to very real concerns about the emotional toll of being tested all the time, I worry that we are asking students to be too grown-up, too soon. As I illustrated repeatedly in these papers, students are certainly capable of rigorous tasks. But, we need to let kids be kids. Turning back to the MoDeLS work (Hoyakem & Schwarz, 2015), in order to practice modeling with their solar stills, students spent up to 8 weeks focused on the same pair of models. That seems like a big ask of 10-year-olds. We need to support students where they are by capturing their interests, and honoring their attention spans. In my mind, that means shorter experiences provided more frequently, ideally coordinated with learning experiences over a number of years. And yes, I will invoke the word that appears all too infrequently in the literature: embedded within activities that are *fun*.

Similar to the ways in which funding priorities have emphasized large-scale randomized control trials, funding has also shaped studies that involve curriculum development. Even large grants typically cover only 5 years of development. Because curriculum design is time-intensive, researchers have to make tough choices about the amount of material they can deliver. Then, when the funding runs out, the work on the curriculum ends. As a result, private companies, such as *Mystery Science* or *Project Lead the Way,* end up developing and releasing full-year curricula that span multiple grades. These types of comprehensive programs are the ones that end up being widely adopted in schools, regardless of their grounding in research.

Again and again, since my days as a classroom teacher, I have wondered about the power of vertical alignment. Whether it is teachers or curriculum developers, I constantly worry that we do not foster enough conversations between grade levels to ensure cohesive and intentional experiences for students as they progress through their educational experiences. As I mentioned when discussing the solar still models, imagine the difference if the students had developed models twice per unit, four units per year, since they were in Grade 3? Furthermore, what if the modeling experiences had not been random, but they had progressed in a thoughtful way? Especially if each modeling experience was embedded in a meaningful context? Yes, this is asking a lot, but wouldn't a vertically-aligned set of interdisciplinary project-based units be a wonderful thing? I've had tantalizing glimpses during my various experiences as a curriculum designer, and at some point in my career, I'd love to see such a set of units become a reality.

Literacy for the 21st Century

As a literacy researcher, I worry about the growing gap between how literacy is taught in school and how literacy is experienced everywhere outside of school. For a number of historical and systemic reasons, schools have always changed more slowly than the rest of society. But, when it comes to literacy instruction, that lag becomes more pronounced every year. Online culture has progressed from Facebook to Instagram to Snapchat to TikTok in less than a decade. Students maintain their own YouTube channels and, especially since the pandemic, spend as much time in the worlds of Minecraft and Fortnite as they do in their neighborhood playground.

Literacy in the 21st century is increasingly multimodal. That is why the papers in this dissertation, and so much of my work, are concerned with multimodal composing. Whether it is taught in schools or not, it is increasingly how people communicate with one another. As the Wayfinding Unit demonstrates, instruction in multimodal composing does not necessarily require the use of computers. With only pencils and paper, students can gain facility with the conventions of multimodal representation.

Of course, computers do have affordances compared to paper. Now that the nation's teachers have spent a year working in digital spaces, I am curious to see if schools will be more willing to embrace digital modes after students return to in-person instruction. I would never advocate to use technology for technology's sake, but I do hope that teachers are more willing to take advantage of technological tools. For instance, for both the solar still models and the canoe project sketches, multiple students expressed dissatisfaction with their drawing skills. Of course, I am a firm believer in students having more instruction in technical drawing. But, technology offers so many intriguing alternatives. Rather than drawing the solar stills, the students could have taken a photo every day. Then, stitched together, the students would have been able to see the changes clearly. By doing so, they would be able to observe fine details that they may not have recorded if drawing. Or, as Andrew (university mentor) pointed out to his group during the canoe project:

> If it were me doing this, I would be at a computer, and I would get everything drawn in 3-D using the computer, I wouldn't do any hand drawings. But, we have a paper and a pencil, so we made do with what we have.

The findings in this canoe project paper would have looked very different if the mentors had shown the students how to model ships using *TinkerCAD*. Some programs, like those used to create computer-generated imagery in films, animate items according to the rules of physics. That being said, I would caution that any use of technology highlights the human aspects of why we use technological tools, rather than replacing interpersonal relationships.

During my days as a classroom teacher, I tried to alternate between physical and digital projects: an in-person speech followed by creating a virtual museum, building a bat house followed by a team debate, composing an e-book followed by performing poetry and dance on-stage. This same thinking influenced the pair of projects for the Wayfinding Unit: constructing canoe models followed by recording videos. I am consistently curious about the trade-offs between modalities. Does modeling a solar still using *Collabrify Flipbook* or an annotated set of digital photos, lead to different conceptual understandings about the phenomenon? In what ways do digital models influence the development of metamodeling knowledge? Something that I have observed anecdotally, and wonder about studying more formally, is if students working digitally are more amendable to making revisions, particularly repeated revisions, of a digital artifact compared to an item composed with pencil and paper.

Working Together

In Study 1, I described the affordances of peer feedback when modeling. In Study 2, I discussed how student groups worked together, under the guidance of a mentor, to construct their canoe models. In both of these cases, the motivation for having students work together was grounded in the task at hand. I often worry that "group work" in elementary schools is used for convenience, or because of resource limitations. I would ask educators and curriculum designers to consider roles when suggesting that students work with one another. For example, when modeling the solar stills, working in pairs was a way to guarantee each student an audience and to receive feedback. For the canoe project, students were assigned to groups of three. Over the years, trios have worked well for me in science and engineering activities because it usually means one student is holding/dropping/pushing, one student is measuring, and one student is recording the data. Trios did not work as well with the canoe project, and I would like to think more carefully about what role each student could play in the triad.

I would also like to advocate for increasing involvement of members of the local community with expertise in the specific topic being investigated. In the case of the canoe project, it was university students majoring in marine engineering. In my former classroom, and in my other work, I have successfully leveraged members of the community with experience in carpentry to help build bat houses and bee houses, STEM educators in Hawaii to provide feedback on environmental videos, and an astronomer to instruct students in how to view the convergence of Jupiter and Saturn. While any volunteers from the community can potentially contribute to classrooms, students particularly benefit when experienced others bring specific disciplinary knowledge related to the task at hand or the topic being explored.

Parallel to my dissertation studies, I have done quite a bit of work on the affordances of introducing experienced others into classroom spaces, both in-person and virtually. I have many questions related to this area. What are the contexts and conditions fostered by an educator that support productive roles for the experienced other in the classroom and how do these differ across grade levels, content areas, and instruction surrounding the visit(s)? What are the contexts and conditions that support the experienced other to communicate and interact with the students and how do these differ across grade levels, content areas, and instruction surrounding the visit(s)? In the same way that I wonder about vertically-aligned curricula, I also wonder about the impact on students if interactions with experienced others, like their work with the marine engineering students, happened regularly throughout their years of school. In what ways would frequent interactions with experienced others across multiple years shift:

1. learners' awareness of and affinity for various careers and/or plans for their own futures?
2. learners' perceptions regarding the identities of who participates, or is empowered to participate, in particular careers and life paths?

   learners' attitudes and engagement regarding specific subject areas?

Curricula as Living Documents

As much as I love designing curricula, it is a task that is never finished. That is for the best; especially with science and engineering; new discoveries are made on a daily basis. Informing students of those ongoing discoveries is key to letting them know that the process of knowledge creation is present-tense, not past. Recognizing the need for constant iteration, I am dedicated to the process of design-based research (Brown, 1992). As I reach the end of this dissertation, I would like to share the current version of the Wayfinding Unit. Taking into account the lessons learned from the enactment discussed in these pages, and being responsive to the needs of remote learning due to the pandemic, I prepared a third iteration. The Table of Contents and links to the revised lesson plans for Version 3 can be found in Appendix L.

The current version of the Wayfinding Unit made improvements to both usability and content. The majority of the changes were to make the unit more convenient for educators: compiling teacher lesson plans and student materials into printable files, developing a materials list, and making the digital version of the student notebook easier to navigate for students working remotely. Other changes were spurred by the ever-changing nature of material on the internet. Each year, the online planetarium platform used in two lessons has become unavailable. For the third time, I had to locate a suitable replacement website and redo the directions and questions based on the capabilities of the new site.

I made the most significant content change to Lesson 3, both due to equity concerns. In a bid at including primary sources, the lesson originally included a piece written by the author of a book the students had read during the previous lesson. However, the piece included two references to Christopher Columbus as an explorer. Although the references were in passing, the inclusion of a European White male responsible for genocide as an example of an "explorer" was completely at odds with the goals of the unit as a whole. Simultaneously, I felt that I had not done an adequate job of explaining the connection between Polynesia and Hawaii, or Hawaii's complicated relationship with the United States. So, I removed the text with the Columbus reference and replaced it with a new text, "What is Polynesia?"

Equity: First, Last, and Always

I mentioned equity on the first page of this manuscript, and I will mention it here on the last. As I wrote earlier, I designed the Wayfinding Unit with equity in mind. However, the analyses I conducted for this dissertation were a stark reminder that we can always do better regarding representation. By focusing on Polynesian cultures, I was proud to develop a unit that highlighted the achievements of Pacific Islanders. However, at the same time, the unit does not feature an image of a single Black individual. Part of this has to do with the demographics of Hawaii, and inequities in the STEM fields, but, I could have done a better job when selecting materials. Similarly, I assumed that a student-centered unit like this would guarantee consistent participation for all students. From watching footage of Brianna and Sarafina, I know that is not the case. Acknowledging those shortcomings, curricula is always a work in progress, as I noted above. Those are issues I will be sure to address in Version 4. As for other potential improvements to the unit in the future, I asked that very question to the students during our end-of-unit interviews. Tameika had a single request, which she repeated three times, so I leave the final words of this dissertation to her: "More activities."

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Appendix A

Table of Contents: Grade 5 Wayfinding Unit 2019-20 (Year 2)

How can we find our way in the world by using only the clues that are in our environment?

*** WEEK 1: Voyaging - Why Then, Why Now? ***

Lesson 1: Launching of the Wayfinding Unit (9/30/19)

Introduction: Imagining navigating across Michigan, with and without technology
Instruction: * Choral reading of *Before the Story* text
* Viewing of open ocean video
* Writing about their thoughts/feelings before taking an unknown journey
Conclusion: Viewing of "On the Water" video to reflect on sights, sounds, and spirit

Lesson 2: Reading *Island below the Star* (10/1/19)

Introduction: Reviewing the unit question
Instruction: * Interactive reading of *Island below the Star*
* Writing an opinion about why someone would journey across the ocean
Conclusion: Viewing of "Reflections from Home" video to begin connecting to the present

Lesson 3: Reading about the Polynesian Voyaging Society (10/2/19)

Introduction: Writing in response to reading *Letter from the Author* by James Rumford
Instruction: * Reading the End-Note from *Island below the Star*
* Interactive reading (with slideshow) of *Hokule'a* NPR article (part 1 of 2)
Conclusion: Answering any lingering questions before continuing the article tomorrow

Lesson 4: Investigating the Size and Brightness of the Sun (10/3/19 & 10/4/19)

Introduction: Recalling the first half of the *Hokule'a* article
Instruction: * Interactive reading (with slideshow) of *Hokule'a* NPR article (part 2 of 2)
* Viewing Star Trail Time Lapse video
* Physically modeling the rotation of the Earth and its revolution around the Sun
* Viewing and discussing the video of the Earth/Sun physical model
* Writing an argument about the size and brightness of the Sun
Conclusion: Combining the 3 C-E-R components into a single, cohesive written argument

*** WEEK 2: Preparing for the Voyage - What Do We Need? ***

Lesson 5: Investigating Turning Saltwater into Freshwater (10/7/19)

Introduction:	Imagining packing for a vacation compared to a canoe trip across the ocean
Instruction:	* Interactive reading of *Provisions for Polynesian Voyages* text
	* Brainstorm a class list of potential items to pack
	* Interactive reading of *Water, Water, Everywhere* text
	* Making and investigating a solar still
Conclusion:	Predicting the amount of fresh water produced by each solar still

Lesson 6: Graphing Water Use (10/8/19)

Introduction:	Interactive reading of *Basics of Wayfinding* text
Instruction:	* Drafting, comparing, and revising packing lists
	* Graphing water use in Hawaii and calculating individual/crew water needs
Conclusion:	Discussing water calculations and debating how much extra water to pack

Lesson 7: Calculating Weight of Personal Gear and Clothes (10/9/19)

Introduction:	Interactive reading of *Rules of Conduct* and *What is Downwind Sailing?* texts
Instruction:	* Comparing and revising packing lists
	* Calculating the weight of personal gear and clothes
Conclusion:	Recording data for the solar still

Lesson 8: Calculating Total Canoe Weight (10/10/19)

Introduction:	Viewing of "What is the Worldwide Voyage?"
	Interactive reading of *Crew Blog: Life is in the Clouds*
Instruction:	* Calculating the total weight of the canoe
	* Calculating the rate of water production of a solar still
	* OPTIONAL: Writing a persuasive letter to explain their packing choices
Conclusion:	Interactive reading of *Winds, Currents, and Latitudes* text
	Viewing of "What is the line between modern and traditional navigation?"

*** WEEK 3: Set the Course - Which Way? (Stars, Sun, and Moon) ***

Lesson 9: Exploring the Virtual Planetarium (10/14/19)

Introduction: Viewing of Polynesian Wayfinders Ted-Ed video

Instruction: * Interactive reading of *Set the Course / Hawaiian Star Compass* texts
* Investigating star movement with the Virtual Planetarium
* Viewing of "How do you know when you are at the equator?"

Conclusion: Calculating the rate of water production of a solar still

Lesson 10: Describing Patterns in the Stars (10/15/19)

Introduction: Re-viewing the Star Trail Time Lapse video

Instruction: * Reading of *Hoku, the Star*
* Investigating the movement of Arcturus with the Virtual Planetarium

Conclusion: Viewing of "Polynesian Voyaging Technology"

Lesson 11: Inquiring about the Moon (10/16/19)

Introduction: Viewing of "How does the moon phase affect the sail plan?"

Instruction: * Inquiring with the Light and Clues from the Moon slideshow
* Interactive reading of *Crew Blog: The Navigators and the Night Sky*

Conclusion: Modeling the phases of the moon

Lesson 12: Investigating the Earth's Wobble (10/17/19)

Introduction: Reviewing learnings about the stars and the moon

Instruction: * Investigating the Earth's wobble with spinning round candles
* Reading of *Why is Polaris the North Star?*
* Viewing of The Axis of Rotation
* Modeling solar stills

Conclusion: Providing feedback on solar still models

*** WEEK 4: Hold the Course - How Far? (Wind, Waves, and Currents) ***

Lesson 13*: Following Currents with Maps (10/18/19)

Introduction: Reviewing the 5 Characteristics of a Model
Instruction: * Receiving feedback, revising, and presenting models of solar stills
* Reading of *Hold the Course*
* Investigating the Earth's currents with the *Na'ale, the Ocean Waves* text
Conclusion: Viewing of "How do you handle the canoe in rough swells?"

Lesson 14: Investigating Wave Patterns (10/21/19)

Introduction: Reading of *Find Land*
Instruction: * Investigating wave patterns
Conclusion: Discussing observations from the investigation

Lesson 15: Investigating Wave Speed (10/22/19)

Introduction: Re-viewing of "On the Water" video
Instruction: * Investigating wave speed
Conclusion: Creating and discussing a class line plot

Lesson 16: Writing Scientific Explanations about Waves (10/23/19)

Introduction: Summarizing the wave speed investigation
Instruction: * Writing a scientific explanation for the wave speed investigation
Conclusion: Discussing comparisons between the scientific explanations
Reading of *Crew Blog: Rhythm*

*** WEEK 5: What is happening to the oceans? ***

Lesson 17: Modeling the Life Cycle of Plastic (10/28/19)

Introduction: Viewing of "Hokule'a Sailed Around the World, But Couldn't Escape Plastic"
Instruction: * Reading of *Navigating Change*
* Modeling the life cycle of plastic
Conclusion: Providing feedback on the plastic life cycle models

Lesson 18: Investigating Microplastics (10/29/19)

Introduction: Viewing of "Reality of Plastics" video
Instruction: * Interactive reading of *Microplastics* NPR article
* Viewing of "Microplastics in the ocean" video
* Investigating Microplastics
Conclusion: Revising and adding to plastic life cycle models
OPTIONAL: Viewing of "What happens to microplastics in the ocean?" video

Lesson 19: (Scientifically) Arguing About Recycling (10/30/19)

Introduction: Viewing of Scientific Argument template and Waste Hierarchy image
Instruction: * Viewing three videos (1, 2, 3) to revise and add to plastic life cycle models
* Writing a scientific argument about the effectiveness of recycling
Conclusion: Discussing comparisons between the scientific arguments

Lesson 20: Evaluating The Ocean Cleanup Project (11/1/19)

Introduction: Reading of *Crew Blog: Every Bit Counts*
Instruction: * Using a slideshow of texts and videos to evaluate the Ocean Cleanup Project
Conclusion: Discussing findings from their evaluations

*** WEEK 6: Final Projects (1 of 3) ***

Monday (11/4/19): Mālama Honua Challenge

Lesson 21: Launching the Mālama Honua Challenge

Introduction: Viewing of "The Earthshot" video

Instruction: * Researching Elemental Excelerator and taking notes

Conclusion: Sharing patterns of problems and solutions from their research

Tuesday (11/5/19): Canoe Project (Planning Day)

Introduction: Reading of *To Build a Canoe* (at the beginning of Canoe Design Planner)

Instruction: * Preview the pages 3-5 of the Canoe Design Planner

* Review the parts of the canoe using the Canoe Tour animation

* Planning Day: Working on Planners with university volunteers (1:00-2:30pm)

Wednesday (11/6/19): Mālama Honua Challenge

Lesson 22: Research for the Mālama Honua Challenge

Introduction: Viewing of "The 'Lost City' Finding Its Future" video

Instruction: * Researching Young Voices for the Planet and taking notes

Conclusion: Sharing patterns of problems and solutions from their research

Thursday (11/7/19): Canoe Project (Building Day)

* Students will work with university mentors to build their canoe models

University volunteers will work with the students from 1:00-2:30pm

Friday (11/8/19): Mālama Honua Challenge

Lesson 23: Additional Research for the Mālama Honua Challenge

Introduction: Viewing of "Every Day is Earth Day" video

Instruction: * Researching BrightVibes.com and/or Environment blogs posted by the Polynesian Voyaging Society and taking notes

Conclusion: Sharing patterns of problems and solutions from their research

*** WEEK 7: Final Projects (2 of 3) ***

Monday (11/11/19): Mālama Honua Challenge

Lesson 24: Identifying a Problem and Solution(s) for the Mālama Honua Challenge

Introduction: Viewing of "The Interceptor, Explained" video

Instruction: * Identifying a problem for the Mālama Honua Challenge

* Defining the criteria for success for the Mālama Honua Challenge

Conclusion: Receiving feedback from peers on their potential solutions

~~**Tuesday (11/12/19): Mālama Honua Challenge**~~ **SNOW DAY - Lesson Postponed to Friday**

~~**Lesson 25**: Putting Ideas Together for the Mālama Honua Challenge~~

~~Introduction: Reading of *Crew Blog: Navigating Our Educational Visions*~~

~~Instruction: Putting Ideas Together for the Mālama Honua Challenge~~

~~Conclusion: Receiving feedback from peers on their plan~~

Wednesday (11/13/19): Canoe Project (Testing Day - Field Trip to University)

Morning - Students will draw diagrams of their initial design in their testing packet

Noon - Students will board the bus at Pine (they will bring their models and testing packets)

12:45pm - Students arrive at MHL. Welcome and safety talk.

1:00-1:45pm - Group A tests. Group B tours. (15 students per group)

1:45-2:00pm - Flex time and bathroom break.

2:00-2:45pm - Group A tours. Group B tests. (15 students per group)

2:45pm - Students get back on the buses for return trip

3:30pm - Students dropped off at Pine

Thursday (11/14/19): Canoe Project (Presentations and Debrief Conversation)

* Groups will share the results of their testing
* General debrief discussion
* Students will draw diagrams of their final design in their testing packet
* If any time is remaining, students will work on their Mālama Honua Challenge projects

Friday (11/15/19): Mālama Honua Challenge (Early Release Day)

Lesson 25: Putting Ideas Together for the Mālama Honua Challenge

Introduction: Reading of *Crew Blog: Navigating Our Educational Visions*

Instruction: Putting Ideas Together for the Mālama Honua Challenge

Conclusion: Receiving feedback from peers on their plan

*** WEEK 8: Final Projects (3 of 3) ***

Monday (11/18/19): Mālama Honua Challenge (Writing & Filming)

Tuesday (11/19/19): Post-Assessment
Remaining time will be devoted to the Mālama Honua Challenge

Wednesday (11/20/19): Mālama Honua Challenge (Writing & Filming)

Thursday (11/21/19): Mālama Honua Challenge (Writing & Filming)

Friday (11/22/19): Mālama Honua Challenge (Writing & Filming)

*** WEEK 9: Wrap-up ***

Monday (11/25/19): Mālama Honua Challenge (Writing & Filming)

Tuesday (11/26/19): Mālama Honua Challenge (Writing & Filming)

Wednesday (11/27/19) - Friday (11/29): THANKSGIVING BREAK

*** WEEK 10: End-of-Unit Events ***

Monday (12/2/19): Mālama Honua Film Festival & End-of-Unit Student Interviews

Tuesday (12/3/19): End-of-Unit Student Interviews

Appendix B

Sample Lesson Plan

Week's Theme: Lesson #:	**WEEK 2: Preparing for the Voyage - What Do We Need?** **Lesson 5**
Title: Suggested Time:	Investigating Turning Saltwater into Freshwater 1.5 hours
Overview	In this lesson, students read about how the Polynesians prepared for their long voyages, drawing on their knowledge of food preservation. After this introductory text, the students brainstorm what they would pack for such a journey. Then, students learn about the importance of fresh water for maintaining life. They build a small model of a solar still to collect fresh water from salt water. They predict how much water the still will produce over a period of time and think through what that means for ensuring that they would have sufficient fresh water for a journey across the sea.
Learning Objectives	Students will be able to brainstorm how they would provision a boat for a journey by connecting ideas in a text with what they know. They will interpret graphical information to support making claims about the importance of water to human survival. They will figure out how to construct a solar still system and gather data about how a solar still works.

Standards	Students will be working towards: NGSS: **5-PS1-2 Matter and Its Interactions** Measure and graph quantities to provide evidence that regardless of the type of change that occurs when heating, cooling, or mixing substances, the total weight of matter is conserved. **5-PS1-4 Matter and Its Interactions** Conduct an investigation to determine whether the mixing of two or more substances results in new substances. CCSS-ELA: **CCSS.ELA-LITERACY.RI.5.4** Determine the meaning of general academic and domain-specific words and phrases in a text relevant to a grade 5 topic or subject area.

Materials / Resources	● *Provisions for Polynesian Voyages* text
	● Interactive Reading Guide for *Provisions* text
	● *"Water, water, everywhere, nor any drop to drink." Why this is a big problem!* text
	● Interactive Reading Guide for "*Water, water, everywhere"* text
	● Solar Still Directions
	● Solar Still materials (one set per group):
	    ○ 1-gallon bucket or similar
	    ○ Small plastic container
	    ○ Salt
	    ○ Plastic cling wrap
	    ○ Large rubber band (1 per group)
	    ○ Small stones or washers
	    ○ Magnets (2 per group)

Teacher preparation	● Make copies of the *Provisions* text (1 per student) ● Make copies of the "Water, water everywhere" text (1 per student) ● Make copies of the Solar Still Directions (1 per student) ● Print a copy of the Interactive Reading Guide for *Provisions* ● Print a copy of the Interactive Reading Guide for *"Water, water"* ● Prepare sets of solar still materials (one set for each group of 3) ○ NOTE: Place one magnet under the bucket and one in the bottom of the small container to keep it in place.

Lesson Sequence *Include description of grouping and pacing strategies. Students should be actively engaged in multiple ways.*	**Introduction (hook, purpose setting, prior knowledge connection, etc.):** Remind students that, before investigating why the sun appears to be brighter than much larger stars, they were learning about voyages of the Polynesian Voyaging Society. Ask the students what they would pack if they were going on vacation to DisneyWorld. After some students share, ask if they would pack differently if they were going on a canoe journey with the Polynesian Voyaging Society. Let the students know that today, they will think about how *they* would prepare for such a voyage. They will read about how historians think the Polynesians prepared for their voyage. Then, they will study a particularly important provision for such a journey. Finally, they will build a system called a solar still, which they will investigate over the next several days.
	Instruction (guided practice, activity, checks for understanding, etc.): Pass out copies of the *Provisions for Polynesian Voyages* text to the students. Use the Interactive Reading Guide to read and discuss how ancient voyagers are believed to have provisioned their boats for their long journeys. After finishing the text, share the following prompt with the students and have a class discussion. Record ideas on a class chart. • Imagine you are sailing along the route of the Polynesian Voyaging Society from the Marquesas Islands to Hawaii. The journey is 2,336 miles and will take at least a few weeks, if not a few months! You will not stop at any land while you are sailing. What would pack you pack for the trip? *NOTE: Over the course of the rest of the week, students will create personal lists, calculate the weights of each item they intend to bring, and make changes as they learn about additional needs and constraints. For this lesson, they are in brainstorming mode and all answers are acceptable.* Following this initial brainstorming, pass out copies of the *"Water, water, everywhere"* text to the students. Use the Interactive Reading Guide to support the students to learn about the essential nature of water to our survival. Investigation: *For this investigation, students should work in groups of 3.* Pass out the Solar Still Directions. Ask one member of each group collect a set of solar still materials.

	IMPORTANT: Do not distribute water yet! Invite the students to follow the Solar Still Directions to explore, construct, and make initial predictions about their solar still systems.
	Conclusion (reflection, demonstration of learning, sharing out, etc.): After the stills are constructed and the students have answered the question, have a discussion about how the system works: where does the saltwater go, and where does the fresh water collect? Have the students share their predictions about the amount of fresh water the solar still will produce (how much water? how long to produce that amount?) After the class comes to consensus that the saltwater goes in the large bowl, and the fresh water collects in the small container nested inside the bowl, they are ready to add saltwater to the system. Ask a representative of each group to prepare the saltwater. Each group will need a teaspoon of salt mixed into 8 fluid ounces of water. While still empty, ask the students to place their solar still on top of the class radiators (if investigating when it is cold outside) or in a spot that receives ample sunlight (if investigating when it is warm outside). *NOTE: Without a heat source, such as the radiator or direct sun, the solar stills will not work very well.* With the stills in a stable place, they may carefully pour 8 oz. of the saltwater into the outer ring of their still. With the small container held in place by a magnet in the bottom of the small container (paired with a magnet under the bucket), the stills should be covered with plastic wrap and weighed down with a few small stones or washers. Remind students that they will be taking daily measurements over the rest of the week to determine the amount of fresh water produced by the solar still system.

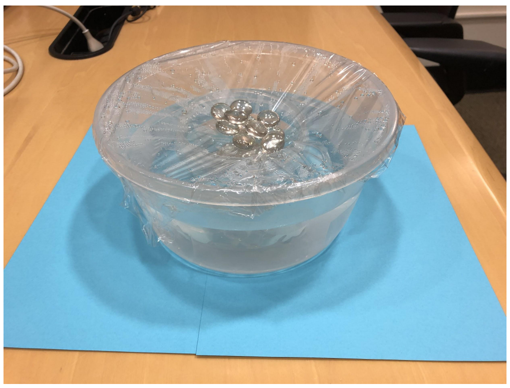
Appendix C

Directions for Making and Investigating a Solar Still

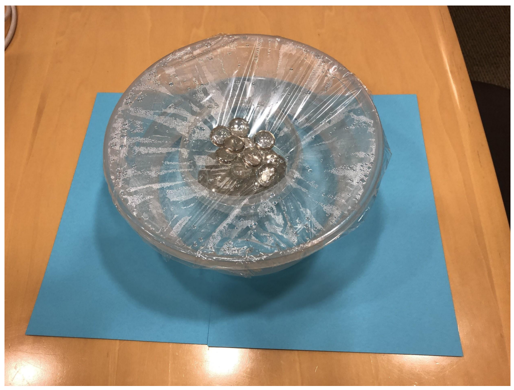
Now that you understand the importance of having fresh water to drink, you are going to learn how to make a simple solar still.

Get your materials and use the pictures below to assemble your solar still.

Inside view of an empty solar still



Solar still with plastic wrap and weights



Top view of completed solar still

Now that you have your solar still assembled, think about how it works.

Work with your group to answer the questions:

1. Why is there a sheet of plastic wrap tightly covering the bucket?

2. Why is there a small container inside?

3. Why are there weights making the plastic wrap dip in the middle?

4. This is called a solar still; what you do think that means about where we should place our stills? Why would that be an important place?

5. Describe what you think will happen inside the system that you have made:

6. Make a prediction about how much water will collect in the center container over the next 24 hours? How much over the next 4 days?

Add 8 fluid ounces of saltwater to your solar still and place it in a warm spot.

Appendix D

Plan for Lesson 12

Week's Theme: Lesson #:	**WEEK 3: Set the Course - Which Way? (Stars, Sun, and Moon)** **Lesson 12**
Title: Suggested Time:	Investigating the Earth's Wobble 1.5 hours
Overview	In this lesson, students use tops to make observations about the Earth's rotation over time. They will read a text and watch a video to learn about how patterns of stars in the sky change in predictable ways over long spans of time. Going back to their solar still investigations, students will make observations of what happened to their solar stills under the heat lamps. They will create models (drawn or digital) about their solar stills.
Learning Objectives	Students will be able to explain how the patterns of stars in the sky change in predictable ways over long periods of time. Students will be able to create models explaining the movement of heat energy and water within their solar stills.
Standards	Students will be working towards: NGSS: **5-ESS1-2 Earth's Place in the Universe** Represent data in graphical displays to reveal patterns of daily changes in length and direction of shadows, day and night, and the seasonal appearance of some stars in the night sky. **5-ESS2-1 Earth's Systems** Develop a model using an example to describe ways the geosphere, biosphere, hydrosphere, and/or atmosphere interact. CCSS-ELA: **CCSS.ELA-LITERACY.SL.5.5** Include multimedia components (e.g., graphics, sound) and visual displays in presentations when appropriate to enhance the development of main ideas or themes.

Materials / Resources	- Round candles (1 per group of 3 students) - Toothpicks (1 per candle) - Rotation Observation sheet *Why is Polaris the North Star?* text - The Axis of Rotation video (2 minutes 55 seconds) https://www.youtube.com/watch?v=9n04SEzuvXo 5 Characteristics of a Model slideshow - Model of a Solar Still worksheet - Solar Still Model feedback sheet
Teacher preparation	- Make copies of the Rotation Observation sheet (1 per student) - Make copies of the *Why is Polaris the North Star?* text (1 per student) - Make copies of the Model of a Solar Still worksheet (1 per student) - Make copies of the Solar Still Model feedback sheet (1 per student) - Open the Axis of Rotation video - Open 5 Characteristics of a Model slideshow
Lesson Sequence *Include description of grouping and pacing strategies. Students should be actively engaged in multiple ways.*	**Introduction (hook, purpose setting, prior knowledge connection, etc.):** Ask students to remind you about some of the things they have learned about the stars and the moon and how they can be used for navigation. Let the students know that they will now be further exploring the motion of the Earth, and the impact that might have on navigation over the centuries.
	Instruction (guided practice, activity, checks for understanding, etc.): Let students know that they will be modeling the rotation of the Earth. While doing so, they will be making observations about how that motion might impact navigators. Pass out copies of the Rotation Observation sheet to the students. After reviewing the directions, put students in groups of 3. Distribute one candle and one toothpick to each team. Provide the students with some time to investigate and record observations. Bring the students back together and have a discussion about what they observed. Pass out copies of the *Why is Polaris the North Star?* text to the students. ***Suggested prompts:*** *How did our investigation provide evidence to support this article?* *What would this mean for the Polynesian navigators? If their ancestors 5,000 years ago wrote down their star compass to be used now, could we use it? Why or why not? If the Polynesian Voyaging Society wants to pass down their current knowledge to navigators in the future, what should they do?*

	When the discussion reaches a natural conclusion, view The Axis of Rotation video. After viewing, answer any remaining questions. *Creating Drawn Models of the Solar Stills* Let students know that you will check back in with your solar still investigations. The stills have been exposed to the heat lamps daily for three days now. Have students observe their solar stills and record the current amount of freshwater. Inform the students that they will create a model of their solar still. Remind students about the modeling activity they engaged with during the previous lesson. ***Suggested prompts:*** ● *What is a model?* ● *Why do scientists create models?* ● *Are models always something you build? What other kinds of models can we create?* Project the 5 Characteristics of a Model slideshow. The solar still the students have created is already a model. Review the five characteristics and discuss how the set-up they have been observing operates as a model. However, this type of model has limitations. Scientists often like to create models that are easier to share: either drawn or digital. Today, that is the type of model the students will work on. Ask a student to read the first characteristic: *All models answer a question*. As a class, brainstorm the questions that students' models will answer. The questions should be related to how the solar still can be used to turn salt water into freshwater. Tell students that in order to plan an effective model, they need to decide what parts/components need to be in the model. Ask students to *turn-and-talk* to their neighbor and then share out ideas. Record these ideas on the board. ● Note: Other than the visible parts of the set-up, students should be sure to include heat energy as a component in their models. After the students have decided on the components of the model, ask them if everything on the list is necessary for answering the investigation question? Students should identify: two bowls, location of salt water, location of freshwater, the plastic covering, a heat source, some way of representing the movement of the water within the system (evaporation, condensation, and

	precipitation), and the transfer of heat to the water. Discuss how each component could be represented and create a key showing how they will represent each part. Tell students to think about how they can show connections and a cause in their model. Using the Model of a Solar Still worksheet or *Collabrify Flipbook*, ask students to draw a model from the data collected in the investigation.
	Conclusion (reflection, demonstration of learning, sharing out, etc.): Direct students' attention to *Characteristic #4 - Models are shared for feedback.* Establish norms for sharing models, including the importance of listening. Have students share their models with a partner and get feedback using the Solar Still Model feedback sheet. Select a few student pairs to share their models and their feedback with the class. Invite students to provide compliments and questions to the presenter. When students share, direct students to notice the similarities and differences among the models. Let the students know that tomorrow, they will change focus from stars, the Sun, and the Moon to winds and currents. They should keep the process for creating models in mind, as they will be modeling again.

Appendix E

Plan for Lesson 13

Week's Theme: Lesson #:	**WEEK 4: Hold the Course - How Far? (Wind, Waves, and Currents)** **Lesson 13***
Title: Suggested Time:	Following Currents with Maps 1.5 hours
Overview	In this lesson, students share their solar still models with a partner and receive feedback. After revising their models, a few students will share their models with the class for discussion. Then, students look at maps of ocean currents to learn how they can be a help or a hindrance to a canoe voyage. They will also explore how the impact of humans on the oceans can be traced by following currents.
Learning Objectives	Students will be able to present their knowledge and ideas about the working of a solar still using a model. Students will be able to identify patterns in currents to explain how the hydrosphere and the biosphere interact.
Standards	Students will be working towards: NGSS: **5-ESS2-1 Earth's Systems** Develop a model using an example to describe ways the geosphere, biosphere, hydrosphere, and/or atmosphere interact. CCSS-ELA: **CCSS.ELA-LITERACY.RI.5.3** Explain the relationships or interactions between two or more individuals, events, ideas, or concepts in a historical, scientific, or technical text based on specific information in the text. **CCSS.ELA-LITERACY.RI.5.7** Draw on information from multiple print or digital sources, demonstrating the ability to locate an answer to a question quickly or to solve a problem efficiently.

Materials / Resources	• 5 Characteristics of a Model slideshow • Model of a Solar Still worksheet • Solar Still Model feedback sheet • *Hold the Course* text • *Na'ale, the Ocean Waves* text • PVS Ask the Crew video: "How do you handle the canoe in rough swells?" (1 minute 22 seconds) http://www.hokulea.com/ask-crew-question-kala-baybayan-handle-canoe-rough-swells/
Teacher preparation	• Open 5 Characteristics of a Model slideshow • Make copies of the *Hold the Course* text (1 per student) • Make copies of the *Na'ale, the Ocean Waves* text (1 per student)

Lesson Sequence
 	
Include description of grouping and pacing strategies. Students should be actively engaged in multiple ways.
	Introduction (hook, purpose setting, prior knowledge connection, etc.):
	
	Remind students about the solar still modeling activity they engaged with during the previous lesson.
	Suggested prompts:
	• *What is a model?*
	• *Why do scientists create models?*
	
	Project the 5 Characteristics of a Model slideshow.
	
	Ask a student to read the first characteristic: *All models can be used to explain or predict phenomena*. You may have to explain what a phenomenon is (something that we can observe in nature. The singular is *phenomenon* and the plural is *phenomena*). Have the students recall what question they are trying to answer with their solar still model: this is the *phenomenon* they are trying to explain.
	
	Ask a student to read the second characteristic: *All models have components*. Have students help you generate a list of the components that should be present in their solar still models.
	Suggested prompts:
	• *Is everything on this list necessary for answering the investigation question?*
	• *Are we missing anything?*
	
	Ask a student to read the third characteristic: *Models show relationships among the components.* Ask the students to describe the relationships among the components that are essential in this model.
	• There are two important relationships within the solar still:
	    ○ The transfer of heat from a heat source to the salt water.
	    ○ The miniature version of the water cycle that happens within the still: the *evaporation* of the salt water, the *condensation* of fresh water droplets on the underside of the plastic wrap, and the *precipitation* as the water droplets run down the plastic wrap and drip into the center bowl.
	
	Have students take out the Model of a Solar Still worksheet.

	Instruction (guided practice, activity, checks for understanding, etc.): Ask a student to read the fourth characteristic: *Models are shared for feedback.* Ask why it is important to receive feedback on your model. Establish norms for sharing models, including the importance of listening. Provide time for students to share their models with a partner and get feedback using the Solar Still Model feedback sheet. After students have had time to review a partner's model, ask a student to read the fifth characteristic: *Models are revised based on new data*. Ask why is it important to be willing to revise a model. Ask for volunteers to share one suggestion they received on their feedback sheet and whether or not they are going to make that revision. Push students to provide reasons for their choice. Have the students complete the "Revisions" section on the bottom of their feedback sheet. Then, provide time for students to revise their models. Select a few students to share their models and their feedback with the class. Invite students to provide compliments and questions to the presenter. When students share, direct students to notice the similarities and differences among the models. *Transition to Week 4: Exploring Wind, Waves, and Currents.* Let the students know that, as important as fresh water is to drink, it is equally important to understand the vast ocean of salt water all around the canoe. Over the next few days, they will explore how those natural clues can not only help determine direction, but also help to determine distance and the location of land. Pass out copies of the *Hold the Course* text to the students. During the reading, there are two places to pause and do some quick calculations. Let the students know that stars, the Sun, and the Moon are not the only natural clues that can help with navigation. Currents, predictable flows of water through the ocean, can be used in many ways on a long-distance voyage. Pass out copies of the *Na'ale, the Ocean Waves* text. This text does not have a separate interactive reading guide, as the questions are embedded throughout the text. Read the text as a class, stopping to answer and discuss the questions.

	Conclusion (reflection, demonstration of learning, sharing out, etc.): Watch the Ask a Crew video from the Polynesian Voyaging Society on "How do you handle the canoe in rough swells?" Let the students know that they will continue to discuss wind, waves, and currents.

Appendix F

Design Planner

For the next few days, you and your group, assisted by mentors from the University of -----, will go through the process of planning, building, and testing a canoe. Inspired by the ancient Polynesians, you will use modern materials to plan and build a small model canoe. We will then journey to the campus of the University of -----, so that you can test your model in the Wind/Wave Tank in the Marine Hydrodynamics Lab.

Like the members of the Polynesian Voyaging Society, remember that you will experience success with experimenting and a bit of invention!

As the article mentioned, no one knows exactly what the ancient Polynesian canoes looked like. Below are some ideas of possible designs:

[images removed due to copyright restrictions]

Below are two different diagrams of the Hokule'a, with labeled parts, that may serve as a guide for your plans:

[diagrams removed due to copyright restrictions]

Before you begin your plans, know that your canoe model is limited to being 1 foot long, 1 foot wide, and 1 foot tall. This is an important **constraint** to keep in mind.

Although a complete canoe has many parts, your model must include the following four components:

- **Hull**
- **Deck**
- **Mast**
- **Sail**

You will also need to decide if you will include a **boom** or a **steering paddle**. You will also think about the **rigging** you will use to keep your sail(s) in place.

Working with your mentor, you and your group will use this design planner to make choices about your canoe model. Record your thinking carefully, including your choices of materials and the dimensions of each component that you select.

Your careful notes are essential. You will need your completed plans in order to receive your materials on the Building Day.

Good luck!

Component 1: Hull

The *hull* is the part of the canoe that floats in the water and supports the rest of the canoe. Polynesian canoes had two hulls, so your model should also include two hulls.

You have four options for hull materials:

			
Flexible foam	Pipe foam	Rigid foam	Plastic bottles

Please circle your material choice for your two hulls.

Why do you think that material is the best choice?

Component 2: Deck

The *deck* is the floor-like part of the canoe that connects the two hulls. The deck contains all of the living area and most of the storage area for the canoe.

For the deck, each group will receive a piece of corrugated plastic board that measures 18 inches by 24 inches. *Remember: your canoe cannot be more than 12 inches long.*

What are the *benefits* of having a **wide** deck? What about *drawbacks*?

____

____

____

What are the *benefits* of having a **narrow** deck? What about *drawbacks*?

____

____

____

Would you like to layer your deck to make it thicker? If yes, where might it be helpful to layer your deck? Why?

____

____

____

Record the dimensions of your deck:

Length: _____________inches x Width: _____________ inches

Component 3: Mast

The *mast* is the large pole or poles that support the sails.

You have three options for mast materials:

 Plastic tube	 Wood dowel (1/2 inch)	 Wood dowel (1/4 inch)

Please circle your material choice for your mast.

Why do you think that material is the best choice?

____

____

____

____

Some Polynesian canoes only have one mast. Other canoes, like the Hokule'a, have two masts. Will your canoe have one mast or two? Why?

____

____

____

____

Component 4: Sail

The *sail* is a flexible material that catches the wind to propel the canoe.

You have five options for sail materials:

				
Burlap	Cotton	Nylon (hot air balloon)	Nylon	Plastic tarp

Please circle your material choice for your sail(s).

Why do you think that material is the best choice?

____

____

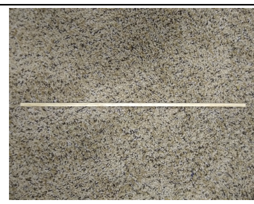
____

In the space below, sketch the shape of your sail. Include the measurements along each side. *Note: Unlike yachts or other western sailboat designs, Polynesian canoes only have one sail per mast. However, if your design has two masts, you will also have two sails.*

Optional component: Boom

The *boom* is a pole that helps to keep the sail open.

You have four options for boom materials:

 Small dowels	 Balsa wood	 Craft sticks (thin)	 Craft sticks (wide)

Please circle your material choice for your boom(s).

Why do you think that material is the best choice?

____

____

____

What are the *benefits* of having a **boom**? What about *drawbacks*?

____

____

____

____

____

____

Optional component: Rigging

Rigging is a general term for the ropes, chains, wires, etc. used to support the masts, sails, and other components of a canoe.

You may include as many pieces of rigging that are necessary to hold you canoe together, to support your mast(s), and to keep your sail(s) in place.

You have six options for rigging materials:

 Cotton twine	 Jute twine	 Thick yarn
 Nylon strap	 Wire (hanger)	 Wire (thin)

Please circle your material choice(s) for your rigging. [Note: you may use as many or as few of these rigging materials as you need.]

Optional component: Steering Paddle

A *steering paddle* is a vertical blade under the water that helps to change the canoe's direction. Because you are building a model, you will not be able to steer your canoe. However, you may still want to include a steering paddle to help your canoe sail in a straight line.

You have two options for steering paddle materials:

	
Craft sticks (thin)	Craft sticks (wide)

If you would like to include a steering paddle on your canoe, please circle your material choice.

Connections:

Your group will have to make many decisions about how to connect the various components of your canoe.

Other than drilling holes or cutting notches, you have six materials to choose from when connecting components:

<table>
<tr>
<td>

Duct tape</td>
<td>

Craft glue</td>
<td>

Tacky glue</td>
</tr>
<tr>
<td>

Assorted glues</td>
<td>

Rubber cement</td>
<td>

Safety pins</td>
</tr>
</table>

Your group should take time to discuss and make notes about how you will connect the various parts of your canoe.

- How will you connect the hulls to the deck?
- How will you connect the mast(s) to the deck?
- How will you connect the sails to the mast(s)?
- If you decide to use a boom, how will the boom attach to the sail?
- How will you keep your sail in place?

Now that you have made decision about your materials, please draw a complete diagram of your canoe. Label the materials. Include measurements. If possible, label and/or describe the points where one component will connect to another.

Top View:

Front View: **Rear View:**

Side View:

Optional: Exploded Diagram

Appendix G

Data Collection Packet

My name: ________________________________

Group members: ____________ ______________ ______________

Documenting Your Initial Design

Now that you have built your canoe model, please draw a complete diagram of your initial design. Label the materials. Include measurements. Label and/or describe places where one component connects to another.

Side View:

Top View: **Front View:**

Testing Your Canoe Model

Measurements:

Place your model in the Wind/Wave Tank. Using your stopwatch, record how long it takes your canoe to travel from Start to Finish. Record your times below:

	Trial 1	Trial 2
Initial design		

Observations:

What worked well with this design?

What did not work so well with this design?

**** Take your canoe to the "Repair and Rethink" room.*
*With the help of the U-M volunteers, make changes to your design. ****

Briefly describe the changes you made to your model:

**** Return to the Wind/Wave Tank with your revised model and retest.*
*Please improve and retest your model multiple times. ****

In the tables below, record measurements and observations for your revised models:

	Trial 1	Trial 2	What worked well?	What did not work?
Revised Model #1				
After testing this design, make improvements. Briefly describe what you changed:				

	Trial 1	Trial 2	What worked well?	What did not work?
Revised Model #2				
After testing this design, make improvements. Briefly describe what you changed:				

	Trial 1	Trial 2	What worked well?	What did not work?
Revised Model #3				
After testing this design, make improvements. Briefly describe what you changed:				

Documenting Your Final Design

Now that you have tested your canoe model and improved it a few times, please draw a complete diagram of your final design. Label the materials. Include measurements. Label and/or describe places where one component connects to another.

Side View:

Top View:

Front View:

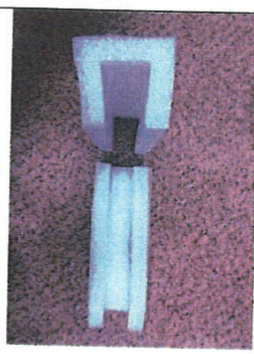
Appendix H

Tameika's Completed Design Planner

Component 1: Hull

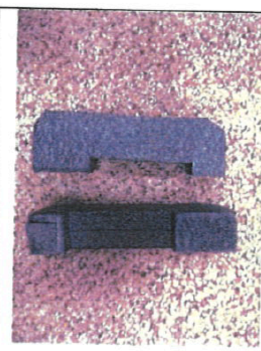
The *hull* is the part of the canoe that floats in the water and supports the rest of the canoe. Polynesian canoes had two hulls, so your model should also include two hulls.

You have four options for hull materials:



Flexible foam

Pipe foam



Rigid foam

Plastic bottles

Please circle your material choice for your two hulls.

Why do you think that material is the best choice?

We think foam is a lighter material than a waterbottle.

Component 2: Deck

The *deck* is the floor-like part of the canoe that connects the two hulls. The deck contains all of the living area and most of the storage area for the canoe.

For the deck, each group will receive a piece of corrugated plastic board that measures 18 inches by 24 inches. *Remember: your canoe cannot be more than 12 inches long.*

What are the *benefits* of having a **wide** deck? What about *drawbacks*?

you would have a Sturdier deck.

What are the *benefits* of having a **narrow** deck? What about *drawbacks*?

Having a narrow deck is good to because it's lighter.

Would you like to layer your deck to make it thicker? If yes, where might it be helpful to layer your deck? Why?

yes We want to layer our deck. We want to layer in the middle so it won't be easy to break.

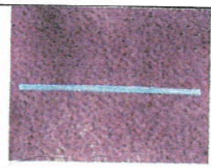
Record the dimensions of your deck:

Length: 8 inches x Width: 6 inches

Component 3: Mast

The *mast* is the large pole or poles that support the sails.

You have three options for mast materials:

		
Plastic tube	Wood dowel (1/2 inch)	Wood dowel (1/4 inch)

Please circle your material choice for your mast.

Why do you think that material is the best choice?

Sturdy thick

Some Polynesian canoes only have one mast. Other canoes, like the Hokule'a, have two masts. Will your canoe have one mast or two? Why?

Component 4: Sail

The *sail* is a flexible material that catches the wind to propel the canoe.

You have five options for sail materials:

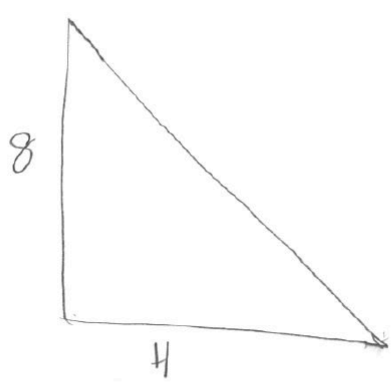
				
Burlap	Cotton	Nylon (hot air balloon)	Nylon	Plastic tarp

Please circle your material choice for your sail(s).

Why do you think that material is the best choice?

Doesn't have holes so air can't go through.

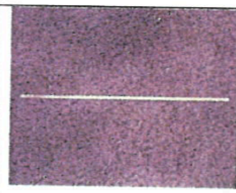
In the space below, sketch the shape of your sail. Include the measurements along each side. *Note: Unlike yachts or other western sailboat designs, Polynesian canoes only have one sail per mast. However, if your design has two masts, you will also have two sails.*



Optional component: Boom

The *boom* is a pole that helps to keep the sail open.

You have four options for boom materials:

			
Small dowels	Balsa wood	Craft sticks (thin)	Craft sticks (wide)

Please circle your material choice for your boom(s).

Why do you think that material is the best choice?

Sturdy

What are the *benefits* of having a **boom**? What about *drawbacks*?

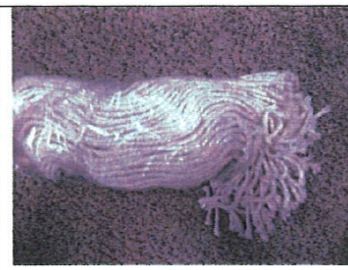
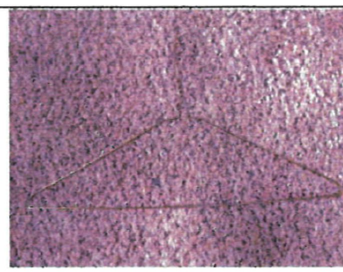
A boom helps the sail stay open so the sail can catch wind.

Optional component: Rigging

Rigging is a general term for the ropes, chains, wires, etc. used to support the masts, sails, and other components of a canoe.

You may include as many pieces of rigging that are necessary to hold you canoe together, to support your mast(s), and to keep your sail(s) in place.

You have six options for rigging materials:

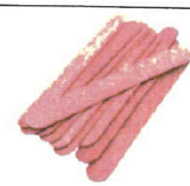
		
Cotton twine	Jute twine	Thick yarn
		
Nylon strap	Wire (hanger)	Wire (thin)

Please circle your material choice(s) for your rigging. [Note: you may use as many or as few of these rigging materials as you need.]

Optional component: Steering Paddle

A *steering paddle* is a vertical blade under the water that helps to change the canoe's direction. Because you are building a model, you will not be able to steer your canoe. However, you may still want to include a steering paddle to help your canoe sail in a straight line.

You have two options for steering paddle materials:

	
Craft sticks (thin)	Craft sticks (wide)

If you would like to include a steering paddle on your canoe, please circle your material choice.

Connections:

Your group will have to make many decisions about how to connect the various components of your canoe.

Other than drilling holes or cutting notches, you have six materials to choose from when connecting components:

 Duct tape	 Craft glue	 Tacky glue
 Assorted glues	 Rubber cement	 Safety pins

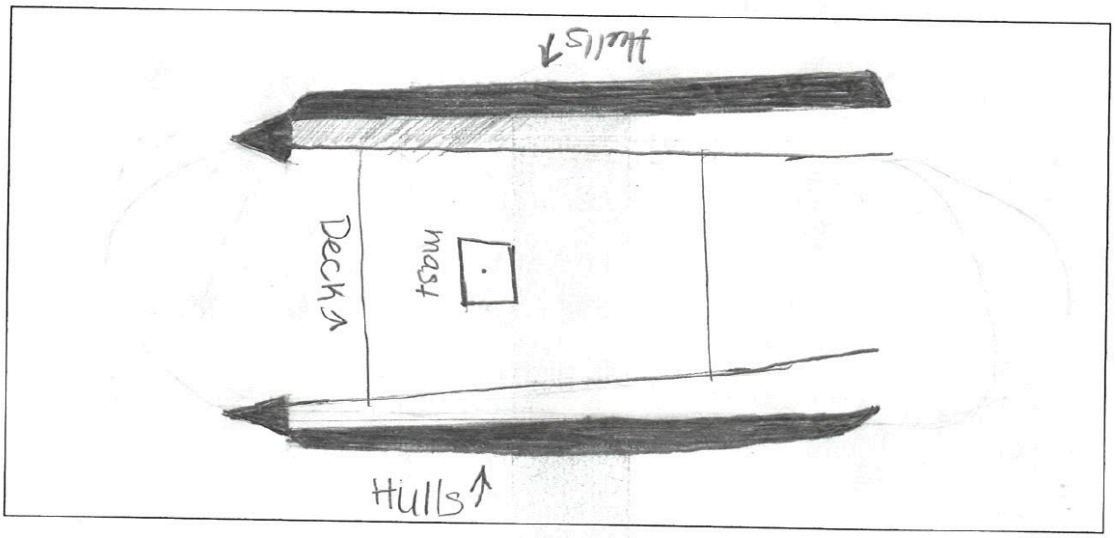
Your group should take time to discuss and make notes about how you will connect the various parts of your canoe. Wood glue

- How will you connect the hulls to the deck?
- How will you connect the mast(s) to the deck?
- How will you connect the sails to the mast(s)?
- If you decide to use a boom, how will the boom attach to the sail?
- How will you keep your sail in place?

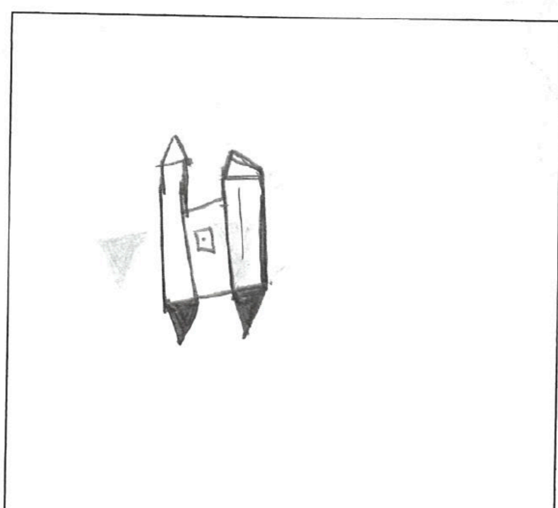
Now that you have made decision about your materials, please draw a complete diagram of your canoe. Label the materials. Include measurements. If possible, label and/or describe the points where one component will connect to another.

R

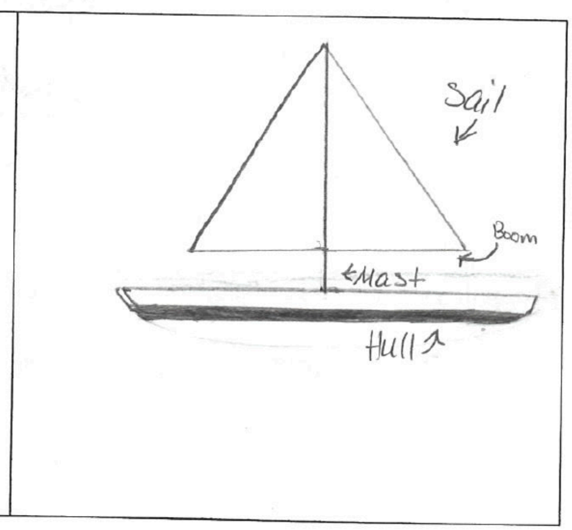
Top View:



Front View:



~~Rear~~ Side View:



NOTE: Tameika did not complete the separate "side view" page. Instead, she drew her side view here and did not draw a rear view. Also, she did not complete the optional exploded diagram.

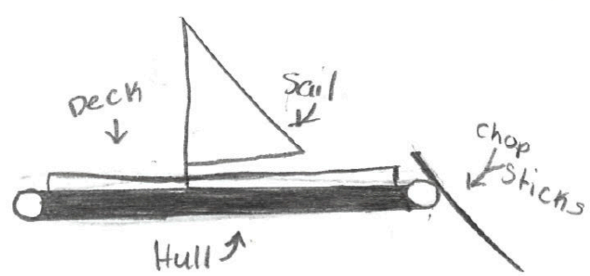
Appendix I

Tameika's Completed Data Collection Packet

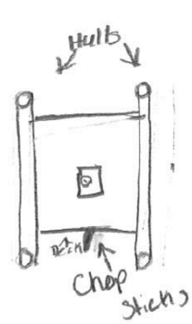
Documenting Your Initial Design

Now that you have built your canoe model, please draw a complete diagram of your initial design. Label the materials. Include measurements. Label and/or describe places where one component connects to another.

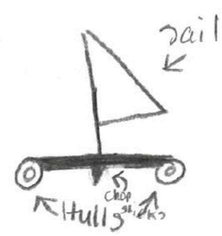
Side View:



Top View:



Front View:



Testing Your Canoe Model

Measurements:

Place your model in the Wind/Wave Tank. Using your stopwatch, record how long it takes your canoe to travel from Start to Finish. Record your times below:

	Trial 1	Trial 2
Initial design	59.40	9.5

Observations:

What worked well with this design?

When we turned the Sail around.

What did not work so well with this design?

The Sail and steering paddle didn't work so well.

**** Take your canoe to the "Repair and Rethink" room.*
*With the help of the U-M volunteers, make changes to your design. ****

Briefly describe the changes you made to your model:

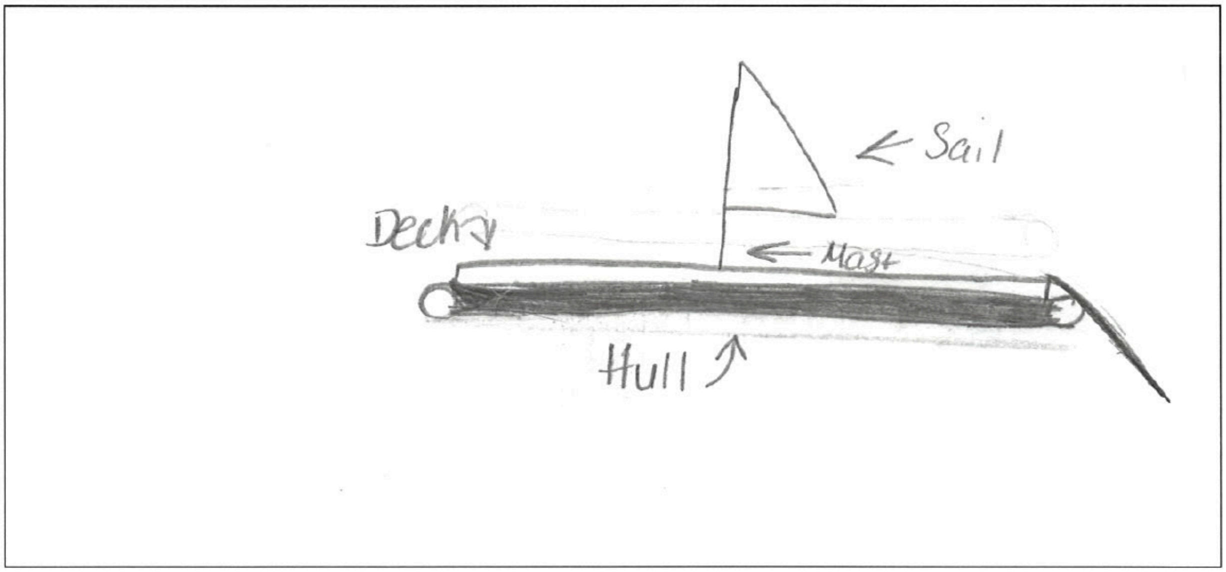
Me and my group are adding another sail so the canoe will balance

**** Return to the Wind/Wave Tank with your revised model and retest.*
*Please improve and retest your model multiple times. ****

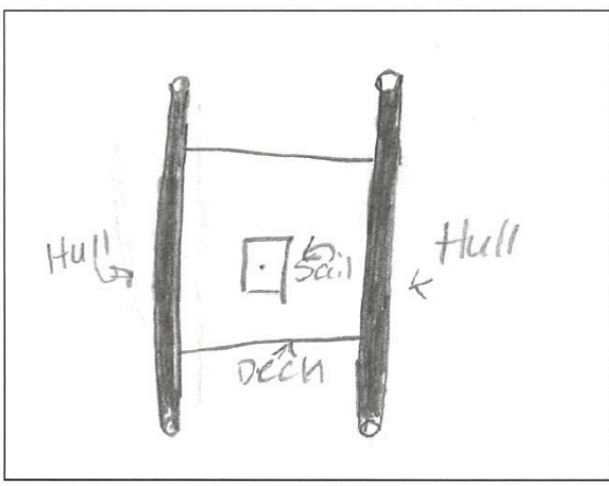
Documenting Your Final Design

Now that you have tested your canoe model and improved it a few times, please draw a complete diagram of your final design. Label the materials. Include measurements. Label and/or describe places where one component connects to another.

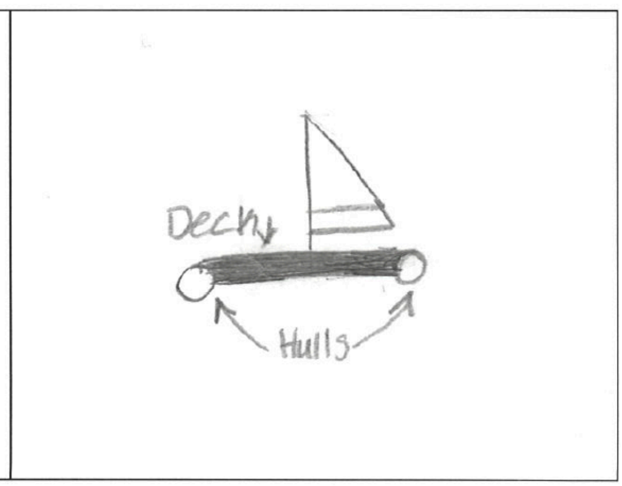
Side View:



Top View:



Front View:



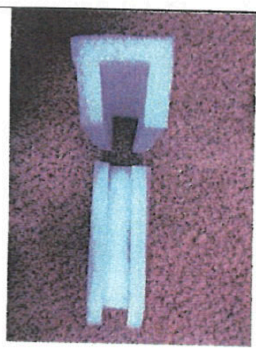
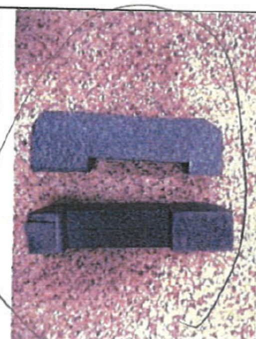
Appendix J

Sarafina's Completed Design Planner

Component 1: Hull

The *hull* is the part of the canoe that floats in the water and supports the rest of the canoe. Polynesian canoes had two hulls, so your model should also include two hulls.

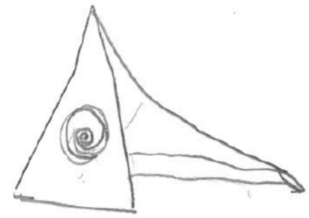
You have four options for hull materials:

			
Flexible foam	Pipe foam	Rigid foam	Plastic bottles

Please circle your material choice for your two hulls.

Why do you think that material is the best choice?

Rigid foam so it won't sink and won't blow away!



Component 2: Deck

The *deck* is the floor-like part of the canoe that connects the two hulls. The deck contains all of the living area and most of the storage area for the canoe.

For the deck, each group will receive a piece of corrugated plastic board that measures 18 inches by 24 inches. *Remember: your canoe cannot be more than 12 inches long.*

What are the *benefits* of having a **wide** deck? What about *drawbacks*?

more room, And more accessories! But, what if it was too wide and got stuck in a cavern!

What are the *benefits* of having a **narrow** deck? What about *drawbacks*?

if it was too narrow it would get through a cavern, But it would be too Small.

Would you like to layer your deck to make it thicker? If yes, where might it be helpful to layer your deck? Why?

Yes, because in case it floods so it won't sink

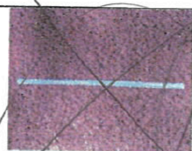
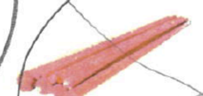
Record the dimensions of your deck:

Length: 10 inches x Width: 9 inches

Component 3: Mast

The *mast* is the large pole or poles that support the sails.

You have three options for mast materials:

 Plastic tube	 Wood dowel (1/2 inch)	 Wood dowel (1/4 inch)

Please circle your material choice for your mast.

Why do you think that material is the best choice?

Because it will fit in the hole and it will be secured by rubber cement,

Some Polynesian canoes only have one mast. Other canoes, like the Hokule'a, have two masts. Will your canoe have one mast or two? Why?

1 because it's more natural

Component 4: Sail

The *sail* is a flexible material that catches the wind to propel the canoe.

You have five options for sail materials:

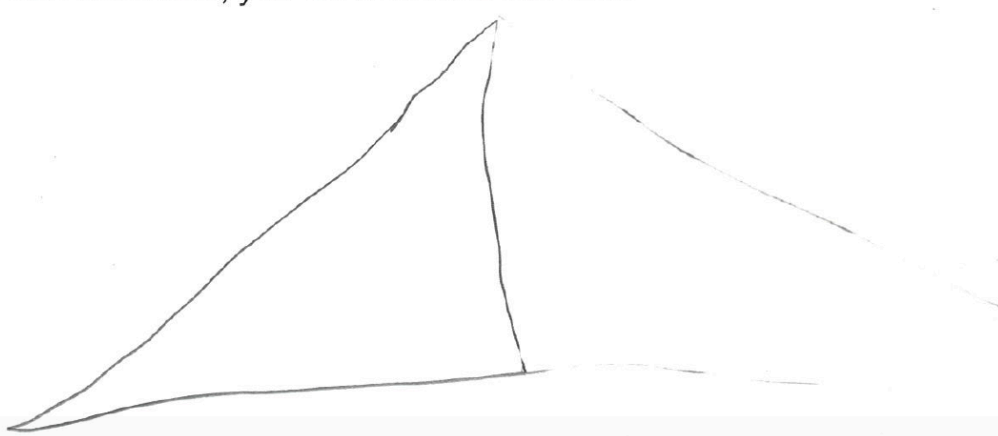
				
Burlap	Cotton	Nylon (hot air balloon)	Nylon	Plastic tarp

Please circle your material choice for your sail(s).

Why do you think that material is the best choice?

Because it can deflect rain,

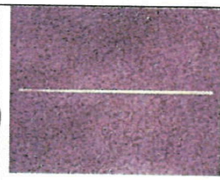
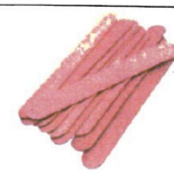
In the space below, sketch the shape of your sail. Include the measurements along each side. *Note: Unlike yachts or other western sailboat designs, Polynesian canoes only have one sail per mast. However, if your design has two masts, you will also have two sails.*



Optional component: Boom

The *boom* is a pole that helps to keep the sail open.

You have four options for boom materials:

			
Small dowels	Balsa wood	Craft sticks (thin)	Craft sticks (wide)

Please circle your material choice for your boom(s).

Why do you think that material is the best choice?

Because it's small and won't takeup Space.

What are the *benefits* of having a **boom**? What about *drawbacks*?

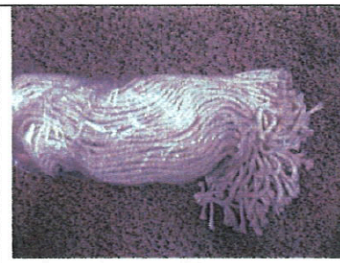
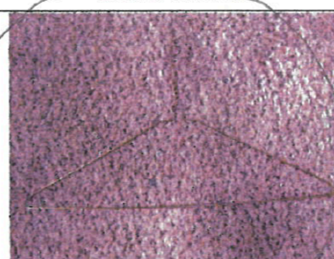
The goods are: it will help move the boat, But it could take up too much room.

Optional component: Rigging

Rigging is a general term for the ropes, chains, wires, etc. used to support the masts, sails, and other components of a canoe.

You may include as many pieces of rigging that are necessary to hold you canoe together, to support your mast(s), and to keep your sail(s) in place.

You have six options for rigging materials:

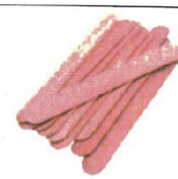
		
Cotton twine	Jute twine	Thick yarn
		
Nylon strap	Wire (hanger)	Wire (thin)

Please circle your material choice(s) for your rigging. [Note: you may use as many or as few of these rigging materials as you need.]

Optional component: Steering Paddle

A *steering paddle* is a vertical blade under the water that helps to change the canoe's direction. Because you are building a model, you will not be able to steer your canoe. However, you may still want to include a steering paddle to help your canoe sail in a straight line.

You have two options for steering paddle materials:

 Craft sticks (thin)	 Craft sticks (wide)

If you would like to include a steering paddle on your canoe, please circle your material choice.

Connections:

Your group will have to make many decisions about how to connect the various components of your canoe.

Other than drilling holes or cutting notches, you have six materials to choose from when connecting components:

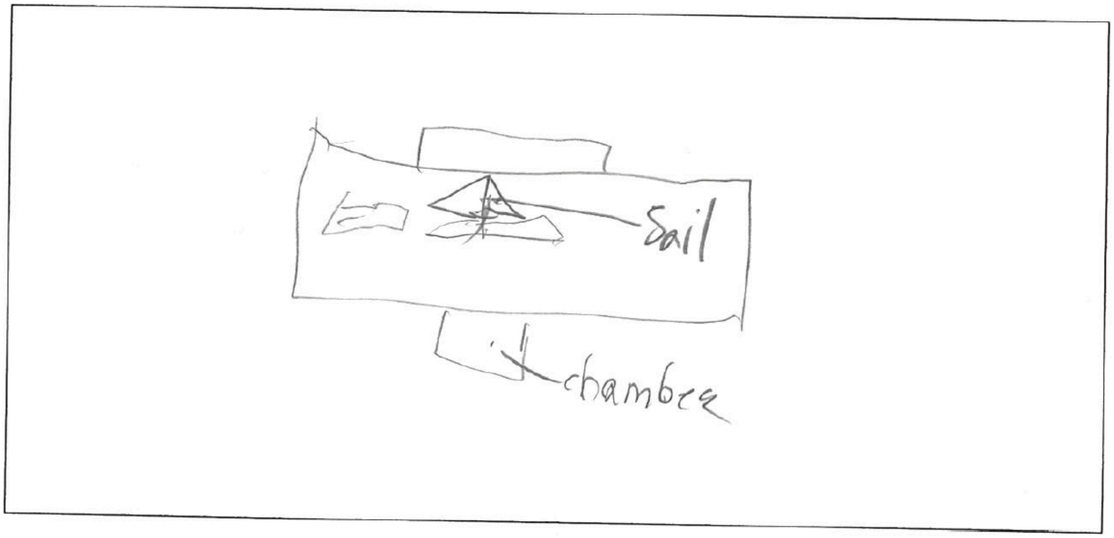
		
Duct tape	Craft glue	Tacky glue
		
Assorted glues	Rubber cement	Safety pins

Your group should take time to discuss and make notes about how you will connect the various parts of your canoe.

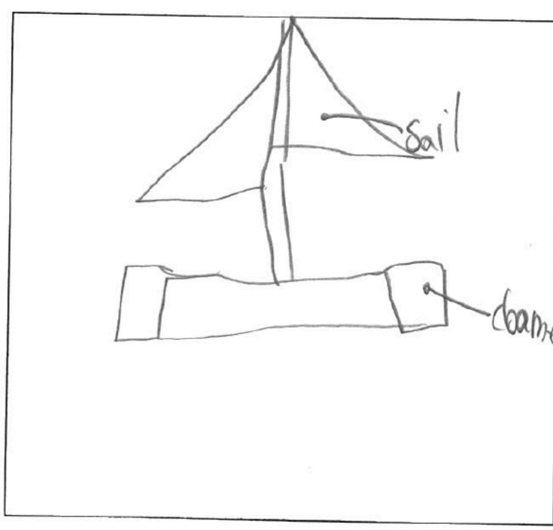
- How will you connect the hulls to the deck?
- How will you connect the mast(s) to the deck?
- How will you connect the sails to the mast(s)?
- If you decide to use a boom, how will the boom attach to the sail?
- How will you keep your sail in place?

Now that you have made decision about your materials, please draw a complete diagram of your canoe. Label the materials. Include measurements. If possible, label and/or describe the points where one component will connect to another.

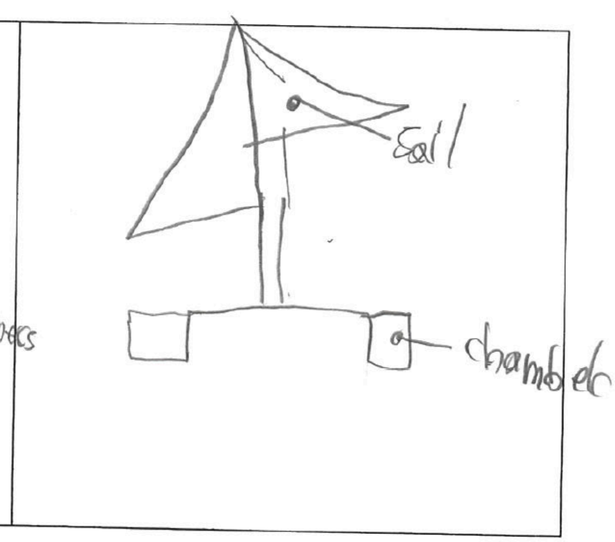
Top View:



Front View:

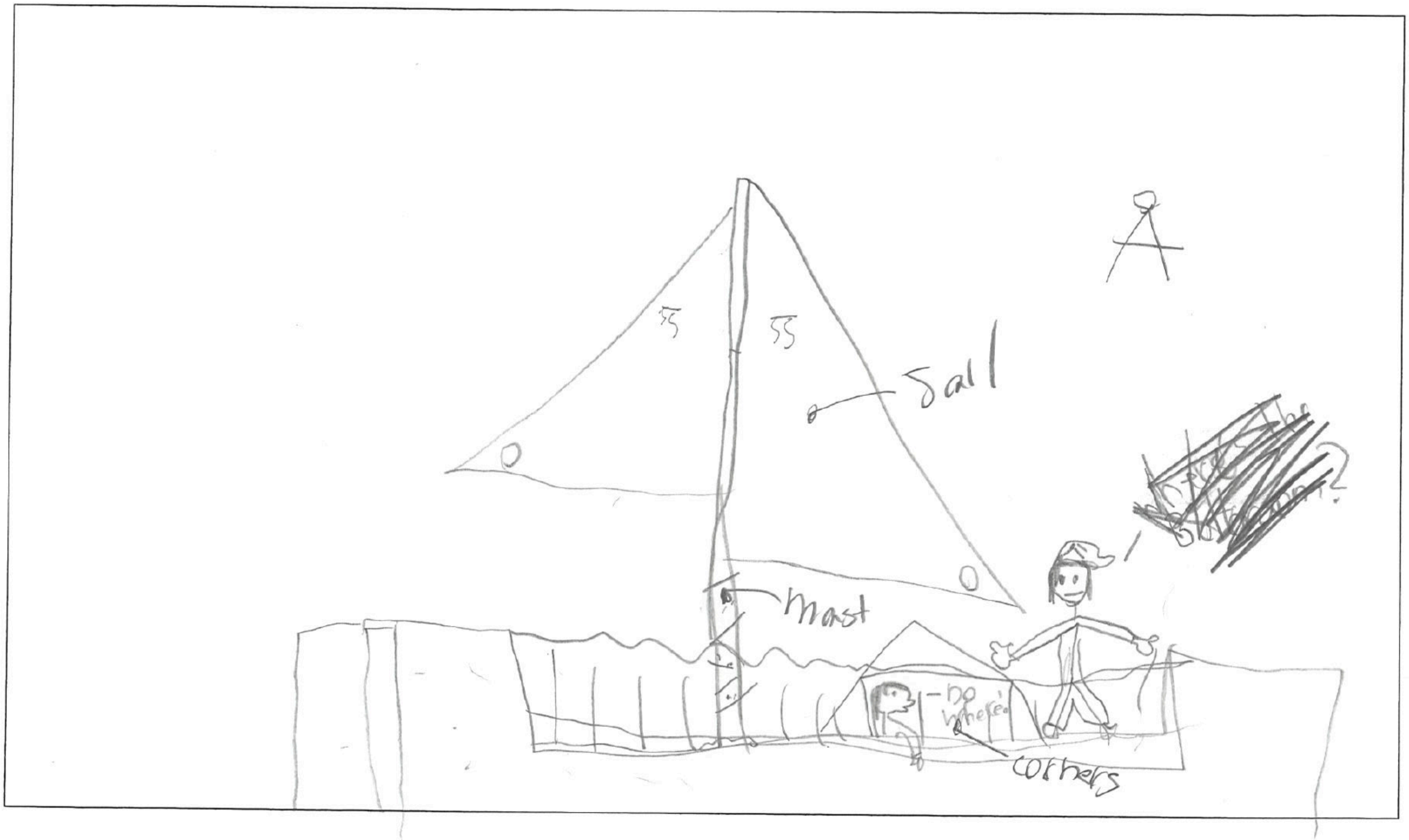


Rear View:



NOTE: Sarafina did not complete the separate "side view" page. Instead, she drew her side view on the exploded diagram page and did not draw an exploded diagram.

Optional: Exploded Diagram



Appendix K

Sarafina's Completed Data Collection Packet

Documenting Your Initial Design

Now that you have built your canoe model, please draw a complete diagram of your initial design. Label the materials. Include measurements. Label and/or describe places where one component connects to another.

Side View:

Top View:

Front View:

Testing Your Canoe Model

Measurements:

Place your model in the Wind/Wave Tank. Using your stopwatch, record how long it takes your canoe to travel from Start to Finish. Record your times below:

	Trial 1	Trial 2
Initial design		

Observations:

What worked well with this design?

____

____

What did not work so well with this design?

____

____

**** Take your canoe to the "Repair and Rethink" room.*
*With the help of the U-M volunteers, make changes to your design. ****

Briefly describe the changes you made to your model:

____

____

**** Return to the Wind/Wave Tank with your revised model and retest.*
*Please improve and retest your model multiple times. ****

In the tables below, record measurements and observations for your revised models:

	Trial 1	Trial 2	What worked well?	What did not work?
Revised Model #1	F	F	?	?
After testing this design, make improvements. Briefly describe what you changed:				

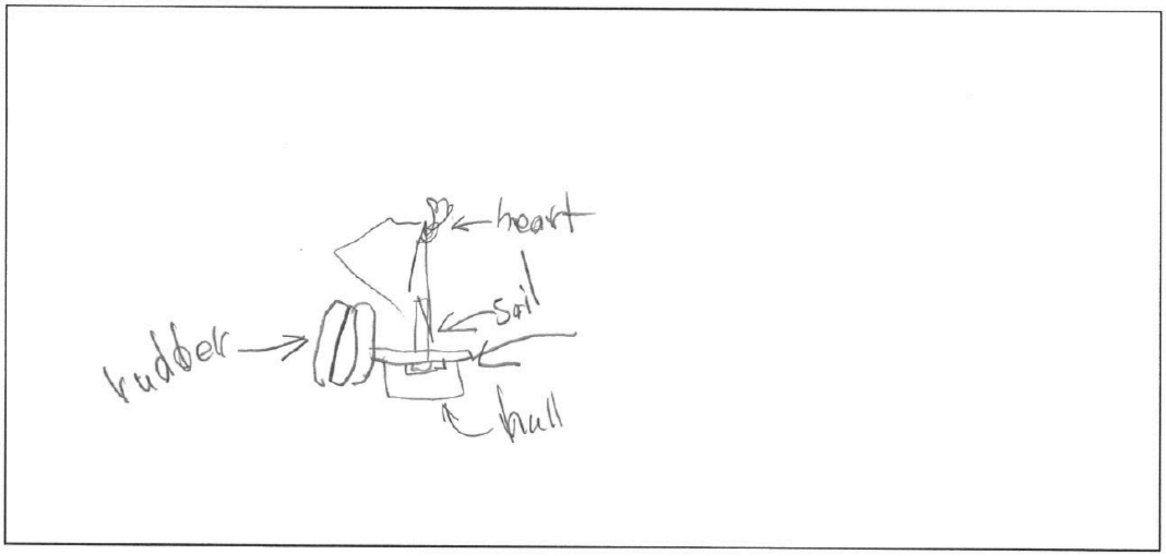
	Trial 1	Trial 2	What worked well?	What did not work?
Revised Model #2	C	D	?	?
After testing this design, make improvements. Briefly describe what you changed:				

	Trial 1	Trial 2	What worked well?	What did not work?
Revised Model #3	A+	B+	?	?
After testing this design, make improvements. Briefly describe what you changed:				

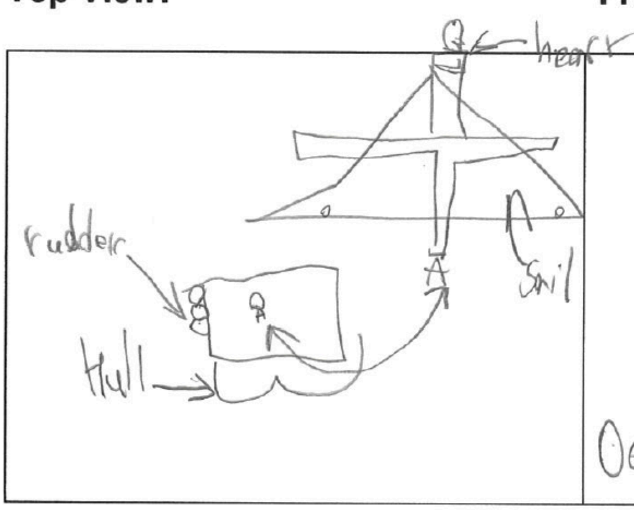
Documenting Your Final Design

Now that you have tested your canoe model and improved it a few times, please draw a complete diagram of your final design. Label the materials. Include measurements. Label and/or describe places where one component connects to another.

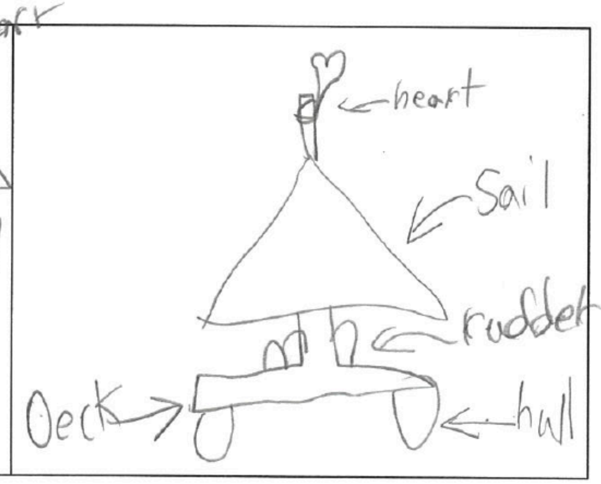
Side View:



Top View:



Front View:



Appendix L

Wayfinding Unit for Grade 5 [v3]

Driving Question:
How can we find our way in the world by using only the clues that are in our environment?

Unit Duration: 8 weeks (approx.)
5 weeks @ 4 lessons per week + 3 weeks for two final projects

Lesson Length: Each lesson takes approximately 1.5 hours

Final Projects: (A) Mālama Honua Challenge & (B) Canoe Project
You may choose to complete either or both projects depending on the time and materials you have available. We recommend two weeks for the Mālama Honua Challenge and one week for the Canoe Project, but each project could be condensed or extended depending on your circumstances.

Accommodations: For students who need reading support, we recommend installing the free text-to-speech extension called Read Aloud.
(Available for Chrome and Firefox)

All lesson plans and associated resources are linked from the Storyline below.
All materials may also be accessed directly from this Google Drive folder.

An online, multimedia version of the student notebook is available on the Collabrify Roadmap platform. Please send an email for access.

For questions, please contact Gabriel DellaVecchia at dellaveg@umich.edu

Administer the Pre-Assessment

*** WEEK 1: Voyaging - Why Then, Why Now? ***

Lesson 1: Launching of the Wayfinding Unit

Introduction: Imagining navigating across Michigan, with and without technology

Instruction:
* Choral reading of *Before the Story* text
* Viewing of open ocean video
* Writing about their thoughts/feelings before taking an unknown journey

Conclusion: Viewing of "On the Water" video to reflect on sights, sounds, and spirit

Lesson 2: Reading *Island below the Star*

Introduction: Reviewing the unit question

Instruction:
* Interactive reading of *Island below the Star*
* Writing an opinion about why someone would journey across the ocean

Conclusion: Viewing of "Reflections from Home" video to begin connecting to the present

Lesson 3: Reading about the Polynesian Voyaging Society

Introduction: Writing in response to reading *What is Polynesia?*

Instruction:
* Reading the End-Note from *Island below the Star*
* Interactive reading (with slideshow) of *Hokule'a* NPR article (part 1 of 2)

Conclusion: Answering any lingering questions before continuing the article tomorrow

Lesson 4: Investigating the Size and Brightness of the Sun

Introduction: Recalling the first half of the *Hokule'a* article

Instruction:
* Interactive reading (with slideshow) of *Hokule'a* NPR article (part 2 of 2)
* Viewing Star Trail Time Lapse video
* Physically modeling the rotation of the Earth and its revolution around the Sun
* Viewing and discussing the video of the Earth/Sun physical model
* Writing an argument about the size and brightness of the Sun

Conclusion: Combining the 3 C-E-R components into a single, cohesive written argument

*** WEEK 2: Preparing for the Voyage - What Do We Need? ***

Lesson 5: Investigating Turning Saltwater into Freshwater

Introduction:	Imagining packing for a vacation compared to a canoe trip across the ocean
Instruction:	* Interactive reading of *Provisions for Polynesian Voyages* text
	* Brainstorm a class list of potential items to pack
	* Interactive reading of *Water, Water, Everywhere* text
	* Making and investigating a solar still
Conclusion:	Predicting the amount of fresh water produced by each solar still

Lesson 6: Graphing Water Use

Introduction:	Interactive reading of *Basics of Wayfinding* text
Instruction:	* Drafting, comparing, and revising packing lists
	* Graphing water use in Hawaii and calculating individual/crew water needs
Conclusion:	Discussing water calculations and debating how much extra water to pack

Lesson 7: Calculating Weight of Personal Gear and Clothes

Introduction:	Interactive reading of *Rules of Conduct* and *What is Downwind Sailing?* texts
Instruction:	* Comparing and revising packing lists
	* Calculating the weight of personal gear and clothes
Conclusion:	Recording data for the solar still

Lesson 8: Calculating Total Canoe Weight

Introduction:	Viewing of "What is the Worldwide Voyage?"
	Interactive reading of *Crew Blog: Life is in the Clouds*
Instruction:	* Calculating the total weight of the canoe
	* Calculating the rate of water production of a solar still
	* OPTIONAL: Writing a persuasive letter to explain their packing choices
Conclusion:	Interactive reading of *Winds, Currents, and Latitudes* text
	Viewing of "What is the line between modern and traditional navigation?"

*** WEEK 3: Set the Course - Which Way? (Stars, Sun, and Moon) ***

Lesson 9: Exploring the Virtual Planetarium

Introduction:	Viewing of Polynesian Wayfinders Ted-Ed video
Instruction:	* Interactive reading of *Set the Course / Hawaiian Star Compass* texts
	* Investigating star movement with the Virtual Planetarium
	* Viewing of "How do you know when you are at the equator?"
Conclusion:	Calculating the rate of water production of a solar still

Lesson 10: Describing Patterns in the Stars

Introduction:	Re-viewing the Star Trail Time Lapse video
Instruction:	* Reading of *Hoku, the Star*
	* Investigating the movement of Arcturus with the Virtual Planetarium
Conclusion:	Viewing of "Polynesian Voyaging Technology"

Lesson 11: Inquiring about the Moon

Introduction:	Viewing of "How does the moon phase affect the sail plan?"
Instruction:	* Inquiring with the Light and Clues from the Moon slideshow
	* Interactive reading of *Crew Blog: The Navigators and the Night Sky*
Conclusion:	Modeling the phases of the moon

Lesson 12: Investigating the Earth's Wobble

Introduction:	Reviewing learnings about the stars and the moon
Instruction:	* Investigating the Earth's wobble with spinning round candles
	* Reading of *Why is Polaris the North Star?*
	* Viewing of The Axis of Rotation
	* Modeling solar stills
Conclusion:	Providing feedback on solar still models

*** WEEK 4: Hold the Course - How Far? (Wind, Waves, and Currents) ***

Lesson 13: Investigating Wave Patterns

Introduction: Reading of *Find Land*
Instruction: * Investigating wave patterns
Conclusion: Discussing observations from the investigation

Lesson 14: Investigating Wave Speed

Introduction: Re-viewing of "On the Water" video
Instruction: * Investigating wave speed
Conclusion: Creating and discussing a class line plot

Lesson 15: Writing Scientific Explanations about Waves

Introduction: Summarizing the wave speed investigation
Instruction: * Viewing of Wave Refraction video
* Writing a scientific explanation for the wave speed investigation
Conclusion: Discussing comparisons between the scientific explanations
Reading of *Crew Blog: Rhythm*

Lesson 16: Following Currents with Maps

Introduction: Reading of *Hold the Course*
Instruction: * Investigating the Earth's currents with the *Na'ale, the Ocean Waves* text
Conclusion: Viewing of "How do you handle the canoe in rough swells?"

*** WEEK 5: What is happening to the oceans? ***

Lesson 17: Modeling the Life Cycle of Plastic

Introduction: Viewing of "Hokule'a Sailed Around the World, But Couldn't Escape Plastic"
Instruction: * Reading of *Navigating Change*
* Modeling the life cycle of plastic
Conclusion: Providing feedback on the plastic life cycle models

Lesson 18: Investigating Microplastics

Introduction: Viewing of "Reality of Plastics" video
Instruction: * Interactive reading of *Microplastics* NPR article
* Viewing of "Microplastics in the ocean" video
* Investigating Microplastics
Conclusion: Revising and adding to plastic life cycle models
OPTIONAL: Viewing of "What happens to microplastics in the ocean?" video

Lesson 19: (Scientifically) Arguing About Recycling (Slideshow containing all videos with pauses)

Introduction: Viewing of Scientific Argument template and Waste Hierarchy image
Instruction: * Viewing three videos (1, 2, 3) to revise and add to plastic life cycle models
* Writing a scientific argument about the effectiveness of recycling
Conclusion: Discussing comparisons between the scientific arguments

Lesson 20: Evaluating The Ocean Cleanup Project

Introduction: Reading of *Crew Blog: Every Bit Counts*
Instruction: * Using a slideshow of texts and videos to evaluate the Ocean Cleanup Project
Conclusion: Discussing findings from their evaluations

*** Final Project A: Mālama Honua Challenge ***
How can we help Island Earth?

Lesson 21: Launching the Mālama Honua Challenge
Introduction: Viewing of "The Earthshot" video
Instruction: * Researching Elemental Excelerator and taking notes
Conclusion: Sharing patterns of problems and solutions from their research

Lesson 22: Research for the Mālama Honua Challenge
Introduction: Viewing of "The 'Lost City' Finding Its Future" video
Instruction: * Researching Young Voices for the Planet and taking notes
Conclusion: Sharing patterns of problems and solutions from their research

Lesson 23: Additional Research for the Mālama Honua Challenge
Introduction: Viewing of "Every Day is Earth Day" video
Instruction: * Researching BrightVibes.com and/or Environment blogs posted by the Polynesian Voyaging Society and taking notes
Conclusion: Sharing patterns of problems and solutions from their research

Lesson 24: Identifying a Problem and Solution(s) for the Mālama Honua Challenge
Introduction: Viewing of "The Interceptor, Explained" video
Instruction: * Identifying a problem for the Mālama Honua Challenge
* Defining the criteria for success for the Mālama Honua Challenge
Conclusion: Receiving feedback from peers on their potential solutions

Lesson 25: Putting Ideas Together for the Mālama Honua Challenge
Introduction: Reading of *Crew Blog: Navigating Our Educational Visions*
Instruction: Putting Ideas Together for the Mālama Honua Challenge
Conclusion: Receiving feedback from peers on their plan

*** Final Project B: Canoe Project ***

Phase 1: Planning

Introduction:	Reading of *To Build a Canoe* (at the beginning of Canoe Design Planner)
Instruction:	* Previewing pages 3-5 of the Canoe Design Planner * Reviewing the parts of the canoe using the Canoe Tour animation * Completing the Canoe Design Planner
Conclusion:	Receiving feedback from peers on their plan

Phase 2: Building

Introduction:	Discussing the importance of referencing their Canoe Design Planner
Instruction:	* Building their canoe models
Conclusion:	Sharing and troubleshooting difficult aspects of construction

Phase 3: Testing and Improving

Introduction:	Sketching diagrams of their initial design in their testing packet
Instruction:	* Using a baby pool and a fan, testing their canoe models * Making changes to their models and re-testing * Recording all data and observations in their testing packet
Conclusion:	Sketching diagrams of their final design in their testing packet

Phase 4: Sharing

Introduction:	Debriefing the overall testing/improving experience
Instruction:	* Each group presenting the results of their testing and their improvements
Conclusion:	Discussing patterns of problems and solutions from their testing

Administer the Post-Assessment