A Year-Long Study of Fourth Graders' Sense-Making with Modeling across Phenomena

by

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DEDICATION

This dissertation is dedicated to Ms. Waller and her 4th grade students.

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ABSTRACT

The research question guiding this study was, *How do features of models and the contexts in which they are taught and used influence upper elementary students' sense-making and engagement in the practice of constructing and using models*? An emphasis on engaging students in authentic and meaningful inquiry has led to a renewed focus on incorporating the scientific practices in science instruction. One practice central to the work of scientists is scientific modeling (Duschl, 2008; Manz, 2012). This study investigated how engaging in the practice of scientific modeling through the interpretation and construction of models influenced students' sense-making about scientific concepts and epistemological ideas related to modeling.

The study took place in one 4th grade class across an entire academic year of science instruction. The teacher enacted a project-based learning science curriculum, comprised of three units, the development of which was guided by the *Next Generation Science Standards* and *Common Core State Standards.* Each unit had a different central phenomenon (i.e., erosion, renewable energy sources, communication), but all units covered concepts related to energy and energy transfer. During each unit, students interpreted or constructed physical, paper-and-pencil, or animated computerized models.

Case study and design-based research methods were used to conduct an instrumental case study of the modeling events in one classroom with 36 students. Data sources included: video and audio recordings, field notes, researcher memos, student artifacts, assessments, and interviews with focal students during each instructional unit. The case was comprised of multiple sub-cases at the levels of the class and individual students. Class sub-cases detailed the ways in which engagement in the practice of modeling influenced students' discussions during whole-class instruction in each of the three units. Individual students' sub-cases documented the conceptual and epistemological sense-making trajectories of focal students within and across units of instruction. Focal students were selected for each unit to reflect a range of prior knowledge – low, typical, high – using unit pre-assessment measures.

The interpretation and construction of different types of models across a range of phenomena supported students and the teacher to introduce and take up ideas related to the scientific concepts in the units and epistemological aspects of modeling. Focal students demonstrated growth in their conceptual understandings related to the phenomena in each unit; however, students struggled to apply their understanding related to energy transfer in the more abstract contexts of renewable energy sources and communication. In addition, low levels of prior knowledge influenced specific students' sense-making, suggesting that students may require a threshold of prior knowledge to engage productively in the practice of modeling. Students demonstrated a trajectory of epistemological sense-making that began by discussing the purpose of models, followed by ways to improve the communicative power of models, and then the use of data to inform model construction. Constructing models provided insight into students' sense-making related to concepts and epistemological ideas related to modeling. The ability to include animation of student-constructed models also provided opportunities for students to show processes at work in the phenomena studied (e.g., erosion caused by moving water, electricity generation using wind and water, and the relationship between volume and distance). These findings suggest that engaging in the practice of modeling can support students' scientific sense-making. Implications for curriculum design, instructional practice, teacher learning and professional development, and policy are considered.

Chapter I

Introduction

"If someone is like, studying them like waves and stuff like we were, and they couldn't see like real waves in person, they could make a model of how they think that waves work so they could make a model then trust it and know about waves and stuff."

Students' sense-making of models and the practice of modeling is at the heart of this dissertation study. In this quote from HK, he explained why models are helpful to his learning and demonstrated how the use of models contributed to his sense-making regarding the role of waves in the process of erosion and the use of models in communicating that process. Scientific sense-making is a dialogic process that involves both the construction and critique of claims in the pursuit of the construction and refinement of scientific knowledge (Ford, 2012). This process relies on dialogue both between and within individuals. In both collective and individual sense-making, construction and critique must be present, which requires students to learn specialized types of discourse and dispositions, such as understanding how to use evidence to construct or critically examine a claim (Ford, 2012; Manz, 2012).

Engaging in scientific sense-making allows students to participate in certain ways of talking and reasoning that are characteristic of scientific practice, resulting in engagement in the processes instead of just the products of science (Ford, 2012). In addition, sense-making provides students with opportunities to understand why they are engaging in certain practices or assuming particular dispositions in response to a problem, thus making instruction sensible to students (diSessa, 2004). Understanding how students engage in sense-making about scientific phenomena, how sense-making develops across time, and how this process supports deeper learning and transfer can inform instructional practices and provide insight into developmental trajectories of how sense-making develops.

One scientific practice that is central to the work of scientists is scientific modeling (Nersessian, 2008). Historically, this practice has been considered too complex for young children due to the abstract nature of many models (Acher, Acrà, & Sanmartí, 2007; Duschl, 2008; Manz, 2012); however, both empirical studies and the *Framework for K-12 Science Education* (NRC, 2012a) have argued for the use of models and modeling in elementary science education. Models allow children to represent their thinking in a concrete way for themselves and others, and then interact with that representation to develop their conceptual and epistemological understandings (Acher et al., 2007). In addition, engaging in the practice of modeling provides opportunities for both individual and collective sense-making about scientific phenomena (Ford, 2012; Manz, 2012; Passmore, Gouvea, & Giere, 2014).

Research regarding the development of the practice of modeling in the elementary grades has provided examples of how elementary students of all ages can engage in the practice of modeling and with a variety of models in several topic areas. However, these studies are often limited to one topic area and do not document student engagement in the practice of modeling across multiple topic areas. This study addresses this gap in the literature by investigating how students engage with the practice of modeling and how engagement in this practice supports sense-making about scientific phenomena as well as the development of epistemological understandings related to modeling across multiple topics of study. Understanding how students engage with multiple types of models across multiple topics and how the practice of modeling develops across a year of instruction could inform the design of curriculum and instruction. In addition, this research can also inform the design of professional development in order to support teachers to engage students in the interpretation of models and the practice of modeling.

Research Question

The purpose of this study was to document the development of students' conceptual and epistemological sense-making though engagement in the practice of scientific modeling. The research question guiding this work is: *How do features of models and the contexts in which they are taught and used influence upper elementary students' sense-making and engagement in the practice of constructing and using models*?

Instructional Context of the Study

This study took place in Ms. White's 4th grade classroom. She taught 35 students, 28 of whom were in her class all day and 7 of whom traveled to her classroom for science and social studies instruction from another class. Ms. White was a first-year participant in the *Multiple Literacies in Project-Based Learning* Project, a multi-year design-based research study that developed year-long project-based learning science instruction for 3rd and 4th grades.

Research Methods and Design

The data sources for this study were: video and audio recordings of classroom enactment, field notes detailing whole-class instruction, researcher memos, student artifacts, assessments, and interviews with focal students during each instructional unit. Each day of science instruction was video- and audio-recorded and field notes were taken, which focused on whole-class portions of instruction. Students completed unit pre- and post-assessments, each with the same questions. Assessments included items regarding both conceptual and epistemological ideas related to modeling. Focal students were chosen using unit pre-assessment data to represent a range of prior knowledge – high, typical, and low – with respect to the central phenomenon of study in each unit. Focal students participated in interviews regarding their pre-assessment and post-assessment answers and the models they used and constructed during each unit. A subset of focal students participated in multiple units, which allowed me to document their sense-making across multiple units.

In order to study the ways in which engaging in the practice of modeling influenced students' conceptual and epistemological sense-making, I employed design-based (Brown, 1992) and case study methods (Stake, 1995). This study was an instrumental case study of the modeling events in Ms. White's classroom. The case was comprised of multiple sub-cases that documented whole-class instruction related to the use and construction of models for each of the three units as well as individual focal students' sense-making during each unit.

I constructed the sub-cases of whole-class instruction related to the modeling events during the curriculum by conducting categorical and descriptive analyses of each modeling event using field notes, video transcripts, researcher memos and class artifacts to characterize the ways in which Ms. White and her students engaged in the practice of modeling and the conceptual and epistemological ideas related to modeling that were introduced or taken up during the modeling events. I also conduced descriptive analyses of focal students interviews and artifacts to construct the sub-cases of individual students' sense-making across each unit, and in some cases across multiple units.

Organization of Dissertation

In the next chapter, Chapter 2, I discuss the conceptual framework, which includes the empirical literature and theoretical perspectives that informed this study. In Chapter 3, I provide an overview of the research design and methods used to collect and analyze the data to address my research question. In Chapters 4 through 6, I share the findings from Units 1 through 3, with each chapter focusing on one unit of instruction. I conclude in Chapter 7 with a discussion of my findings and their implications, the limitations of the study, and directions for future research.

CHAPTER II

Conceptual Framework

A Framework for K-12 Science Education argued that the incorporation of science and engineering practices, along with disciplinary core, ideas and cross-cutting concepts, in new science standards and curricula would provide an "authentic science education experience for all students" (NRC, 2012a, p. 265). This approach to meaningful learning could also support deeper learning, which the Committee on Defining Deeper Learning and 21st Century Skills defined as "transferable knowledge, including content knowledge in a domain and knowledge of how, why, and when to apply this knowledge to answer questions and solve problems" (NRC, 2012b, p. 6). Given the benefits of engaging students in the practice of modeling to promote deeper learning, researchers must understand the different features of the instructional context that support students' sense-making and productive engagement in the practice of modeling and the use of models.

The current study is informed by the literature regarding how the practice of modeling has been incorporated and measured in elementary science. The literature review first considers conceptual issues regarding models, the practice of modeling and epistemologies related to modeling; part two of the literature review considers empirical research regarding the instructional use of modeling; and part three provides the theoretical framework guiding the design of the current study.

Models and the Practice of Modeling

Models. Models are critically important in the construction, development, and communication of scientific knowledge (Gilbert, 2004). They serve as "a bridge between scientific theory and the world-as-experienced ('reality')" and are a specific type of scientific explanation (Lehrer & Schauble, 2010). This study drew on Lehrer & Schauble's (2010) definition of models as "analogies in which objects and relations in one system, the model system, are used as stand-ins to represent, predict, and elaborate those in the natural world" (p. 9). The role of models in constructing explanations is important for distinguishing their purpose as a tool to be used in the service of explaining a phenomenon, as opposed to the end product. In addition, the emphasis on models as analogies foregrounds important epistemological aspects of models, specifically that the components and the relationships between them in the model represent the components and relationships in the phenomenon, but they are distinctly different entities. The models serve as 'functional analogs' of the phenomenon (Lehrer, Schauble, & Lucas, 2008) because of the similarities shared between the model and the target phenomenon (the phenomenon that the model is designed to represent) with respect to the underlying mechanisms of both systems.

Due to the focus on underlying mechanisms and processes in models, they are also simplified representations (Louca, Zacharia, Michael, & Constantinou, 2011; Passmore et al., 2014; Schwarz et al., 2009). The model highlights specific elements of the target phenomenon, relationships between these elements, and rules that govern the system that the modeler considers important in order to explain the behavior of the phenomenon and the associated underlying processes (Gilbert, 2004; Louca & Zacharia, 2015; Manz, 2012; Nersessian, 2008; Schwarz et al., 2009). This property of models can make them difficult to interpret because they often do not share literal similarities with the phenomenon of interest (Lehrer & Schauble, 2012).

For example, when constructing a model to explain how humans can see things using their eyes, one might include a single arrow going from the sun to the object, and another single arrow from the object to the person's eyes. This model simplifies the concept of light waves traveling from the light source to the object and then from the object to the eye. Yet, the model does not include the other light rays that travel to the rest of the environment. This model is a simplified version of the phenomenon and can be used to provide an explanation for how we see things but does not include features that allow the user to explain why we see shadows or why we struggle to see objects in dimmer light. As such, additional models are necessary to explain these aspects of the phenomenon. There is no one model that can explain all aspects of a phenomenon; nonetheless, models can be revised so that they are better approximations of a phenomenon (Louca & Zacharia, 2015; Schwarz et al., 2009). Alternatively, additional models can be constructed to explain other aspects of the phenomenon (Passmore et al., 2014).

Models can be placed into three major categories: mental models, expressed models, and consensus models (Gilbert, 2004). *Mental models* are models that individuals construct in their minds to represent their own understanding of a particular phenomenon and make sense of the world (Gilbert, 2004; Passmore et al., 2014; Penner, 2000). However, mental models are inaccessible to others but can be made public through the creation of expressed models (Gilbert, 2004). *Expressed models* serve as tools that allow individuals to reify their thinking and engage in collective sense-making about the model and phenomenon (Penner, 2000). One outcome of collective sense-making is the construction of a *consensus model* that reflects the thinking about the phenomenon as agreed upon by a group (Gilbert, 2004).

Expressed models allow students to think about natural phenomena using a concrete representation (Penner, 2000). There are many types of expressed models that have been incorporated into science curricula, including (but not limited to) analogies, physical models, computerized simulations, and equations (Lehrer & Schauble, 2000, 2012; Nersessian, 2008). Some examples of physical models are the model of an ecosystem using a 2-liter soda bottle (Lehrer et al., 2008), or a computer simulation showing the behavior of molecules (Baek & Schwarz, 2015; Schwarz et al., 2009).

Models can serve as a powerful learning tool that help make the invisible visible to learners and support sense-making about complex scientific ideas. However, simply providing students with finalized models to use can prove a disservice to their understanding about how models, and the knowledge communicated by those models, are constructed (Duschl, 2008). Students should participate in the model-building process and the practices that are involved in modeling in order to engage in sense-making about scientific phenomena and how models are used to construct and communicate scientific theories. This study foregrounds the use and construction of models to make sense of phenomena and to support students in engaging in individual and collective sense-making using models.

The practice of modeling. The construction of models occurs through the practice of modeling (Fretz, Wu, Zhang, Davis, Krajcik, & Soloway, 2002; Manz, 2012). Studies that incorporate the practice of modeling have drawn from the work of experts to identify the processes by which scientists construct, test, and revise models as a way to inform authentic scientific practice (Halloun, 2007; Louca & Zacharia, 2015). The modeling cycle has been described by many researchers (Fretz et al., 2002; Louca & Zacharia, 2015; Louca et al., 2011; Manz, 2012; Schwarz et al., 2009). This cycle supports conceptual understanding through the process of modeling but can also support students' engagement in the epistemological aspects of science that are pertinent to the practice of modeling. For example, understanding of important epistemological ideas of science, such as that knowledge is not a fixed entity and the use of evidence in supporting the development and communication of knowledge, can be supported through the use of the modeling cycle (Baek & Schwarz, 2015).

The construction of models often begins with a stimulus, such as an experience that provides individuals with the opportunity to make observations or collect data about a natural phenomenon (Louca & Zacharia, 2015). Next, individuals construct a model that can be used to explain their observations or data during the *model construction* phase. During this phase, individuals also must make decisions about which elements of the phenomenon will be included, or amplified, in the model, and which elements will be omitted (Manz, 2012). Model construction involves an iterative process of moving between observations about the phenomenon and the model to determine how well the model explains the observations or experiences (Louca et al., 2011). Individuals may also have to invent elements to incorporate in their models that help explain invisible entities of the phenomenon, such as molecules or light rays traveling a distance (Lehrer & Schauble, 2012; Louca & Zacharia, 2012). During the *model evaluation* phase, the model is applied to a new situation to determine how well it can predict the behavior of a phenomenon in a new context (Louca & Zacharia, 2015; Louca et al., 2011). The model is tested using data or observations to determine how well it is able to represent or explain the phenomenon. Revisions to the model are made so that it can more accurately explain or predict a wider range of phenomenon during the *model revision* phase (Louca & Zacharia, 2015; Louca et al., 2011).

Students' engagement in the practice of modeling can also support the development of mechanism-based explanations and students' sense-making of phenomena (Zangori, Vo, Forbes, & Schwarz, 2017). Forbes, Zangori, and Schwarz (2015) identified five characteristics mechanism-based explanations that represent aspects of students' sense-making through the practice of modeling: components, or the selection of relevant aspects of the phenomenon that support the explanations; sequences, or the relationships between components; explanatory processes, "the connections students articulate between cause and effect for system processes" (p. 1423); mapping, the ways in which students relate their model to the target phenomenon; and scientific principle, students' connections to scientific theories to explain the phenomenon. The focus of models as a vehicle for developing and communicating mechanism-based explanations through engagement in the cycle of modeling can also support the development of epistemological understandings regarding the purpose of models and a focus on underlying mechanisms, instead of surface features. In addition to engaging students in the modeling cycle described above, this work suggests criteria for assessing students' sense-making through the use of models as a tool for explaining phenomena.

The emphasis on practices in science supports students to engage in deeper learning instead of memorization of facts. Engagement in practice also provides opportunities for students to develop cognitive dispositions similar to the ones used by scientists, such as critical thinking and the coordination of theory and evidence, which have also been identified as important 21st century skills (NRC, 2012b). Learning science as a process of inquiry instead of the process of fact finding also provides insight into epistemological ideas about science; for example, that there may be multiple alternative interpretations of data, multiple plausible answers, and that the goal of science is not to find the right answer but to find "the most defensible solution to the problem" (Schwab, 1966, p. 70). Learning how to participate in science results from interactions with others and the artifacts they create within the domain of science (Lehrer & Schauble, 2006; Nersessian, 2008; Schwab, 1966).

It is important to note that the practices that students engage in during school are not considered to be replicas of the practices that scientists use. Instead, students are exposed to core principles that guide scientists' thinking and knowledge-building and will aid in communicating understandings about "how we know what we know and why we believe it" (Duschl, 2008, p. 269). This perspective privileges epistemological understanding of activities within modeling, including: when they are used; how they are used; why they are used; and criteria for evaluating their strengths and weaknesses (Schwarz et al., 2009). Engaging students in the practice of modeling through the use of the modeling cycle enables them to co-construct conceptual and epistemological understandings (Lehrer et al., 2008), instead of focusing on the final product of science (Duschl, 2008). This perspective guided the development of instructional materials in the current study.

While this approach provides a more authentic representation of science, it also adds greater complexity that can create a confusing representation of science for students (Lehrer & Schauble, 2012; Passmore et al., 2014). One way to address this complexity is to communicate the centrality of sense-making in scientific endeavors (Passmore et al., 2014). Scientists engage in sense-making through the use of scientific practices as a way to understand the world (Nersessian, 2008; Passmore et al., 2014).

Models can serve as a tool to support sense-making about phenomena and about the process of knowledge construction. Passmore and colleagues (2014) proposed that engagement in the practice of modeling can support sense-making by providing opportunities for students to reason *with* and *about* models. When one reasons *with* models, one is using the model as a tool to make sense of a natural phenomenon. Conversely, when one is reasoning *about* models, one is evaluating the model as a tool and refining it in order to improve it use in sense-making (Passmore et al., 2014). Each reasoning process informs the other to improve the utility of the model (Passmore et al., 2014). Ultimately, the user's learning is shaped by the tool, but the tool is also shaped by the user (Passmore et al., 2014). Sense-making may be constrained by the properties of the model, but sense-making will also be constrained by how the user interacts with the model. This framework demonstrates how integrating both conceptual and epistemological aspects of modeling can support student sense-making about phenomena.

Research on the phases of the modeling cycle informed the types of instructional supports I developed in order to engage students in reasoning with and about models they used and constructed. The use of models to support students in sense-making about phenomena can also provide opportunities for them to develop epistemological understandings about models and modeling. In the next section, I will review how epistemological understandings related to modeling have been defined and measured.

Epistemological Understandings of Modeling

Meta-representational competence. The interplay between sense-making with and sense-making about models also highlights important epistemological ideas involved in the practice of modeling. The creator of the model must make decisions regarding which components and relationships within the target phenomenon to include and which to ignore, resulting in the amplification of certain aspects of the phenomenon (Manz, 2012). The decisions regarding which aspects to amplify will depend on the model's purpose and the explanation to which the model will contribute (Gouvea & Passmore, 2017; Lehrer & Schauble, 2010).

diSessa's (2004) work on meta-representational competence (MRC) can provide insight into students' development in the practice of modeling. MRC encompasses the considerations regarding the design, use, and examination of scientific representations. diSessa (2004) provided a synthesis of work in which he and his colleagues had been engaged regarding the development of students' understandings regarding the use and construction of scientific representations. He argued that students develop their own native competencies for working with and constructing representations through their everyday experiences, but that these competencies are often non-scientific and do not position the use and construction of representations as an opportunity for inquiry, critique, and revision. The contexts in which students invent and use representations are termed *functional niches*. When students construct representations that appear discordant with the expectations of scientific representation, one explanation could be that students were applying understandings or representational rules associated with non-scientific functional niches and "the properties of old functional niches show as maladaptation to new functional niches" (diSessa, 2004, p. 307). Despite potential difficulties moving from everyday to scientific function niches, students demonstrate strong abilities to invent new representations (diSessa, 2004), which could benefit them in the practice of scientific modeling.

diSessa (2004) also argued that understanding the role of a representation is a prerequisite for being able to engage in judgement about the quality of the representation. Supporting students to more deeply understand the role that a given representation is expected to serve will better support them to engage in the judgement and critique of that representation. The work by diSessa and colleagues also provides insight into more specific struggles students face when constructing representations. Their research found that students: (a) were very familiar with the use of color in their drawings, but its use begins arbitrarily before developing into more purposeful uses; (b) preferred realistic depictions of components in representations; and (c) drew on historical reasons for drawing (i.e., to tell a story) when drawing their own representations, which can influence their decisions regarding the components and purpose of the representation. Previous research related to elementary students' engagement in the practice of modeling has also found that children struggle to differentiate between drawings and more abstract scientific models (Schwarz et al., 2009). One approach to supporting students to develop more scientific approaches to making decisions regarding the components in their drawings is to draw students' attentions to the salient features that reflect the purpose of the representation and ignore the non-salient features. This could orient students to important features and emphasize their relevance. The youngest students that diSessa and colleagues worked with during this project were 6th grade students. However, the findings summarized by diSessa (2004) can provide insight into the struggles that may be experienced by elementary students while they are using and constructing one type of scientific representation, scientific models.

Epistemologies related to modeling. In addition to meta-representational considerations related to model, students should develop epistemological aspects related to the practice of modeling. Epistemological understandings involve the nature of scientific knowledge, and how such knowledge is constructed and evaluated (Metz, 2011). There are many different approaches to defining and determining the extent to which elementary students are capable of epistemological reasoning (Kuhn, 1999; Metz, 2011; Sandoval, 2005). Making epistemological ideas about science explicit to students and providing opportunities for students to develop their own epistemological understandings works against the notion of what Duschl (2008) described as "final form science" (p. 269). In addition, epistemological understandings of science are important components of transferable knowledge and supporting students to understand how knowledge is constructed and applied in different situations (NRC, 2012a, 2012b). Studies regarding the development of students' epistemological ideas related to science are numerous. Therefore, I will constrain my discussion to previous research regarding students' epistemological development as it relates to the use of models and the practice of scientific modeling.

Sandoval (2005) argued that an important distinction among types of epistemologies is the difference between formal epistemologies and practical epistemologies. Formal epistemologies are the ideas that students hold about knowledge and knowledge construction in formal science, while practical epistemologies are "the set of beliefs that students have about their own knowledge production in school science-the epistemological beliefs that guide practice" (Sandoval, 2005, p. 648). Practical epistemologies are closely linked to how students view themselves in the context of science and are reflected through the decisions that students make in the context of practice, such as: what counts as evidence, how much evidence is necessary to support a claim, and what kinds of data are needed to answer a question.

Another characteristic of studying practical epistemologies is that these epistemologies are closely tied to content that the students are studying. Sandoval (2005) emphasized the importance of not separating content knowledge from epistemological understanding and grounding questions about students' epistemological beliefs in the context in which they are studying. Therefore, studying students' engagement in the practice of modeling using multiple phenomena provides the opportunity to study the development of students' practical epistemologies in an authentic way.

Schwarz and colleges provided an example of how the development of epistemological understandings about modeling have been rooted in practice (Baek, Schwarz, Chen, Hokayem, &

Zhan, 2011; Schwarz & White, 2006; Schwarz et al., 2009). They identified knowledge specific to the modeling practice that is important to understanding how models function in science. They refer to this type of knowledge as *meta-modeling knowledge* (MMK) (Schwarz & White, 2006). Engaging in the practice of modeling involves practical aspects of constructing, using, revising, and communicating with models as well as epistemological aspects of modeling, such as understanding how and why modeling practices are knowledge-building activities (Baek et al., 2011). Students develop these understandings while working within a conceptual domain, resulting in co-development of both conceptual and meta-modeling knowledge (Lehrer et al., 2008; Manz, 2012; Schwarz et al., 2009).

Schwartz et al. (2009) studied the development of MMK within the context of an inquiry-based science unit. Students engaged in the modeling cycle throughout the unit in order to engage them in the practice of modeling and support conversations regarding aspects of MMK. The authors assessed student models that were created as artifacts during the unit and associated student interviews for evidence regarding shifts in two epistemological aspects of modeling: "models as generative tools for explaining and predicting phenomenon" and the revision of models to reflect new data or understandings. Schwartz and colleagues (2009) found that models drawn by 5th grade students incorporated more invisible components and reflected a shift from illustrative to more abstract drawings by the end of the intervention. In addition, students shifted from describing the phenomenon in their models constructed in interviews prior to the start of the intervention to explaining a process or using their model to explain a related phenomenon in interviews after the end of the intervention. This study suggests that engagement in the practice of modeling can support students to develop epistemological understandings related to modeling and that students' artifacts and interviews can provide insight into this development.

MMK is different from practical epistemologies because it draws on how models function in formal science to inform the types of epistemological knowledge about scientific modeling that students should develop, as opposed to identifying the types of epistemological understandings that arise out of engagement with the practice of modeling. However, both could be beneficial to study in relation to students' engagement in the practice of modeling, as documenting the epistemological ideas that students generate through practice and comparing these with the epistemological ideas of formal science can provide insight into ideas that might overlap.

Baek and Schwarz (2015) provided an example of one way to study aspects of MMK that arise and develop during engagement in the practice of modeling. They traced the epistemological beliefs of two 6th-grade students that arose from engagement in a unit on condensation and evaporation. They called these beliefs *epistemologies in modeling* (EIM) and defined them as epistemological beliefs that are applied while engaging in the practice of scientific modeling. EIMs are context-specific, situated within practice and are influenced by prior knowledge. They found that the students' EIMs shifted during the unit as a result of curricular events and interactions with classmates and the teacher, reinforcing the claim that collaboration can support students' engagement in scientific practice (Marx et al., 1997). They also characterized the students' EIMs as being both coherent and fragmented at different times as the unit progressed and the students worked to understand ideas related to the complexity of their explanations and their use of empirical evidence within their models.

In order to trace the development of students' EIMs, Baek and Schwarz (2015) developed coding schemes for the two EIMs of interest: (1) the inclusion of explanatory features in models from descriptive (Level 1) to mechanistic (Level 3); and (2) the incorporation of empirical evidence in their claims from (a) not understanding the definition of empirical evidence (Level 1) to (b) valuing and incorporating empirical evidence over other forms of evidence into their models (Level 3). In addition, they used social semiotics framework to analyze the impact of different curricular events on students' changing EIMs. This study provides an example of how students' epistemologies can be studied in the context of the development of the practice of modeling.

While Baek and Schwarz (2015) analyzed discourse during discussion time, they did not interview the students to probe their reasoning for decisions that influenced their EIMs. One possible reason for this is that the researchers stated that EIMs demonstrated during practice may differ from EIMs demonstrated afterwards when students are reflecting on what they did. However, Sandoval (2005) noted that a limitation of many studies is that they document the development of students' epistemological beliefs implicitly by analyzing student artifacts, instead of explicitly asking students for the reasoning behind their epistemological decisions. Therefore, Sandoval recommended that both artifact analysis and discourse analysis should be used when investigating students' practical epistemological beliefs. The components of MRC identified by diSessa (2004) have some overlap with aspects of MMK and EIMs. Previous work on the development of MRC can also provide insight into the development of these overlapping aspects and inform the design of instructional supports. For this study, I drew on ideas from MRC, practical epistemologies, and MMK to identify the specific epistemologies related to modeling that I explored in this study, the measures that I developed and used to document changes in students' epistemologies related to modeling, and my data analyses.

Scientific sense-making and epistemological understandings can be used to capture students' engagement in the practice of modeling; however, both of these measures will be operationalized differently depending on the features of the modeling context in which students are engaged. In the next section, I discuss how the use and construction of different types of models can be used to support students' sense-making and epistemological understandings related to modeling.

Incorporation of Models and the Practice of Modeling in Elementary Science

Expressed models are one tool that can help individuals make sense of scientific phenomena. They can be used to both develop and reify students' mental models of scientific phenomena (Penner, 2000). In addition, the construction and development of physical models create a public representation of an individual's thinking and understanding, which allows the model to be used in discussion with others as a tool for learning (Manz, 2012; Penner, 2000). The construction of expressed models shifts the emphasis of the modeling process from internal, individual thinking to external, collaborative thinking. The creation of expressed models can also document changes in students' sense-making over time and provide insight into learning pathways (Clement, 2000).

Different types of models provide different types of information and can be used for different purposes (diSessa, 2004; Wilkerson-Jerde, Gravel, & Macrander, 2015). For example, when modeling the relationship between temperature and the speed of molecular movement, equations and computer simulations can both be used to predict the behavior of molecules, but equations will model this relationship numerically while a computer simulation will show the relationship visually. These differences in use and representation of information also lead to differing levels of complexity among different types of models. Models that share a more literal resemblance to the target phenomenon are more accessible to younger children than models that hold very little or no resemblance to the target phenomenon (Lehrer & Schauble, 2012).

Scientists often use multiple types of models in their work due to the complex nature of natural phenomena and the constraints of any one type of model (Ero-Tolliver, Lucas, & Schauble, 2013; Nersessian, 2008; Passmore et al., 2014). Therefore, decisions about the type of models that should be used in a particular situation require understanding about the benefits and limitations of different types of models (Ero-Tolliver et al., 2013; Lehrer & Schauble, 2012; Lehrer et al., 2008; Louca & Zacharia, 2015). While it is unreasonable to expect young children to achieve this type of sophisticated coordination in elementary school, a reasonable expectation would be that young children who are exposed to multiple types of models when investigating a phenomenon begin to develop their "representational repertoire" (Ero-Tolliver et al., 2013, p. 2151), and begin to develop an epistemological understanding that different types of models provide different kinds of information (Schwarz et al., 2009). Exposure to multiple types and uses for models could also support the development of students' MRC.

The literature on the incorporation of models and the practice of in elementary science instruction has utilized several different types of models. This research provides insight into the benefits and challenges that students experienced while interpreting and constructing different types of models and the instructional context within which students engaged in the practice of modeling. I used this research to inform the development of instructional supports for this study and my hypotheses regarding ways in which different types of models can support students' sense-making about phenomena and the development of their epistemological beliefs related to modeling.

Physical microcosm. Physical microcosms provide an "entree" into modeling processes because they retain literal similarities between the model and the target phenomenon (Lehrer & Schauble, 2012, p. 174), resulting in lower cognitive requirements. One type of physical microcosm is the creation of physical objects; for example, kindergarten students created physical microcosms of a plant in order to capture the functionality of the plant's different parts (Louca & Zacharia, 2015). They purposefully chose materials that allowed them to model how the plant functioned. Some students chose to model the plant's roots using straws because one of the functions of the roots is to suck up water from the ground (Louca & Zacharia, 2015). The creation of this type of model came after students struggled to represent the functions of different plant parts using a drawing and decided that a different modeling medium would be more appropriate (Louca & Zacharia, 2015). The literal mapping between aspects of the phenomenon and components of the model (i.e., roots/straws) emphasized the relationships between structure and function in the model.

Penner, Lehrer, and Schauble (1998) also used the creation of physical objects to engage children in designing a functional model of a human elbow. The researchers observed that, despite explicit instruction to focus on function in their models, students initially focused on recreating physical similarities between their elbow and their model. However, as students tried to use their model to predict and explain the functioning of an elbow, they were prompted to revise their models to include elements that would better support them to predict and explain the function, as opposed to just the appearance, of the elbow. Though their engagement in the modeling cycle and the support of their teacher, students were able to construct knowledge and develop understandings about how the elbow functions through the iterative process of constructing, evaluating, and revising their models.

In both studies, children were engaged in all aspects of the construction-evaluation-revision cycle of modeling. The physical objects were tools to help students recognize relationships in the model that went beyond appearance, such as relationships between structure and function. These studies suggest that interacting with physical models can support students to evaluate these models since they were able to assess how well the model explained the phenomenon by interacting with the model. In addition, using physical models foregrounded the function of the model, an important aspect of MRC and the perquisite for being able to critique and judge models (diSessa, 2004). Neither study explored the ideas students held about the importance of representing function over appearance and how effective the physical models were in supporting the development of this epistemological idea. However, the study by Louca and Zacharia (2015) suggests that students began illustrating grappling with the limitations of different types of models, a key epistemological idea related to models.

Another type of physical microcosm are models that include remnants, or parts of the target phenomenon (Lehrer & Schauble, 2012). Ero-Tolliver et al. (2013) engaged 1st grade students in the process of constructing, observing and evaluating physical microcosms of the process of decomposition as a part of a year-long study on the process of decomposition. Students constructed physical models to observe the process of leaf decay using lettuce leaves. With their teacher's help, students made decisions about the design of the models, including the decision to construct four different lettuce-leaf models that differed in the type of soil use and the amount of water the model received and which aspects of the outside environment to incorporate in their models. Over the course of several weeks, students made observations and had to reason about what caused different rates of decay in their different models.

The models served as a tool in discussions about the process of leaf decomposition. Ero-Tolliver et al. (2013) argued that engaging young students in the practice modeling using a physical microcosm that included remnants, or aspects of the target phenomenon in the model (e.g., leaves or dirt) provided a good introduction for these students with no prior modeling experience due to: (a) the similarities between the model and phenomenon, (b) the fact that this activity engaged them in all aspects of the modeling process, and (c) the activity allowed them to consider how their model could help them explain the phenomenon of leaf decay. In addition, this study occurred over the course of an academic year, with modeling being one component of the unit. The use of modeling also allowed students to observe the process of decomposition and connect the prior knowledge that they had constructed previously in the unit with what they observed in the model. These observations by the researchers were only possible due to the extended timeframe of the study.

Manz (2012) studied the use of different types of models over a year of instruction to observe how the practice of modeling developed and supported 3rd grade students to construct knowledge about the reproductive success of plants. Students constructed physical microcosms to study methods of seed dispersal in their classroom. Their investigation included modeling outdoor processes of seed dispersal through the use of a fan, tub of water, and their own clothes. Students conducted tests with each of these materials to determine how well the process dispersed seeds over a distance and then were prompted by the teacher to consider how they could use these tests to make claims about seed dispersal outside. Manz (2012) reported that students participated in all aspects of the modeling process during this instructional activity. Students selected their seeds of interest from outside, made close observations about the seed, conducted tests about seed travel in different conditions, had to define measures in order to collect data during these tests, and then made claims about seed travel outside based on their close observations and tests using the models.

Students also constructed and interpreted different types of models during this study, including drawings and trade book texts. Manz (2012) explains that these representational forms were used to support students to observe invisible processes, such as seed dispersal, plant reproduction, and the relationship between form and function. During these instructional activities, students were using everyday objects that closely approximated natural processes and seeds from the actual environment. The use of remnants of the target phenomenon that students were modeling supported their ability to draw comparisons between the models and the phenomenon of seed dispersal (Manz, 2012). This study provided insight into how the use of multiple types of models supported students' individual and collective sense-making about a particular phenomenon. In addition, the study was conducted over an entire academic year which afforded the opportunity to study the development of students' individual and collective sense-making about reproductive success in plants and the role of modeling in supporting these processes by making students' ideas public for others to observe and critique.

Physical microcosms are not just relevant for younger elementary-school students but also can provide meaningful experiences for older elementary students. Sixth-grade students constructed a model of the ecosystem of a local pond to investigate the stabilization of ecosystems using a 1-liter soda bottle (Lehrer et al., 2008). Students attempted to create an ecosystem in their soda bottle in which aquatic plants and animals could survive. Students experienced varying degrees of success in stabilizing their model ecosystems and had to troubleshoot problems that they experienced in order to improve their models. Because these students were older elementary school students (and some would consider 6^{th} grade to be middle school), they had more autonomy in designing their models and were encouraged to work with their peers to address difficulties that arose with greater frequency than in the studies of 1^{st} and 3^{rd} graders reported above.

Interviews conducted after the conclusion of the unit revealed that about half of the students considered the models to be scale models (i.e., literal representations) of the local pond and the other half of the students characterized the models as "functional analogs" (Lehrer et al., 2008, p. 524), meaning that the model represented how the pond functions but was not a miniature version of the pond. This difference among the students highlights a potential challenge using physical microcosms. Due to their physical similarities with the target phenomenon, some students considered them to be a part of the phenomenon, instead of a representation of how the phenomenon functions (Lehrer & Schauble, 2012). This potential challenge reminds us that students must be supported by the teacher to understand the purpose of the model and the epistemological nature of models, such as the fact that models serve as representations of phenomena as opposed to being a piece of the actual phenomenon. This epistemological idea is represented in the studies that I previously discussed; however, this study emphasizes the importance of making explicit connections between the model and the phenomenon in order for students to develop an understanding of which components of the phenomenon are represented in the model and the nature of the relationships between these components.

The studies by Ero-Tolliver et al. (2013), Manz (2012), and Lehrer et al., (2008) provide examples of how engagement in the practice of modeling over an extended timeframe supports the development of conceptual and epistemological aspects of modeling, and how engagement in meaningful inquiry and use of scientific practices to support sense-making. This type of meaningful inquiry and engagement further supports the argument that extended time is required to document students' engagement in the practice of modeling and the development of sense-making.

The studies described above provide an example of a progression in how physical microcosms can be used in elementary school, and how an emphasis on epistemological understanding can increase as students progress through the grades. In 1st grade, the role of epistemology in the curriculum was present as students considered which aspects of the outside environment should be included and excluded, but consideration of how the design would affect the explanatory power of the model was implicit in their discussion and heavily supported by the teacher (Ero-Tolliver et al., 2013). In the 6th grade context, students were grappling with how well their models addressed their research questions, how to best measure ecological stabilization, and the kinds of claims they could make from their model and data (Lehrer et al., 2008). As students constructed and used physical microcosms, they were faced with questions about how well their models could be used to explain phenomena. This important consideration supported them to think about the primary purpose of models and modeling, which is to explain and predict phenomena.

These studies suggest that physical microcosms are useful at all levels in elementary school and the ways in which they are used and the types of claims that students can make using these models can increase in sophistication as children progress through school. Even though physical microcosms are considered to more accessible to younger children than other types of models, due to the overlap of similarities between the phenomenon and the model, they can provide foundational knowledge about the practice of modeling and should not be restricted to younger students (Lehrer & Schauble, 2012). In addition, several of the studies demonstrated the benefit of observing the practice of modeling over an extended period of time to track how this practice develops. In my dissertation study, I observed students over an entire year of instruction to capture how the practice of modeling and sense-making using models develops over time. In addition, I used interviews as one of my methods of data collection in order to probe students' epistemological ideas about modeling, similar to the work of Lehrer et al. (2008).

Computerized simulation. Computer simulations are another type of model that has gained popularity as computer technology becomes more accessible in classrooms. In practice, simulations represent scientists' current knowledge about natural phenomena and can produce data that allow scientists to test, revise, and improve their theories (Nersessian, 2008). Computer simulations can also be very useful in constructing and investigating phenomena that cannot be directly observed or manipulated, such as the behavior of molecules (Baek & Schwarz, 2015; Kawasaki et al., 2004; Wilkerson-Jerde, Gravel, & Macrander, 2015), the influence of forces on objects (Louca & Zacharia, 2015; Schwarz & White, 2006), and the ramifications of changes in an ecosystem (Kamarainen, Metcalf, Grotzer, & Dede, 2015). Computer simulations expose children to dynamic environments that allow them to visualize relationships and abstract concepts and think about processes at play in the phenomenon (Louca & Zacharia, 2015; Wilkerson-Jerde et al., 2015). The ability of computer simulations to make unobservable processes visible to students can improve the accessibility of these processes for young children (Kawasaki et al., 2004). However, this type of model can be difficult for children to understand because, similar to physical microcosms, they must look beyond literal similarities between the model and the phenomenon, and instead focus on relationships between variables in the model.

Previous research illustrates the varied ways that computerized simulations can be incorporated into curricula. One way to utilize computer simulations is to allow students to manipulate the conditions within an already constructed simulation. In this context, learning occurs through the manipulation of the model (Nersessian, 2008). Manipulation of the simulation is important for learning, as students will not be able to learn as much from the model if they cannot interact with it. Interaction with the simulation allowed students to make sense with models and the simulation served as a tool that supported students' sense-making (Passmore et al., 2014). Baek and Schwarz (2015) found that fifth-grade students' engagement with a computer simulation about the macroscopic and microscopic behavior of molecules in different states of matter influenced the revision of their models in ways that increased the explanatory power of the model for how the processes of evaporation and condensation occurred. Kawasaki and colleagues (2004) used a computer simulation for a similar purpose in an instructional unit on the concept of density and its effect on sinking and floating for a combined 3rd and 4th grade class. Students could manipulate the density of the materials in this simulation to determine how interactions between materials of different densities affects sinking and floating.

An interesting difference between the simulation used by Baek and Schwarz (2015) and the simulation used by Kawasaki et al. (2004) is the difference in physical similarity between the target phenomenon and the model. The simulation used by Baek and Schwarz provided a very realistic laboratory set-up, while the simulation used by Kawasaki and colleagues consisted of two boxes with different numbers of dots inside. In both cases, the authors reported that students took up aspects of the simulations in their own models and explanations. Informed by the research involving the use of physical microcosms, young students may struggle to relate the relationship between the simulation and the natural phenomenon if the computer simulation does not maintain enough literal similarity with the phenomenon. However, the degree of similarity that is required should be further investigated, given that simulations with varying degrees of similarity to target phenomena have been used successfully with different ages of elementary school students.

Computer simulations can be powerful learning tools that make invisible entities visible for students. However, the constraints of manipulating a pre-made simulation instead of constructing the simulation can make the underlying causal mechanisms more difficult to uncover (Penner, 2000). Programs that support students to construct their own simulations have been primarily studied with middle- and high school-aged students (Jackson, Stratford, Krajcik & Soloway, 1996; Louca & Zacharia, 2015; Wilkerson-Jerde, et al., 2015); however, these programs have not been used with younger students, possibly due to the demands on students' facility with computers and the abstractness of the simulations produced using programs (Louca & Zacharia, 2015). Simulations must provide a powerful enough experience so that students will be able to uncover the underlying mechanisms and relationships between components in the model, as opposed to just focusing on the surface appearance of the simulation. In addition, prior knowledge plays an important role in providing students with enough context to make sense of the underlying mechanism (Kamarainen et al., 2015; Lazonder, Wilhelm, & van Lieburg, 2009). Students with lower amounts of prior knowledge will struggle more to make sense of mechanisms or identify relationships between components in a simulation as compared to students with higher amounts of prior knowledge (Lazonder et al., 2009). While these findings on the influence of prior knowledge were collected in the context of using computerized simulations, they suggest that prior knowledge may influence students' use of other types of models in similar ways. There were no simulations used in the context of the current study; however, research on students' sense-making with simulations, namely the influence of prior knowledge, influenced my selection criteria for focal students in the study and my hypothesis that prior knowledge may play a role in students' trajectories of sense-making about concepts and epistemological ideas related to modeling.

Paper-and-pencil. Several articles investigating the use of modeling in elementary science instruction have incorporated paper-and-pencil models, mostly in the form of drawings and diagrams. These types of models have also been referred to as 2-D diagrammatic models by Zangori and colleagues (2017). In most cases, paper-and-pencil models were utilized in combination with other types of models, such as physical microcosms and computer simulations. Drawings and diagrams are most dependent on the way they are used in order to differentiate moments when students use them as representations and when they are used as models. For a drawing or diagram to act as a model, it must be used to explain causal relationships between components in the model, serve as a tool for sense-making, and undergo multiple iterations of testing and revision (Passmore et al., 2014; Penner, 2000; Wilkerson-Jerde et al., 2015). Engaging students in constructing their own paper-and-pencil models allows them to "engage firsthand in these practices of identifying key components, laying out a problem space, and organizing components relationally" (Wilkerson-Jerde et al., 2015, p. 397).

Kindergarten students who investigated the function of different plant parts made multiple iterations of paper-and-pencil models that began as representations of the appearance of their plant and shifted to diagrams of the processes involved in different parts of the plant (Louca & Zacharia, 2015). However, as I explained above in the section on physical microcosms, the students decided that these drawn models did not adequately represent the functions of the parts of the plant and decided to construct a physical microcosm.

Acher and colleagues (2007) reported on 1st grade students' construction of paper-and-pencil models that communicated the structure of different materials. These models explained the composition of materials, including the arrangement and bonds between invisible entities, and the process of transforming water into steam using fire. Through the use of different activities and support from the teacher, these young children were able to explore the ideas involved with the structure of material and communicate their understandings using models. They also considered how the arrangement and composition of water changed when it was heated. The children used their models to compare the structure of different types of materials and communicate the processes involved in water becoming steam (Acher et al., 2007).

Second-grade students also demonstrated development in their understandings regarding the properties of phases of matter through the construction simple paper-and-pencil particle models of matter (Samarapungavan, Bryan, & Wills, 2017). Particle models include the microscopic composition of matter, including the presence of atoms and the bonds between them. The simple particle models referred to by Samarapungavan et al. (2017) included the presence of microscopic entities that took up space, but they did not expect students to refer to these entities as atoms. The authors compared the enactment of an instructional unit involving the construction of particle models of solid, liquid, and gas in two classrooms. They found that students in both classrooms demonstrated development in their understanding of the properties of materials in different states of matter but experienced greater challenge when constructing models to explain the behavior of matter during phase changes. However, students in one classroom demonstrated significantly greater development in their understandings regarding the use of particle models to explain the microscopic behavior of matter as compared to the second classroom.

Samarapungavan and colleagues hypothesized that this was due to differences in the scaffolds that the two teachers provided related to modeling. They reported that both teachers provided students with scaffolds related to modeling; however, the teacher, whose students demonstrated greater gains, spent a greater proportion of time engaging students in the practice of constructing and revising their own models as compared to the second teacher. In addition, the authors noted that "the agency and locus of control in discourse were more evenly matched between students and teacher in [the first teacher's] class," as opposed to being more teacher-centered in the second teacher's class (p. 1014). These findings suggest that young children are capable of developing particle models of model in a heavily-scaffolded settings, and that the nature of teacher scaffolding can influence students' engagement in the practice of modeling.

Engagement in iterative cycles of modeling and investigation supported 3rd grade students' sense-making and construction of paper-and-pencil models to explain the hydrologic cycle (Zangori et al., 2017). Zangori and colleagues compared pre-unit and post-unit models from a unit on the water cycle across two years of instruction. The first year of unit enactment included supplemental pre- and post-unit lessons related to modeling in which students constructed their models. Year 2 of enactment included lessons throughout the unit that engaged students in the practice of modeling. The authors compared the gains in the scores of students' models from pre-unit to post-unit analyze differences in the five characteristics of mechanism-based explanations described in the previous section from Year 1 to Year 2 (see page 11). Zangori et al. (2017) found that students' models demonstrated significant aggregated gains in the five characteristics combined in Year 2 as compared to Year 1, and specifically this growth could be attributed to increases in the components and explanatory processes characteristics. These findings suggest that the iterative engagement in the modeling cycle, peer discussions regarding their investigations which informed revisions to their models, and the creation of a class consensus model supported students' sense-making regarding the components that were necessary for the models and the ways in which these components interacted with one another.

In a similar fashion, 5th grade students in the studies by Baek and Schwarz (2015) and Schwarz and colleagues (2009) constructed paper-and-pencil models of evaporation and condensation. These models communicated information about the molecular processes involved and also documented change in these processes over time. In both of these studies, students constructed multiple iterations of their models as they engaged in different investigations and activities (including using a computer simulation in Baek and Schwarz (2015)). The authors of both studies also emphasized that students revised their models as a result of trying to use their current version to explain and predict new phenomena.

Both Baek and Schwarz (2015) and Zangori et al. (2017) included the construction of consensus models in the curricular interventions. Baek and Schwarz (2015) documented shifts in one student's EIM related to the use of empirical data in the construction of the model as a result of participating in the construction of a small group consensus model. In the study by Zangori et al. (2017), students' growth with respect to their sense-making regarding the components that were necessary to include in models and their explanations of the relationships among these components suggests that the features included in the enhanced modeling curriculum, including the creating of class consensus models, supported students' sense-making.

This research informed the design of the current study with respect to the ways in which paper-and-pencil models can be used with other types of models and how this type of model was used to support students in explaining aspects of phenomena and consider important epistemological ideas related to modeling, such as the communicative power of the model (Baek & Schwarz, 2015) and the limitations of particular types of models (Louca & Zacharia, 2015). In addition, these studies suggest that the construction of consensus models could also support students' conceptual and epistemological sense-making.

Summary. The types of models presented in the literature indicate that a wide range of models have been successfully used with elementary school students, including: physical microcosms, computer simulations, and paper-and-pencil models. Each type of model was used to help students develop conceptual and epistemological understandings about modeling. One aspect of the instructional context that was absent from each of these studies was the investigation of different types of models to support students in making sense of multiple phenomena in different topic areas. While each study provided insight regarding how students can be supported to make sense of a single phenomenon, and in one case using multiple types of models (Manz, 2012), understanding how to support student to engage in the practice of modeling across multiple phenomena is an important area of research. This type of research would support: (a) learning more about how to support students to evaluate the representative limitations of different types of models, (b) evaluating the communicative power of their models, and (c) making sense of the phenomenon of study. This research would also provide opportunities to observe the ways in which students do or do not apply conceptual and epistemological understandings about modeling from one phenomenon to another, which is a measure of deep learning.

In addition, the findings by Samarapungavan et al. (2017) describe important ways in which teachers mediated the practice of modeling for their students. While many of the studies discussed in this section peripherally discuss the role of the teacher in students' engagement in the practice of modeling, the focus of these studies was on students' engagement in the practice of modeling or the development of their conceptual understandings. The teacher is a central figure in the instructional context and understanding more about the ways in which he or she mediates the practice of modeling is important for understanding how to support the development of students' sense-making.

Children's Understanding Regarding Energy

Energy is a cross cutting concept that is prominent in the NGSS standards for 4th grade; therefore, it figured prominently in the current study. Energy is an abstract topic and one about which students have an array of naive conceptions. The study of students' understandings regarding the concept of energy has a long history. Research on students' understanding of the concept of energy has repeatedly found that colloquial uses of the term energy are often different, or in conflict with the scientific uses of the term (Boyes, 1990; Driver, Squires, Rushworth, & Wood-Robinson, 1994; Duit, 1984; Hammer, Goldberg, Fargason, 2012; Neumann et al., 2013). Students also interchange the terms, *energy, power,* and *force,* when discussing energy (Driver et al., 1994; Liu & Tang, 2004). In addition, students used the term *force* in the same way that scientists use *kinetic energy* to describe the movement of an object (Driver et al., 1994).

Lui and McKeough (2005) suggested a developmental progression of an understanding of the concept of energy that had four stages: (1) energy comes from many different sources and can be present in different forms; (2) energy can be transferred; (3) energy is degraded (usually involving a loss of heat; (4) the energy in a system is conserved. They found through that 3rd and 4th grade students (ages 9-11) demonstrated understanding that energy comes from many sources and can be present in different forms but did not demonstrate understanding of energy transfer until Grades 7 and 8.

This research suggests that elementary students may be well-position to develop an understanding of the sources and forms of energy and some ideas related to energy transfer, but that energy transfer may be a challenging concept for 4th graders. Students' engagement in the constructing models to explain aspects of energy transfer could well support their sense-making.

Theoretical Framework

Social Constructivist Theory. The practice of modeling engages students in the construction and use of models as a tool to support sense-making of scientific phenomena. As stated previously, sense-making is a social process that requires engagement in the practices of science (Ford, 2012; Manz, 2012). The Committee on Defining Deeper Learning and 21st Century Skills also identified the importance of social interactions in the development of 21st century skills by explaining, "the transferable knowledge and skills encompass all three domains of competency: cognitive, intrapersonal, and interpersonal, in part reflecting the sociocultural perspective of learning as a process grounded in social relationships" (NRC, 2012b, p. 74). Both social constructivist theory and knowledge integration perspectives of learning share this emphasis on engagement in the practice of scientific modeling to support conceptual and epistemological sense-making.

According to Vygotsky (1978), learning is a social process that is context-specific, mediated by psychological tools, and results in changes in individual's psychological development (John-Steiner & Meehan, 2000; Palincsar, 1998; Scott & Palincsar, 2009). Wells (2000) identified three key features of social constructivist theory: (1) the influence of culture on development, (2) the mediating role of artifacts, and (3) the interdependent relationship between individuals and society. Vygotsky stated that development occurred first on a social level and second on an individual level (Vygotsky, 1978). Learning processes begin as social interactions between individuals (interpersonal) and are then is internalized by the individual (intrapersonal). In other words, higher psychological functioning is situated in a social context as internalization arises from interpersonal interactions (Scott & Palincsar, 2009). Due to the influence of the environment, histories of the contexts in which individuals operate are important to understand due to their role in the development of the current environments and the individual that operate within them. Individuals cannot be studied in isolation because the important roles that past and present contexts play in learning and development must be taken into account. Longitudinal studies of learning environments can provide insight into how the practice of modeling develops within the context of PBL instruction. In addition, studies of this nature can also provide insight into the interplay between curriculum and instruction, as well as how the social interactions among students and the teacher shape engagement in the practice of scientific modeling and the use of models to make sense of phenomena.

The second feature that Wells identified was that tools and artifacts mediate learning by influencing and changing human behavior (Wells, 2000; Vygotsky, 1978). Psychological tools include: language, mathematical symbols, concepts, content knowledge, strategies, and technology (Lee & Smagorinsky, 2000), and allow individuals to engage in shared meaning-making (Wells, 2000). Vygotsky believed that humans were not bound by their genetic abilities and instead were shaped by their environment, including the tools and artifacts used in that environment. Therefore, tools and artifacts convey histories and norms of the community (Wells, 2000). In order to understand and use tools in culturally appropriate ways, individuals must learn from older members in the society (Wells, 2000). Models can serve as tools that mediate interactions between students and the teacher and externalize students' ideas for collective sense-making. In addition, norms regarding how models are used in science have developed over time through the use of models within scientific communities. By engaging students in the practice of scientific modeling, they have the opportunity to engage peripherally in the scientific community through interacting with one of the tools that this community uses.

The third feature identified by Wells is the interdependent relationships between individuals and society. Societies are comprised of “a set of overlapping activity systems with their associated communities of practice” (Wells, 2000, p. 3). These activity systems rely on new membership to sustain them and for old members to teach new members the norms and culture of the system. Therefore, new individuals begin as peripheral participants to the system and move inwards towards the center as they learn more about the system. Tools and artifacts are important in activity systems, because different activity systems have different artifacts that function to convey meaning and knowledge. By engaging students in contexts where they are using scientific practices and grappling with authentic questions, they are able to enter the activity system of science as peripheral participants and are develop cognitive dispositions that are characteristic of experts through observation and participation in practice (Nersessian, 2008). Understanding the contexts in which learning occurs and the commonalities that students identify among familiar and novel contexts also can inform the design of learning environments that support deeper learning and mechanisms of transfer (Engle, 2006).

Knowledge Integration Perspective. In addition to social constructivist theory, the development of students’ sense-making and engagement in the practice of modeling can also be informed by knowledge integration perspectives of learning, specifically the Knowledge Integration Framework (Clark & Linn, 2013; Linn, 2000; Linn, Eylon, & Davis, 2004). This theory shares an important feature with social constructivist theory, namely that social interactions within the learning environment are integral to learning processes.

Knowledge integration perspectives of learning were presented as an alternative theory of traditional conceptual change theories that suggested students' non-canonical ideas needed to be replaced (Linn, 2008). Instead, knowledge integration perspectives argued that students' prior knowledge and experiences served as important building blocks upon which new knowledge can be added. Students routinely encounter scientific phenomena in their everyday lives that contribute to their "repertoire of ideas" of how the world works (Linn, Eylon, & Davis, 2004, p. 30). These understandings are often context specific and result from interpretation of experiences with other individuals and groups, media (e.g., newspapers, websites, etc.), and formal learning experiences (Linn et al., 2004). Therefore, students enter the classroom with their own mental models of scientific phenomena that can act as building blocks for their learning (diSessa, 2000; Linn, 2000). Documenting students' initial ideas regarding phenomena is important in studying learning processes (Clement, 2000). These ideas can be made visible to researchers, teachers, and peers through the construction of expressed models.

Students often hold multiples ideas about a phenomenon, some of which may be identical or may contradict one other but all of which constitute conceptual ecologies (Clark & Linn, 2013). These repertoires of ideas are organized into knowledge webs that are influenced by social, cultural, and epistemic views of science, along with previous experiences (Linn et al., 2004). A knowledge integration perspective of learning argues that eliciting these ideas is an important first step in instruction in order to collect the range of ideas with which students are currently working. When students are confronted with new information and models, they must evaluate their own models and ideas against this new information to determine if this knowledge is new, different, or relevant to them (Linn, 2000, 2005). An important role of instruction is to present students with or expose them to sufficiently powerful experiences, termed *pivotal cases*, that “enable students to sort out previously contradictory or disconnected views of scientific phenomena” (Linn, 2008, p. 708). Linn explains that the use of pivotal cases supports students to draw comparisons between their own ideas and scientifically normative ideas and “encourage students to create narrative accounts of their ideas using precise vocabulary so they can discuss them with others” (Linn, 2008, p. 709). As students engage in sense-making about phenomena through the use of pivotal cases, they will promote some ideas, demote other ideas, change connections among ideas, and more relevant ideas will, ideally, become more systematically used in explanations of phenomena (Clark & Linn, 2013).

Similar to scientific sense-making, knowledge integration involves the evaluation of new and existing ideas and the connections between these ideas in order to make sense of scientific phenomena (Linn et al., 2004). Instruction can facilitate exposure to different models in order to support knowledge integration and provide students with opportunities to add to and evaluate ideas in their repertoire (diSessa, 2000; Linn, 2000; Linn, Clark, & Slotta, 2003). Drawing from the knowledge integration perspective, engagement in the practice of modeling can record the ideas that students are applying to a situation at any given time. In addition, interviews with students about their models could provide insight into the relative hierarchy of ideas that students apply in a given context (i.e., which ideas are central to students’ sense-making, changes in the centrality of students’ ideas).

Through the close study of the nature of social interactions among members of the classroom, how tools and artifacts are developed and used to mediate those interactions, and how collective and individual sense-making unfolds across a year, I will investigate how engagement in the practice of modeling and the use of models supports students’ sense-making about phenomena and emerging epistemologies related to modeling.

CHAPTER III

Research Methods and Design

In this chapter, I describe the methods used in the design of this study, the collection of data, and the data analyses. The purpose of this study was to investigate how 4^{th} grade students in one classroom engaged in the practice of scientific modeling and how engagement with this practice, through the use and construction of models, influenced sense-making about scientific phenomena and epistemological understandings related to models and modeling, in order to identify the following: (a) how engagement in the practice of modeling was supported by the teacher; (b) how the construction of models influenced students' sense-making about the domain of study; (c) how prior knowledge that students brought to the conceptual domains influenced their sense-making about phenomena; (d) how students' sense-making was reflected in their model construction; (e) how students communicated their conceptual and epistemological understanding through the design and use of the models they construct; and (f) how the practice of modeling and sense-making with models influenced transfer of learning across modeling contexts.

Research Context

This dissertation study was conducted within the *Multiple Literacies in Project-Based Learning* (MLs) project. The MLs project seeks to design 3^{rd} and 4^{th} grade science curriculum that integrates science, math, and language literacy opportunities and aligns with NGSS, and select English Language Arts and Mathematics *Common Core State Standards*. The MLs project employs design-based research (DBR) methods to study the implementation of PBL curriculum, student learning outcomes of engagement in PBL, and to inform revisions to the curriculum. DBR methods seek to improve instruction that is theoretically grounded and feasible to enact in the classroom (Brown, 1992). According to Cobb, Confrey, diSessa, Lehrer and Schauble (2003), the goal of design experiments

> "…is to develop a class of theories about both the process of learning and the means that are designed to support that learning, be it the learning of individual students, of a classroom community, of a professional teaching community, or of a school or school district viewed as an organization" (p. 10).

Therefore, the context within which the instruction occurs is critically important to understanding how learning is actualized in a classroom setting.

This work is accomplished through iterative cycles of instructional design, implementation, and revision (Brown, 1992; Cobb, McClain, & Gravemeijer, 2003). There are multiple levels of analyses within DBR, namely bottom-up analyses that occur during the day-to-day instruction that support changes made during implementation to improve learning opportunities for students, called *minicycles*, and top-down retrospective analyses that inform theories of learning and development, called *macrocycles* (Cobb, McClain et al., 2003). The use of minicycles can support the research team's understanding of why the macrocycle unfolded in a specific manner (Cobb, McClain et al., 2003). The use of minicycles and macrocycles supports the comparisons of hypothesized and actual learning trajectories. *Hypothesized learning trajectories* are created using theoretical understandings of learning processes and the conditions in which they occur in order to "place them in harm's way" (Cobb, Confrey, et al., 2003, p. 10), and study "an initial conjecture about a prospective interaction between characteristics of tasks as they are realized in the classroom and student responses may be tested" (Cobb, Confrey, et al., 2003, p. 10). The *actual learning trajectory* documents how learning processes unfold and alternative processes that arise.

The creation of hypothesized learning trajectories involves considering the anticipated developmental starting points of students, the desired developmental endpoints, and the anticipated learning pathways between the starting points and endpoints (Cobb, McClain et al., 2003). The analyses of minicycles and macrocycles inform the development of the actual starting points, end points, and learning pathways and contribute to revised learning pathways.

The data I collected during the implementation of the curriculum informed immediate changes to the curriculum in the following days or weeks, and retrospective analyses after implementation concluded. My retrospective analyses contributed to the revision process for the next round of implementation the following year. In addition, my hypotheses about how to best support students' sense-making and epistemological understandings related to modeling were reflected in how students were positioned to use and interpret models and engage in the practice of modeling as well as the revision choices that are made during the implementation phase.

Instructional Context

Design of the curriculum. Researchers on the broader MLs project designed the units using the features of project-based learning (PBL). PBL engages students in meaningful, authentic inquiry and provides opportunities for participation in the practices of science with the goal of supporting students to develop deep conceptual knowledge and epistemological understandings about how scientific knowledge is constructed and critiqued (Krajcik, McNeill, & Reiser, 2007). PBL's approach to curriculum design and enactment draws from constructivist approaches to learning (Blumenfeld, Krajcik, Marx, & Soloway, 1994). Condliffe, Visher, Bangser, Drohojowska, and Saco (2017) identified several common features of PBL: (a) the use of a driving question, (b) learning goals that incorporate big ideas, (c) the creation of artifacts, and (d) the dedication of significant amounts of time to the completion of the artifacts (Condliffe, 2017). In addition, Marx, Blumenfeld, Krajcik, and Soloway (1997) provide additional features of PBL in science: the use of collaboration and technological tools. I will provide a brief description of each feature of PBL and the way in which each was incorporated in the curriculum used in this study.

Driving questions frame the unit of study and provide motivation and reasons for engaging in inquiry. Marx and colleagues (1997) provided three criteria for driving questions; They must: (1) support students to develop conceptual understandings outlined in state standards, (2) motivate to students to engage with real-world problems, and (3) be feasible for students to investigate and design solutions. These criteria illustrate how the use of driving questions in PBL can support students' sense-making and engagement in disciplinary-specific ways of developing and using knowledge and skills in science. The driving question for each unit in this curriculum introduced students to a problem that they might encounter in their daily lives.

The use of driving questions suggested by Marx et al. (1997) also demonstrates how the common feature of PBL identified by Condliffe et al. (2017) that learning goals address big ideas in science, as opposed to surface level memorization. Consistent with NGSS's multi-dimensional design, the units included multiple opportunities for students to engage with disciplinary core ideas, scientific practices, and cross-cutting concepts. Cross-cutting concepts "bridge disciplinary boundaries, having explanatory value in much of science and engineering" (NRC, 2012a, p. 83). *The Framework for K-12 Education* identified energy and matter as one of the seven cross-cutting concepts, and more specifically, energy transfer as one of the important components of this concept (NRC, 2012a). Therefore, these units incorporated the practice of modeling and the concept of energy transfer into instruction throughout the year.

The creation of artifacts that are responsive to the driving question provides students with opportunities to represent the knowledge they have developed in tangible ways that may be of interest to scientists, students' families, or the community (Tal, Krajcik, & Blumenfeld, 2006). Artifacts can be constructed both throughout the project and as a culminating response to the driving question. Given their tangible nature, these artifacts support student discussion, critique, and revision. In addition, artifacts are often the product of collaboration among students, another essential feature of PBL (Marx et al., 1997). Collaboration can occur at several levels, including among peers in the classroom, with the teacher, or with experts in the local or scientific community (Marx et al., 1997). The curriculum was designed to engaged students in the practice of modeling in both individual and collaborative contexts and at multiple times throughout each unit. Student-constructed models served as the final artifact in Unit 1 and models constructed in Units 2 and 3 were positioned as ways in which students could explain their thinking and ideas to others. In addition, the curriculum provided opportunities for student-constructed models to be publically shared, debated, and discussed. The integral role of collaboration serves another example of how PBL supports the dialogic process of collective sense-making (Ford, 2012).

The final feature of PBL in science is the use of technological tools to conduct investigations, construct representation, and share artifacts (Blumenfeld et al., 1994; Marx et al., 1997). The use of technological tools can provide opportunities for students to use scientific instruments, construct representations of data, conduct research, and share ideas in ways that are not possible using pencil and paper and are closer approximations to the work of scientists (Blumenfeld et al., 1994; Marx et al., 1997). In the context of this study, students used a computer application, *Collabrify Flipbook*, to construct some of their models. *Flipbook* is a drawing and animation tool designed by Dr. Elliot Soloway at the University of Michigan. Students can create drawings on multiple slides and then play the pages in quick succession so that the drawings on the pages appear to be animated.

Overview of 4th grade curriculum. The practice of scientific modeling played a prominent role in each of these units. Students engaged with pre-constructed models and constructed their own models in the course of each unit. Table III.1 provides an overview of the driving questions and the models that students used or constructed in each unit. I will provide a brief summary of each unit, including a description of the phenomena addressed in each unit and the ways in which the interpretation of models and the practice of modeling was incorporated. The 4th grade curriculum was comprised of 3 units[1], each eight weeks long.

Table III.1
Types of Models Incorporated into Grade 4 Units

Unit	Driving Question	Models Used
1	How does water shape the land?	• Physical model of erosion using a stream table • Physical model of water waves using a wave tank • Paper-and-pencil model of erosion
2	Where does the energy to light my house come from?	• Physical model of a water wheel • Paper-and-pencil model to explain how a water wheel transforms energy into electricity • Physical model of a windmill • Paper-and-pencil model to explain how a windmill can transform energy into electricity
3	How can we design and use technologies to improve communication that helps others?	• Paper-and-pencil models of communication using sound

In Unit 1, students explored physical science ideas relating to energy by investigating how water can change landforms through the process of erosion. Their inquiry was framed by the driving question, *How does water shape the land?* Students engaged with physical models of a

[1] The MLs project designed 4 8-week science units for use in 4th grade, however due to time constraints, the teacher was only able to enact three of those units.

stream (referred to as “the stream table”) to observe the process of erosion and conduct an investigation regarding the factors that influence the rate of erosion (e.g., speed of the water or incline of the land). Students were also introduced to the concept of energy transfer as a way to explain the mechanism through which erosion occurred. As their final artifact, students drew paper-and-pencil models at the end of the unit to answer the driving question and explain how the process of erosion could change the shape of the land.

Students continued to investigate forms of energy and the concept of energy transfer in Unit 2, by exploring how generators and other machines convert energy from one form to another. Inquiry in this unit was framed by the driving question, *Where does the energy to light my house come from?* Students built physical models of water wheels and windmills to observe the concept of energy transfer and drew paper-and-pencil models to explain how energy was transferred in both the water wheel and windmill systems in order to light a bulb.

In Unit 3, students explored how living organisms communicate and the roles of energy from sound and light in communication. Students’ inquiry was framed by the driving question, *How can we design and use technologies to improve communication that helps others?* Students constructed paper-and-pencil models during this unit to explain how humans and non-human animals send, receive, and interpret sound and light.

There were supports embedded within the lesson plans to support teachers and students to engage in the use of models, the practice of modeling, and epistemological aspects of models and modeling. These supports included discussion prompts, the design of activities and materials used during lessons. Because language is an important tool that mediates learning and social interactions (Vygotsky, 1978), student engagement in scientific modeling and sense-making was also supported through discourse structures that facilitated collective participation in the inquiry process (Lehrer et al., 2008; Manz, 2012). The specific curricular supports embedded in the curriculum for each unit will be discussed in Chapters 4-7 when I report the findings from this study.

Participants

The participants in this study were Ms. White[2] and the 35 4th grade students in her science class. Ms. White taught 28 of these students for all subjects and received 7 additional 4th grade students from a combined 4th and 5th grade classroom for social studies and science every day. Fifteen of the students had previously participated in the MLs project during their 3rd grade year. Ms. White had taught 4th grade for 3 years. Previously, she was a 2nd grade teacher for 15 years. This was her first year participating in the MLs project and her first experience with PBL.

Ms. White's class was located in a K-5 elementary school in a rural community outside of a large Midwestern city. The makeup of the students in the school was 62% White, 23% African American, 6% are Hispanic/ Latino, 8% two or more races; 60% of students qualified for free or reduced lunch; and only 14.6% of 4th grade students demonstrated proficiency or advanced proficiency on state English Language Arts achievement measures[3]. The average age of 4th grade students in the school was 10.9 years old with a range of 10.1 to 13.0 years old. The racial and socioeconomic makeup, as well as the average age, of this class mirrored that of the school.

Profiles of Focal Students. In order to study individual students' sense-making, I selected a purposive sample of students from Ms. White's class to serve as focal students for each unit. Given the research documenting that students bring an array of formal and everyday

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[2] In order to preserve confidentiality, all names have been changed to pseudonyms.
[3] This level of proficiency is below the statewide proficiency of 46.3% and the districtwide proficiency of 29.1%.

experiences to their sense-making endeavors (Clark & Linn, 2013), I hypothesized that prior knowledge may influence students' sense-making. Therefore, purposive sampling was used to ensure that varying levels of prior knowledge (low, typical, and high prior knowledge) were reflected in the sample. Students' levels of prior knowledge were normed relative to their classmates. I selected six students for Unit 1[4], seven students for Unit 2, and eight students for Unit 3. Focal students participated in additional interviews throughout each of the units.

Focal students were selected using prior knowledge measures that were administered to the whole class before the start of each unit, so that they represented an array of prior knowledge regarding the conceptual topics covered in each unit. An explanation of methods used to assess prior knowledge and select focal students are described in greater detail on page 52. In order to protect participants' anonymity, participants who were chosen as focal students in this study were assigned pseudonyms.

From the total number of focal students, I report findings from the four students who participated as focal students in at least two units and three students who participated in only one unit. This decision was made to provide a representation of different levels of prior knowledge within each unit and changes within individual students' sense-making across units. Table 3.2 provides an overview of the focal students in this study and their relative levels of prior knowledge for each unit in which they participated as a focal student.

Table III.2
Focal student participation in study and amount of prior knowledge relative to peers.

Student name	Unit 1	Unit 2	Unit 3	Total number of units
Alyssa		Typical		1
Caleb		Typical	High	2
Esther		High		1
Kyle	Typical			1
Kiara		Low	Low	2
Nick		Low		1
Samuel	Low	High	Low	3

[4] One focal student was removed from Unit 1 due to her absences during the unit.

Sophie	High	Typical	2
Serenity	Low		1

Data Sources

Multiple data sources were used in the construction of the class and student cases (Table 3.3), including: video and audio recordings, field notes, student artifacts, and formal and informal interviews.

Video and audio recordings. In order to construct the class case, I collected video and audio documenting the enactment of each science lesson in Ms. White's classroom. The video camera was positioned in one corner of the classroom in order to capture whole class instruction and discussions. Ms. White wore a lapel microphone in order to better capture the discussions with students that were not easily captured using the video camera's internal microphone.

Field notes. Along with video and audio, I, or another member of the research team, recorded field notes that documented interactions among teachers and students, a narrative account of whole class instruction, and the ideas that students were sharing during class discussions. The field notes provided details about the nature of the supports related to scientific modeling that the teacher provided to students and the ways in which the teacher and the students interacted with different models. These field notes also included thick descriptions (Stake, 1995), which included details regarding the context of the classroom and the daily instruction, as well as *in vivo* statements made by the teacher or the students whenever possible. Field notes also included memos from the researchers regarding informal conversations with the teacher and moments when researchers (especially myself) provided suggestions for discussion, clarifications regarding steps in the curriculum, or participated in the instruction.

Two researchers were present in Ms. White's room during every day of science instruction, usually myself and one other researcher. Typically, I assumed the role of observer and helper, circulating around the classroom and providing support to Ms. White as needed. The other researcher would record field notes that were a combination of descriptions of instruction or approximate transcripts of class discussion or teacher instruction. The field notes included timestamps that I used to identify *modeling events,* or segments of instruction in which students used or constructed models. The field notes were also used to supplement the video and audio recordings in the few instances of technical difficulties when there was no audio or video recordings of the class.

Student artifacts. In addition to video and field notes, I collected the models that students constructed, both individually and as a class. Students constructed models on paper and using the computer application, *Collabrify Flipbook*. Students' models were used during interviews to support sharing their conceptual and epistemological sense-making related to modeling.

Assessments. In order to capture the differing levels of prior knowledge in the class at the beginning of each unit, students completed assessments regarding the conceptual ideas in each unit and their current epistemological understandings related to modeling. Students completed assessments prior to beginning and immediately after completing each of the three units. The assessments for each of the three units had different formats. There were two assessments administered for Unit 1, a conceptual and modeling assessment. The conceptual assessment for Unit 1 consisted of three pictures of erosion in different contexts and the question, *How did the land get shaped this way?* (Appendix A). The modeling assessment consisted of five questions related to students' ideas about the stream table model that students interacted with during the unit, the kinds of data they can gather, and the claims they can make about the phenomenon of interest using the model (Appendix B).

In both Units 2 and 3, students completed one assessment before and after each unit that assessed both conceptual and epistemological ideas related to modeling (Appendices C & D). These assessments included tasks that required students to construct models to explain aspects of the phenomenon of interest in the unit. For example, in the Unit 2 assessment, students were asked to draw a model to explain how a source of renewable energy could be used to power their homes. This prompt incorporated conceptual knowledge regarding sources of renewable energy, the process through which energy from the energy source is transferred to the generator and then to the home, and the ability to construct a model that communicated this information.

The design of this assessment was informed by previous research on practical epistemologies (Sandoval, 2005) and meta-modeling knowledge (Schwarz et al., 2009). In order to measure students' current epistemological understandings related to modeling, the questions needed to be specific to a model with which they were interacting, instead of broad generalizations about the practice of modeling.

Table III.3
Data sources used in this study.

Data Source	Duration or Frequency	Purpose	Data Analysis
Field notes	Each day that unit is enacted	Provides contextual information about the content that students are learning, how the teacher integrates student models and the practice of modeling throughout the unit Used to identify additional episodes of interest, beyond formal modeling episodes, where models played a role in class instruction	Contextual information for case studies
Student models	Constructed during modeling episodes	Provides a visual representation of student thinking	Qualitative comparisons over time
Assessments	Pre- and post- unit content and epistemologies related to modeling assessments	Measure of content knowledge and students' epistemological knowledge related to modeling administers before and after each unit	Coding for ideas in prior content knowledge and knowledge about models and modeling that students are bringing with them

Interviews	Pre-unit	Semi-structured protocol to gather information about students' content knowledge and their epistemological beliefs about models and the practice of modeling within the context of the phenomenon of interest in the unit Asked students to elaborate on their thinking regarding questions on content and modeling assessments	Coding for ideas in prior content knowledge and knowledge about models and modeling that students are bringing with them
	After modeling episodes	Semi-structured protocol in which students explained their models and the thinking represented in their models Probes included questions regarding how students made sense of particular types of models they were using and constructing (i.e., paper-and-pencil or physical models)	Coding for content and epistemological ideas about models that are represented through their discussions about their models and the process of constructing their models
	Post-unit	Structured protocol to gather information about students' content knowledge and their beliefs about models and the practice of modeling - probe thinking of questions on content assessment and other questions	Coding for ideas related to content knowledge and knowledge about models and modeling that students hold at the end of the unit Compare responses with those reflected in pre-unit interviews to look for change over time
	Novel task	Component of the post-unit interview to gather information regarding the extent to which students could apply the knowledge they constructed during the unit to a novel situation	Coding for ideas related to content knowledge and epistemological understandings related to modeling that were identified during the post-unit interviews
Researcher Memos	Throughout data collection	To record informal and formal conversations with Ms. White during the enactment of the curriculum regarding questions, observations, and ideas generated by teacher or co-constructed by myself and Ms. White	Provides context and informs decisions regarding instruction and changes to the curriculum

Interviews. In order to gain insight into students' sense-making processes, I conducted interviews with focal students at multiple times during each unit. All interviews consisted of a maximum of 10 questions and took between 5-15 minutes to complete. Interview protocols for each interview completed during this study can be found in Appendices E through G.

Unit pre-assessment interviews. I conducted unit pre-assessment interviews with the focal students to document their conceptual understandings regarding the unit's phenomenon of interest and their current epistemological understanding about the nature of scientific models and the use of models in representing and communicating scientific knowledge at the beginning of each unit. During this interview, I asked students to share their thinking regarding their responses to selected questions on the unit pre-assessment. The objective of this interview was to gather data about students' prior knowledge and their initial ideas regarding the phenomenon of the unit, so that I could document changes in students' conceptual knowledge and epistemological understandings over time. These interviews occurred within the first three instructional days of the unit, with the exception of Unit 1 when unit pre-assessment interviews occurred on Day 15 of the unit due to when data collection began for this study.

Modeling interviews. During each unit, I conducted interviews with focal students after modeling events. These semi-structured interviews included questions asking students to explain the models they constructed, evaluate how well the models explain the target phenomenon (including perceived limitations of their models), and share the feedback they received from peers regarding revisions of their models and whether or not they chose to incorporate these revisions.

Previous research has found that epistemological understandings are not reliably reflected in students' models and instead are communicated during interviews (Baek et al., 2011). In addition, the research by Baek and Schwarz (2015) regarding epistemologies in modeling, suggest that students' epistemological ideas related to modeling may be best accessed within the context of using or constructing models. Therefore, probing students' thinking regarding their models soon after they engaged in constructing or using models was important for gaining insight into students' epistemological ideas related to modeling. For this reason, no interviews regarding modeling events occurred during Unit 1, because too much time had elapsed between modeling events and opportunities for interviews. Focal student data collection for this study began approximately 15 days after the start of Unit 1 and 10 days after students had engaged with the primary model in the unit, the stream table model. In both Units 2 and 3, modeling interviews occurred within three instructional days after students used or constructed models.

Questions in the modeling interviews focused on the following aspects of the epistemology of models and modeling identified by the literature as being relevant and important aspects of the practice of modeling for elementary-age students: (a) the role of models to explain or predict phenomena, (b) the iterative and revisable nature of models and the scientific knowledge they communicate, (c) limitations of models to serve as approximations of phenomena instead of as exact replicas, and (d) the use of data to inform the construction of models (Baek et al., 2011; Baek & Schwarz, 2015; Lehrer et al., 2008; Schwarz et al., 2009).

Unit post-assessment interviews. After each unit was completed, I conducted interviews with focal students using questions identical to the pre-unit interview, supplemented by additional questions and a novel task. The novel task investigated how students applied their knowledge and their epistemological understandings related to modeling by using the model they constructed during the unit to explain or predict a novel situation. In Unit 1, the novel task involved an image of a rock formation that had been created through multiple types of water erosion and an image of a river running through a forest (Figure III.1). For the image of the rock formations, students were asked to explain how the rocks were shaped that way. For the image of the river running through the forest, students were asked to predict what the river and the forest would look like in 1,000 years. This task provided opportunities for students to apply conceptual knowledge regarding the process of erosion.

Figure III.1. Images used in the Unit 1 novel task.

In Unit 2, students watched a brief video of a game of billiards (Figure III.2). The video clip showed a person hitting the white billiard ball with a que stick and the white billiard ball hitting the colored billiard balls. First, students were asked to explain why the billiard balls moved. Then, they were shown a model that I drew and were told it was drawn by another student (Figure III.3). Students were asked to provide feedback to the student regarding ways in which the model could be improved. This model was purposefully incomplete to provide opportunities for students to share ways in which the model could be improved. In addition, students were told the model had been created by a peer in order to encourage them to provide constructive feedback, similar to the process they had been engaged in during class. The Unit 2 novel task provided opportunities for students to draw on their conceptual understandings regarding energy transfer and their epistemological understandings about the ways in which models can be used to explain a phenomenon of the movement of the billiard balls.


Figure III.2. Screenshot of the video students viewed during the Unit 2 novel task. In the video, the person holding the pool stick hits the white billiard ball, which then hits the colored billiard balls.

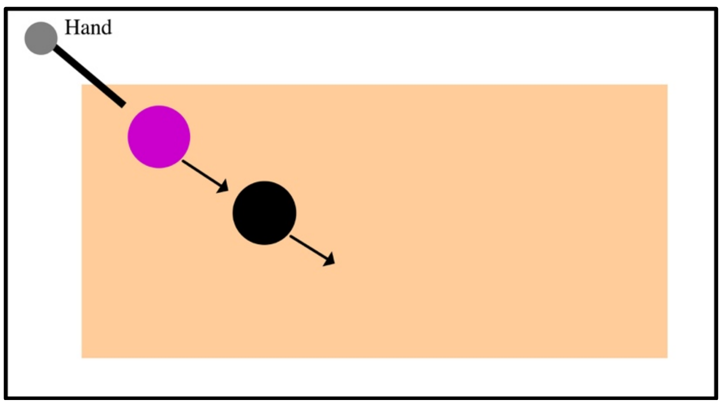


Figure III.3. The model created by an anonymous student that focal students critiqued during the Unit 2 novel task.

In Unit 3, the novel task was comprised of the prompt, *You have been learning a lot about energy this year. How do you think energy might be involved in communication?* This prompt was included in both the unit pre-assessment and post-assessment interviews. This prompt and the pre-/post-assessment comparison were used to gain insight into the ideas regarding energy that students had developed during Unit 1 and 2 and determine if they developed additional ideas during Unit 3. Given the emphasis on energy and energy transfer across the entire 4th grade curriculum, I chose to use this prompt, instead of the traditional novel task, to gain insight into the extent to which students were drawing on ideas from across the year.

Researcher memos. I maintained a log of researcher memos to record reflections regarding conversations with Ms. White throughout the enactment of the curriculum and the data collection process. This log was primarily used to record agendas and reflections of formal after-school meetings with Ms. White, as well as other reflections and notes from informal face-to-face and phone conversations with Ms. White. The field notes also served as a place to record informal conversations that occurred immediately prior to, during, and immediately after instruction. Therefore, these memos were used to record conversations that took place at other times. An example of a memo that was recorded after a planned phone call with Ms. White is included in Table III.4.

Table III.4
Example of memo recorded after a phone conversation with Ms. White.

Phone call with [Ms. White] - 2/8 I spoke with [Ms. White] about the plan for the rest of the unit. She commented that she thought the students did not make the connection between the model of the generator with the thread spool and the real box generator. She thought they were understanding how it worked and the connection to the how it produces electricity before the windmill lesson, but that understanding seems to have gone away while working on their windmills.

Researcher Role

During the data collection phase of this study, I assumed the role of participant observer, in which "the researcher's observer activities, which are known to the group, are subordinate to the researcher's role as a participant" (Merriam & Tisdell, 2016, p. 144). Given that 15 of Ms. White's student had participated in the MLs project during their 3rd grade year, a large percentage of the class was already familiar with my presence in the classroom and my role as an instructor and helper during science. These students considered my role to be the same when I worked with them in 4th grade, which they communicated to the students with whom I was not familiar. In addition, Ms. White was enthusiastic about my assumption of a co-instructor role due to her uncertainty regarding the PBL curriculum and the increased requirements on her classroom management due to the number of children in her classroom, sentiments which she shared during informal conversations with myself and other members of the research group. For example, class demonstrations needed to be done in smaller groups so that all students were able to see the demonstration and participate in the discussion.

Merriam and Tisdell (2016) describe participant observation as "a schizophrenic activity in that the researcher usually participates but not to the extent of becoming totally absorbed in the activity, at least in the way that conducting observation has been traditionally conceptualized" (p. 146). This is an apt description for my role in Ms. White's classroom. Within the timespan of one class period, I would stand on the periphery of the classroom recording field notes, circulate through the classroom helping students to locate their places within their workbooks, and lead short classroom discussions to supplement the discussions led by Ms. White.

I also adopted a full participatory role on certain days when Ms. White was absent. This decision was made in an effort to continue the class's science instruction and because the research team felt the students were comfortable with me in a participatory role. A substitute teacher was present in these cases to provide behavior management support, but I assumed responsibility for the science instruction. Working on the spectrum between participant-observer and full participatory roles provided unique insights into the classroom context as an outsider and the experience of enacting the curriculum as an insider. My participation as both an outsider and an insider in the classroom must also be considered when analyzing the role of the teacher and the decisions made during the enactment. I will address the role further when discussing my subjectivity and positionality in a subsequent section of the chapter.

Data Analyses

I drew on case study methods to characterize students' sense-making about scientific phenomena and their engagement in the practice of modeling (Merriam & Tisdell, 2016; Stake, 1995). Case studies can provide an in-depth description and analysis of a “bounded system” (Merriam & Tisdell, 2016, p. 37), and can be especially useful when the phenomenon’s variables and the context cannot be isolated from each other (Merriam & Tisdell, 2016). Stake (1995) describes a case as a “specific, complex, functioning thing” (p. 2). A case is a system with many components that can be studied to investigate how well these components work together and how outside influences and processes affect the components separately and as a whole (Stake, 1995).

This study is an instrumental case study, in which the particulars of one case are used to address a “research question, a puzzlement, [or] a need for general understanding…” (Stake, 1995, p. 3). The use of an instrumental case study can be beneficial to studying the development of sense-making and the practice of modeling due to the goal of understanding these larger phenomena and the intertwined nature of the classroom environment and instruction. Case study methods emphasize the context of instruction and provide the opportunity to compare the features of the instructional context in which students are constructing and using models to understand the nature of transfer of learning across the year (Engle, 2006). This focus on context complements the DBR methods being employed in the larger research context in which this study occurred, in which understanding the context in which learning occurs is required for generating claims regarding how classroom environments can support learning (Cobb, Confrey, et al., 2003).

The first step in constructing cases is to identify the unit of analysis, which defines the case (Merriam & Tisdell, 2016; Stake, 1995). Units of analysis are “intrinsically bounded” and provide parameters around the locations or participants in data collection. This is a unique characteristic of case study methods (Merriam & Tisdell, 2016). The current study is comprised of the single case of the modeling events that occurred in Ms. White’s classroom. This case included two dimensions: the class and the child. The *class* dimension describes how Ms. White's instruction and whole-class interactions influenced the students' collective sense-making as they interpreted and/ or constructed models within each unit of instruction. Each unit comprised a sub-case of the class dimension. The *child* dimension documents change in each focal child's conceptual knowledge and epistemological understanding throughout a unit and, in some cases, across units. Within her classroom, there were multiple sub-cases of the focal students for each unit that contribute to our understanding of the ways in which the practice of modeling and sense-making developed with the classroom. The use of sub-cases differs from comparative case study, in which multiple cases are constructed (i.e., multiple classrooms or multiple companies) (Merriam & Tisdell, 2016). The decision to construct a single case in this study was made because the in-depth analyses of individual students' sense-making within Ms. White's class contributes to the overall understanding of how the practice of modeling developed within this one particular classroom context.

Whole class data analysis. Field notes were used to construct an enactment timeline of the science instruction in Ms. White's classroom. The accuracy of the enactment timeline was also verified by reviewing the video of each instructional day. From this timeline, I identified days of instruction that included modeling events. In order to address my research question regarding how engagement in the practice of modeling supported students' conceptual and epistemological sense-making, I transcribed segments of instruction in which the class was engaged in discussions regarding: (a) the conceptual ideas that students would draw upon when constructing or using models, (b) when Ms. White or the students referenced or shared models that they had used or constructed, (c) the class was discussing models they had created or used, or (d) when the class constructed class consensus models (only applicable to Unit 3).

I conducted categorical and descriptive analyses of each modeling event to characterize: (a) how Ms. White framed modeling in the context of the unit, (b) how the teacher used supports that are embedded in the curriculum, as well as those she added, (c) how the teacher was supporting students to engage in sense-making using scientific models, and (d) the ideas that students contributed in the whole-class setting related to the practice of modeling and their sense-making about the phenomenon. During the categorical analysis, I inductively generated a list of substantive categories by analyzing the transcripts for any student or teacher talk that was related to models, the practice of modeling, or the conceptual ideas relevant to the models that were used or constructed in the units. Substantive categories reflect descriptions of the data and participants' words and ideas (Maxwell, 2013). In addition, transcripts were also analyzed using theoretical categories that were identified prior to analysis and included ideas related to epistemological aspects of modeling, such as the use of models to explain phenomena (Schwarz et al., 2009) and the use of data to inform the construction of models (Baek & Schwarz, 2015), as well as conceptual ideas related to each unit. In contrast to substantive categories which reflect participant ideas, theoretical categories reflect researcher ideas and reflect prior or developing theory (Maxwell, 2013).

I used these substantive and theoretical categories to construct sense-making maps to track the flow of conceptual and epistemological ideas related to modeling through each unit. Due to the differences in the conceptual terrain of each unit, I constructed separate maps for each unit. In order to document the emergence of new ideas and reoccurrence of previously introduced ideas, I ordered the categories on the sense-making map to correspond with the day of instruction in which the idea was raised. In order to analyze the preponderance of ideas that were raised by students versus the teacher or the researchers, each idea is color coded to show whether a student, teacher, or researcher contributed it to the class's conversation. In addition, there are additional colors to reflect ideas that were co-constructed by the teacher and a student or the researcher and a student.

A descriptive analysis was conducted using the field notes, video transcripts, and researcher memos in order to construct a holistic picture of Ms. White's enactment of the curriculum and collective sense-making during modeling events. Maxwell (2013) describes this kind of analysis as a "connecting strategy" (p. 112). He explains,

> connecting analysis attempts to understand the data (usually, but not necessarily, an interview transcript or other textual material) *in context*…It is thus often seen as holistic in that it is concerned with the relationships among the different parts of the transcript or field notes, rather than fragmenting these and sorting the data into categories (Maxwell, 2013, p. 112, original emphasis).

Stake (1995) refers to this kind of analysis as direct interpretation that employs the use of thick descriptions "to optimize the opportunity of the reader to gain an experiential understanding of the case" (p. 40). These data sources were used to analyze the enactment of the curriculum and how aspects of the curriculum, instruction, and class discussions influenced the class's collective sense-making.

Individual data analyses. In order to study individual students' sense-making regarding conceptual ideas and epistemological ideas related to modeling, I conducted descriptive analyses of focal students' artifacts, unit pre- and post-assessments, and associated interviews within each unit to construct trajectories of sense-making for each student in each unit in which they participated. Similar to the whole-class data analyses, I defined modeling events as models that students had constructed or used. Focal students' artifacts consisted of the models they constructed during the units. Students constructed one or more models during each unit either on paper or using the *Collabrify Flipbook* program. Focal students' models were analyzed simultaneously with their associated interviews in order to provide context and further explanation, which informed the interpretation of students' models.

Students' interviews regarding the models they used and constructed, as well as their interviews regarding the novel task, were transcribed and analyzed using categorizing and descriptive analyses. I looked for examples of sense-making related to conceptual or epistemological ideas and generated substantive categories to reflect these examples. The substantive categories were compared with the sense-making maps generated from the class data to provide insight into ideas from the class's discussions that were present in individual students' explanations, as well as additional ideas that students shared that had not been introduced during class discussions. These categories also informed descriptive analyses of focal students' sense-making during each unit by informing how individual students' sense-making unfolded during each unit.

Focal students' unit pre- and post-assessment were compared to document changes in students' answers across time. Students' interviews regarding their pre- and post-assessments were transcribed and analyzed to provide additional information regarding their responses to questions on the assessments. These analyses were used to construct start-and- endpoints for each focal student related to their conceptual knowledge regarding the phenomenon of the unit and epistemological knowledge regarding models and the practice of modeling. Recall that start-and-endpoints are important aspects of retrospective DBR analyses (Cobb, McClain, et al., 2003). The incorporation of start-and-endpoints informed the retrospective analyses that were conducted on Ms. White's enactment of the curriculum.

Subjectivity, Positionality, and Reflexivity

An important aspect of qualitative research is the subjectivity of the researcher. Subjectivity includes the identities and experiences that influence a researcher's interests, methodologies and analysis of data (Dyson & Genishi, 2005). My own research is motivated by previous experiences as a teacher and my own struggles in teaching science. In addition, I am aware that my own education was privileged due to the socioeconomic status of my family and my whiteness. These factors influence my observations and interpretation of events in the research setting. I am mindful of how these aspects of my identity influence my evaluations of good teaching, good learning, good students, and good schools. In addition, my familiarity with the curriculum and the learning expectations embedded in the curriculum influenced responses and ideas that I was expecting to hear. I was mindful to listen and record all students' ideas, despite how right or wrong I perceived them to be.

Researchers' positionalities differ from their subjectivities because positionality challenges researchers to actively identify "tensions that can surface when conducting research where issues of race and culture are concerned" (Milner, 2008, p. 388). Positionality is an important consideration because researchers are working within a social context with established power relationships.

In my study, I worked to mitigate perceived power differentials between myself, as a researcher at a prominent research institution, and Ms. White. In addition, I worked to establish rapport and a collaborative relationship with the teacher, so that she felt that we were working together to construct knowledge in the classroom. I conferred with her before and after instruction regarding her feelings about the lessons and the ways in which I could be most helpful to her. In addition, I worked to establish myself as a non-threatening figure to the students by not engaging in student discipline when I was present in the classroom. In addition, if students approached me asking for permission to go out of the classroom or change tasks, I always referred them to Ms. White in order to indicate that I was not the authority figure in the classroom and was there to help them learn science. During whole class discussions and teacher-led instruction, I always raised my hand and sought permission from Ms. White to ask a question or add an additional idea as a way to communicate to both her and the students that I considered Ms. White to be the authority figure in the classroom.

Despite this, my role as a participant observer dictated certain aspects of my positionality. As a person who delivered instruction, this position communicated power and authority to the students and Ms. White. Even when I was leading the science instruction, I continued to defer to either Ms. White or the substitute teacher in the room regarding disciplinary decisions or students' requests. In addition, Ms. White's original request regarding my assumption of a co-teaching position arose out of her discomfort with the curriculum. This also reinforced a power differential between her and me, as I stepped into the co-teacher role as a person more knowledgeable about the curriculum.

In order for researchers to purposefully examine their subjectivity and positionality and how these aspects of their identities influence their work as researchers, they must continually practice reflexivity. Reflexivity is an active process that allows researchers to identify aspects of their subjectivity and positionality and how these forces influence the research process. In case study, reflexivity is important so that the researcher can evaluate how their subjectivity and positionality influence how he or she approaches research (Dyson & Genishi, 2005). My positionality and subjectivity have helped shape my interest in my current research questions and

I am continuously evaluating how they play a role in my work as a researcher in society at large and within research settings.

Reliability and Validity

Case study research requires close study and fine-grained analysis of multiple data sources and multiple perspectives in order to "understand *others'* understandings" about the phenomenon of interest in a particular social context (Dyson and Genishi, 2005). As Stake (1995) explains, "the qualitative case researcher tries to preserve the *multiple realities*, the different and even contradictory views of what is happening" (p. 12). The representation and preservation of the multiple realities that exist within a particular context are paramount to achieving reliability and validity of case study findings.

Maxwell (2013) highlights two specific threats to validity: researcher bias and reactivity (p. 124). Recognition of one's subjectivity and biases and the ways in which biases were dealt with during the research process is vital to the validity of the findings. A description of my subjectivity, biases, and the ways in which I addressed these during this study was discussed in the previous section. The second specific threat to validity, reactivity, is important to address in this study. Reactivity refers to the influence that the presence of the research has on the context in which she is studying and the consequences of this influence (Maxwell, 2013). My presence in the classroom during a majority of the science lessons and my interactions with particular students during multiple interviews caused a change in the learning environment for those students and may have influenced their sense-making outcomes. One way in which I worked to reduce reactivity was by conducting interviews with open-ended questions designed to probe student thinking but not to conduct instruction. Even if students shared inaccurate conceptual information, I did not correct them and instead used this information to inform the teacher of potential misconceptions that were still present among the students. This procedure allowed me to record students' sense-making at different times throughout the unit as authentically as possible, while still supporting the development of students' sense-making through my partnership with the teacher.

Due to the subjective nature of qualitative research, the use of multiple data sources provided the opportunity to triangulate data. Triangulation allows researchers to study the same phenomenon through a variety of means and "is a powerful strategy for increasing the credibility or internal validity of your research" (Merriam & Tisdell, 2016, p. 254). I drew upon multiple data sources to study students' individual and collective sense-making, including student artifacts, interviews, video, and researcher observations. The multiple sources of data collected in this study served as tools to compare, refine, and challenge researcher interpretations (Stake, 1995). Merriam and Tisdell (2016) explain, "triangulation using multiple sources of *data* means comparing and cross-checking data collected through observations at different times or in different places, or interview data collected from people with different perspectives or from follow-up interviews with the same people" (p. 245). For example, when constructing the *child* dimension of the case, I analyzed students' models and the interviews in which they explained their models in order to test my interpretations of the sense-making reflected in the models. In addition, the formal and informal conversations throughout the year with Ms. White, recorded in researcher memos, provided a source of triangulation for my interpretations of the class's sense-making.

In addition to triangulation, I also purposely included variability in the students that were included in this study and report the findings as way to look for variation and alternate interpretations in my data through constant comparisons among data. This strategy can strengthen the internal validity of a study by searching for many possible hypotheses, as opposed to selectively including data that support the expected finding or hypothesis (Maxwell, 2013; Merriam & Tisdell, 2016). In addition, providing a wide range of examples strengthens the reliability of the study due to opportunities for repeated findings (Merriam & Tisdell, 2016).

Generalizability

The use of multiple sub-cases also strengthens both the internal and external generalizability of this study. Specifically, demonstrating that the same findings appear multiple times can also provide insight into the internal generalizability of the findings (i.e., the ability of findings to generalize within the case) (Maxwell, 2013). The use of sub-cases also supports the development of naturalistic generalization. According to Stake (1995), "naturalistic generalizations are conclusions arrived at through personal engagement in life's affairs or by vicarious experiences so well constructed that the person feels as if it happened to themselves" (p. 85). The use of multiple sub-cases provides the opportunity for readers to identify features within one or more of the sub-cases, or in the overall case of Ms. White's classroom, to which they can relate and apply their own experiences. In addition, the use of descriptive analyses also support naturalistic generalizations. Descriptive analyses rely on thick descriptions of context, which provide ample details that allow readers to understand the particulars of a case in order to generalize to other situations (Merriam & Tisdell, 2016).

In the next three chapters (Chapters 4-6), I will report the findings from the Units 1-3. In each chapter I will share the findings of the class and individual student sub-cases.

CHAPTER IV

Unit One: Modeling Erosion Caused by Moving Water

The first unit of instruction in Ms. White's 4th grade class, referred to as "the water unit," was organized around the phenomenon of erosion caused by moving water and was framed by the driving question, *What caused the land to be shaped this way?* The curriculum was designed to engage students in experiences with the causes and effects of erosion involving water, including erosion caused by rivers, waves, rain, and floods. This unit took place over 28 days of instruction and totaled 18.95 hours.

This chapter will be organized into four sections: (a) the hypothesized starting points and trajectory of learning that guided the development of the curriculum, (b) the actual trajectory of learning for the class, (c) an analysis of interviews with focal students to illustrate the trajectories of individual sense-making across the unit, and (d) themes in students' sense-making and the ways in which they were influenced by the use and construction of models.

Hypothesized Starting Points and Trajectory of Learning Specific to Erosion and Energy

Research suggests that students may be familiar with the term or the process of erosion but may not have a canonical understanding of the process of erosion caused by water. Blake (2005) found that about half of participants, ages 7-11, were familiar with the process of erosion. However, Martinez, Bannan, & Kitsantas (2012) documented several misconceptions that bilingual students, ages 9 and 10, held regarding the process of erosion. For example, the creation of canyons was caused by catastrophic or magical events, the path of a river was created before water flowed through it, and erosion was finite, rather than ongoing.

In addition to introducing students to the concept of erosion, the curriculum was designed to introduce students to the concept of kinetic energy and energy transfer as a way of explaining the mechanism of erosion. In this unit, students were introduced to the idea that movement provided evidence that an object had energy, and, more specifically, kinetic energy. Research suggests that students enter school with many different ideas regarding energy, especially given the prevalence of the term in everyday language (Boyes, 1990; Driver et al., 1994; Hammer et al., 2012). Lui and McKeough (2005) suggest that a foundational understanding of energy requires the understanding that energy comes from different sources and can be in different forms (see Chapter 2 for a more detailed discussion regarding research related to children's understanding of energy). While the students in the current study investigated the concept of energy more centrally in Unit 2 of Grade 4 (see Chapter 5), in Unit 1 the students were introduced to one source of energy: moving water.

The curriculum called for students to engage with models at various times throughout the unit and for multiple reasons. All the models that students engaged with during the unit, with the exception of the final student-constructed drawn model, were physical models. Physical models can provide an "entrée" into the practice of modeling, due to the large number of remnants, or similarities, between the physical model and the target phenomenon (Lehrer & Schauble, 2012). These remnants lower the cognitive overhead and provide younger students access to engaging with models in meaningful ways (Ero-Tolliver et al., 2013; Lehrer & Schauble, 2012), while introducing them to the idea that a model represents a phenomenon (Lehrer & Schauble, 2010). At the beginning of the unit, students interacted with stream tables to observe the process of erosion and investigate variables that cause erosion in rivers. Later in the unit, students participated in teacher and researcher-led demonstrations using rain containers and a wave table to model the processes of erosion from rain and waves. The unit culminated with students constructing paper-and-pencil models explaining how water shapes the land.

Actual Learning Trajectory

The use of models in Unit 1 was designed to support students' collective sense-making about the process of erosion caused by water and the factors that affect the process. The sense-making map in Figure IV.1 provides an overview of the collective sense-making of the students and the teacher during Unit 1. The ideas reflected in this map include sense-making related to the purpose of models and scientific modeling, as well as conceptual understandings regarding the process of erosion and the concept of energy. In between the days listed in Figure IV.1, students were still engaging in science, but were doing other activities, such as reading text or observing phenomena firsthand (e.g., observing the stream outside the school).

As an overview, there were 28 sense-making ideas documented during the enactment of the unit. The teacher introduced several ideas regarding purposes for using models and the role of models in making observations and collecting evidence in the early portion of the unit. Within the context of different investigations and demonstrations, students were introduced to ideas about the process of erosion and factors that affect it, such as the volume of rain over time and the size of waves. Both students and the teacher reiterated ideas related to the purpose and role of models at the end of the unit when students were engaged in constructed their own paper-and-pencil model.

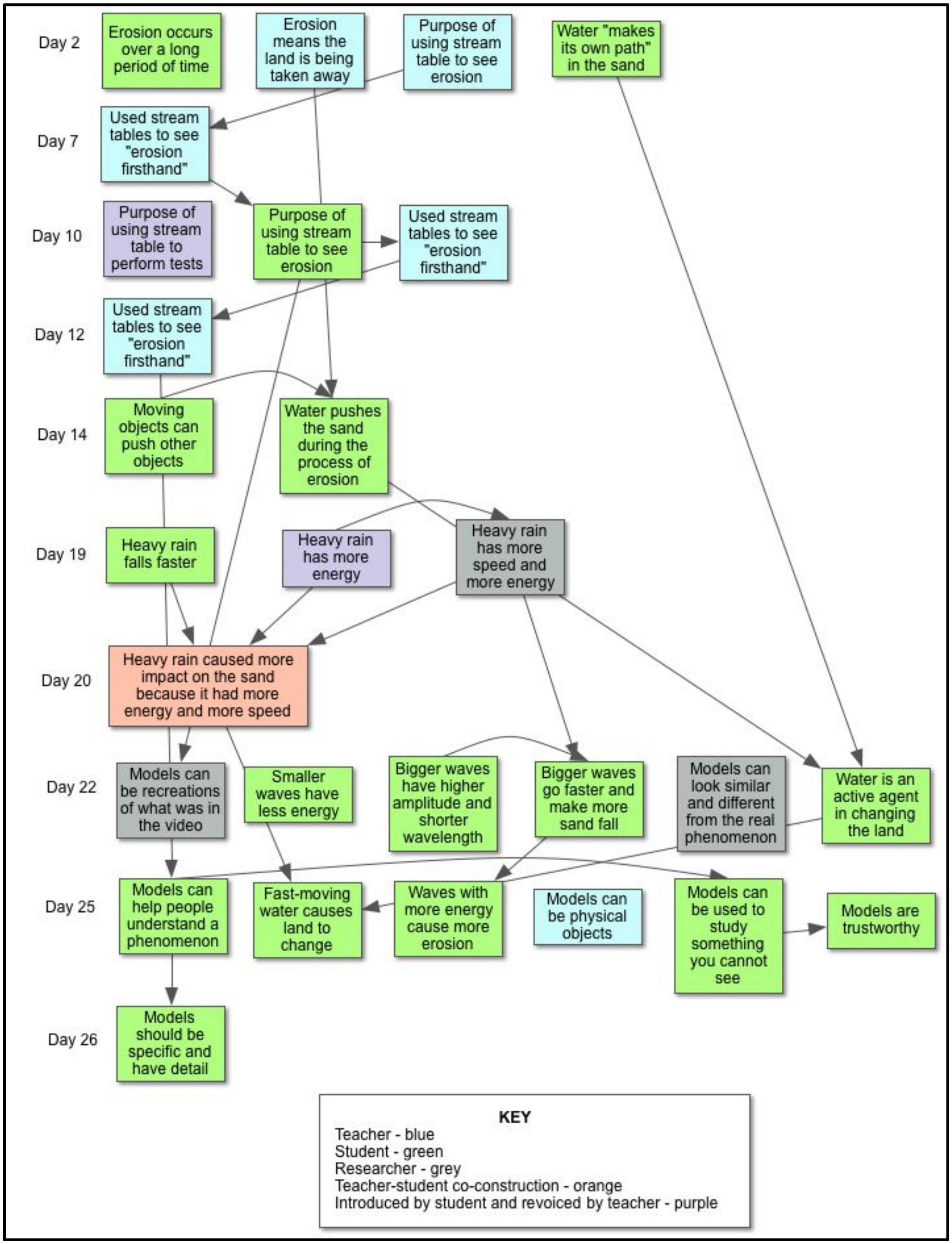


Figure IV.1. Unit 1 sense-making map illustrating the conceptual and epistemological ideas related to models that were introduced and discussed by the teacher, students, and researchers during Unit 1.

Recall that the question guiding this research is "*How do features of models and the contexts in which they are taught and used influence upper elementary students' sense-making and engagement in the practice of constructing and using models?*" The following sub-case elaborates on the flow of sense-making ideas represented in Figure IV.1 and provides insight into how the teacher, curriculum, and class discussion provided opportunities for students to engage in sense-making regarding the process of erosion and purposes for using models and the practice of modeling in Unit 1. This sub-case is organized chronologically by the model that students engaged with and the day of instruction in which the interactions of interest occurred. Table IV.1 provides an overview of the days of instruction that included modeling events.

Table IV.1
Unit 1 Modeling Events

Day #	Date	Lesson and Activities	Time
2	10.12.16	**Lesson 1.2: How does moving water affect the land?** ***Activity 1:*** Class revisits DQ board, reviews community walk and observation chart, and brainstorms how moving water affects the land. ***Activity 2:*** Teacher introduces and demonstrates stream table, manipulating one variable at a time. ***Activity 3:*** Students explore stream tables in small groups and share out observations	45 minutes
10	10.31.16	**Lesson 1.6: What variables affect how moving water changes the shape of land over time?** ***Activity 1:*** Teacher reminds students they will conduct investigations based on their plans in previous lessons. ***Activity 2:*** Students conduct investigation and fill out data sheet.	35 minutes
12	11.8.16	**Lesson 1.7: What variables affect how moving water changes the shape of land over time?** ***Activity 1:*** Teacher revisits unit DQ and lesson DQ and reminds students they'll be analyzing data from previous investigation. ***Activity 2:*** Students analyze and discuss data.	40 minutes
14	11.10.16	**Lesson 2.2: What happens when a fast-moving object collides with another object?** ***Activity 1:*** Class revisits unit DQ and students share what they know about energy. ***Activity 2:*** Students make predictions, observe steel ball demonstration, then revisit/reflect on predictions. ***Activity 3:*** Students plan steel ball investigation and record on planning sheet.	30 minutes
19	11.22.16	**Lesson 3.1: How does rain affect the shape of the land?** ***Activity 2:*** Teacher introduces DQ, class discusses how stream table can function as a model, teacher demonstrates sand tower investigation. ***Activity 3:*** Class discusses their observations, noting how the dependent variable changed. Class constructs scientific explanation. ***Activity 4:*** Class updates DQ board, adding new questions and answers.	35 minutes

20	11.28.16	**Lesson 3.2: How does flooding affect the land in our community and world?** ***Activity 1:*** Teacher review previous day's investigation and tells students they'll continue exploring how rain shapes the land through video, images, and reading. ***Activity 2:*** Class watches video of flooding and makes observations and predictions. ***Activity 3:*** Class reads flooding text.	37 minutes
22	12.1.16	**Lesson 4.2: What is a model that shows different properties of crashing waves?** ***Activity 1:*** Teacher introduces lesson DQ and wave tank. Students watch video clips of waves. Teacher draws side view of each scenario and adds "wavelength" and "amplitude" to each picture. ***Activity 2:*** Students discuss what causes waves to have long amplitude or long wavelength. ***Activity 3:*** Students investigate wave amplitude and wavelength using wave tanks. Researcher uses slinky to model high/low amplitude and long/short wavelength waves. Class discusses.	42 minutes
25	12.8.16	**Lesson 4.5: How does moving water in streams, rivers, rain and waves change the shape of the land?** ***Activity 1:*** Class reviews DQ. Teacher introduces modeling activity. ***Activity 2:*** Students create models including variables.	40 minutes
26	12.14.16	**Lesson 4.5: How does moving water in streams, rivers, rain and waves change the shape of the land?** ***Activity 3:*** Partnerships share model for feedback. Teacher provides prompts to guide feedback.	45 minutes
27	12.15.16	**Lesson 4.5: How does moving water in streams, rivers, rain and waves change the shape of the land?** ***Activity 3:*** Students revise based on feedback. ***Activity 4:*** Students share models with the class.	45 minutes

Models can help us see erosion first-hand: The stream table model. On Day 2 of instruction, Ms. White introduced the stream table by asking the class, "what do you know about how water shapes the land, think about that stream?" One student, GL,[5] introduced the term, "erosion," and the idea that land changes over "thousands and thousands of years." When the teacher asked the class for more details about erosion, Kyle did not build on any portion of GL's response and replied tentatively that "it changes." Ms. White clarified that erosion means "that it takes away." Ms. White demonstrated how to use the stream table and emphasized the importance of making observations. She introduced the idea that models could be used to see a

[5] In order to protect participants' anonymity, participants who were chosen as focal students in this study were assigned pseudonyms. The other participants are referred to by their initials.

phenomenon, such as erosion, when she told students, “you are going to kinda see what we are talking about with the erosion.” Ms. White did not explicitly discuss the stream table as a model with the class, but she did allude to the role of the stream table as a model of the stream from the community walk that the class took during the previous class period. Figure IV.2 shows the stream table model that students engaged with during the unit. During the concluding discussion regarding their observations, no students made connections back to the concept of erosion or their observations of the stream on their community walk that they had taken during the previous class; however, four students shared observations about the changes in appearance of the stream table after adding water.

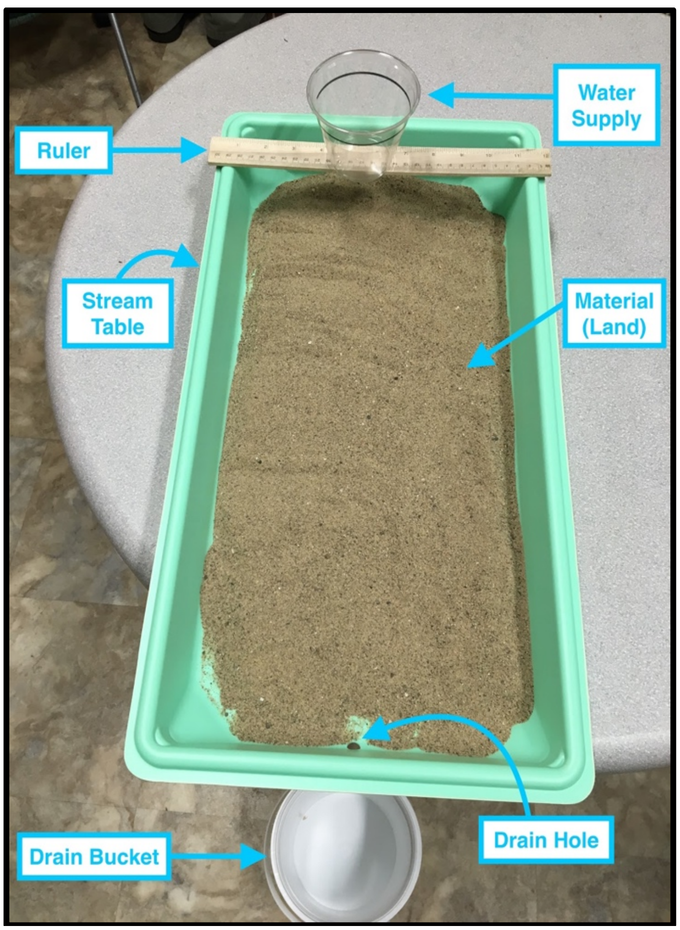


Figure IV.2. Set-up of the stream table model that students engaged with during Unit 1.

On Day 10, students designed and conducted their own investigations of variables that could affect erosion using the stream table. Prior to beginning the investigation, Ms. White prompted the class to reflect on the purpose of the stream table model. This discussion added new ideas and reinforced existing ones in the class's on-going discussion. Kyle shared, "We are studying to see if we use different materials if it will make a difference." Ms. White rephrased this as "performing tests." Kyle's response reflected the purpose that the stream table would serve on that day – to test the differences in the movement of sand in the presence and absence of rocks. This exchange between Ms. White and Kyle was the first instance of revoicing in which Ms. White rephrased Kyle's answer to support the sense-making of the class regarding a new purpose for models that had not been introduced. Revoicing is a classroom discourse strategy that can be used by teachers to link students' experiences with academic vocabulary (O'Connor & Michaels, 1993).

LM provided a different idea, "to see how it does." Ms. White built on this idea by saying, "it is very important when we are looking at this phenomenon that we are studying, when we are looking at these stream tables we can actually see more, do more, we're performing just more than looking at a picture or a map. We're actually observing and watching this change." LM's response reflected the idea that Ms. White had introduced on Day 2 that the stream tables could be used to "see what we are talking about with the erosion" and that she repeated on Day 7 (Figure IV.1). Ms. White elaboration of LM's idea further emphasized that the role of the stream table, and models more generally, is to visualize a phenomenon.

After students completed their investigations of variables that affect erosion, the class constructed a scientific explanation to explain their findings. On Day 12, Ms. White began the lesson by reading from the lesson plan, "We use these stream tables as models. Scientists use these stream tables to collect evidence and support a claim. We are going to start learning what a claim is today. And we use that information, this evidence, to explain different phenomena and to predict what is being studied." This passage from the lesson plan introduced students to another use for models – to collect evidence and support a claim. However, there was no further discussion about this use of the stream table model. During this lesson, students worked together to identify how their dependent variable (in most cases, the appearance of the stream table or the amount of sand in the bucket) changed as a result of changing their independent variable in order to make a claim about how the independent variable affected their dependent variable. Groups' independent variables included the presence or absence of rocks, the slope of the stream table, and the presence or absence of moss. Ms. White and the researchers circulated and worked with groups to identify how their dependent variable changed as a result of changing the independent variable. While working with small groups of students, Ms. White supported students to draw connections between the changes they observed in their stream tables and the process of erosion. During a conversation with HK, Ms. White worked to help him identify the changes in the appearance of the group's stream table.

Ms. W(hite) What changed from doing number one to doing number two? From the sand to the rocks?

HK The one without the sand there was like a big hole without sand –

Ms. W Okay so that's that erosion

HK Yah it eroded that sand…the water eroded the sand and made a really big hole in the sand and more water went down.

Ms. W So what happened when you added the rocks? Did that happen? No. So that was a really big change.

This interaction illustrates how Ms. White used HK's observations from his investigation to reinforce the concept of erosion. Once Ms. White prompted HK to think about erosion, he immediately took up the term and used it correctly in his explanation about what happened to his stream table during one of the trials.

Ms. White introduced students to several ideas about the purpose of models throughout the use of the stream table model: (a) she emphasized the importance of using models to observe the process of erosion "firsthand," (b) continually supported students to make observations using their model and use these observations as evidence, and (c) introduced the idea that models could be used to "perform tests." The idea of using the stream table to see a phenomenon was also shared by one student, LM, when prompted to think about the roles of models, but no other students took up this idea in documented conversations. It is not clear to what extent students understood how their observations of the stream table connected to the process of erosion in real streams and rivers. Lehrer and Schauble (2010) reported that students new to the practice of modeling may struggle to consider a model as representing a phenomenon. While there were many physical similarities between the stream tables and the target phenomenon of a real stream that should have provided access to students to think about their observations of the stream table in the context of the actual stream, the data suggest that students did not make the conceptual leap of the stream table as representing the stream outside of their school. However, students did incorporate conceptual ideas that arose from the use of the stream table model during their discussions in this portion of the unit (Figure IV.1). Students continued to build on these conceptual and epistemological ideas as they moved on to exploring the role of energy in erosion.

Moving objects can push other objects: The steel ball investigation. After students finished using the stream table models, the class transitioned to discussing the concept of energy. While the teacher and the curriculum emphasized the concept of erosion during the use of the stream table models, the concept of energy and its role in the process of erosion was not introduced or discussed with students. On Day 14, students prepared to conduct an investigation exploring how the speed of a moving object affected how far it could cause a second object to move when it was hit. Students used a rubber band attached to a wooden box to launch a steel ball that hit a short round carton. They tested how far the steel ball would push the carton at three different speeds. Students controlled the speed of the ball by pulling back the rubber band on the launcher to three different distances prior to launch. The steel ball investigation was designed to provide an opportunity for students to explore the concept of energy, so that they could use what they observed in the investigation to explain the process of erosion that occurred in the stream table model.

Ms. White began this lesson by priming students to think about the incline they created for the stream tables by placing blocks under one side of the stream table. Students identified the role of the blocks in causing the water to flow down the stream table. At the teacher's request, I (MM) led a demonstration of the steel ball investigation to orient students to the procedure. After I demonstrated the use of the launcher, I elicited students' observations of what they saw happening and prompted students to think about how this investigation related to their experiences with the stream table.

MM We've been working with the stream tables, we have been working with water, why are we now working with steel balls?

DD Maybe it has to do with energy?

Serenity	Depending on how much pressure there is from the source.
MM	HK had an interesting idea.
HK	The launcher and the steel ball is like erosion but the steel ball isn't water.
MM	Okay, so how is it like erosion?
HK	Because the steel ball pushed the little yogurt container because it was in its path.
MM	Okay interesting, because in erosion what happens? What have we noticed?
IP	It's basically just like the same thing with the steel ball and the blueberry tin thing. What if it was like the steel ball could have been the water and the blueberry thing could be the sand?
MM	That's very interesting. So, what we've been seeing in erosion like the steel ball being pushed against the blueberry tin.
HK	But in the stream table it's water.

During this exchange, HK made a connection between the steel ball investigation and the stream table that was taken up by IP. Both students identified that the action of the steel ball hitting the container was similar to the process of the water hitting the sand in erosion. Both HK and IP's responses revealed how they were able to draw on their observations of the steel ball hitting the container to further make sense of what they observed during the stream table investigation. HK's repeated response regarding the difference between the steel ball investigation and the model of the stream table also suggests that he felt strongly that these two experiences had important differences.

At the conclusion of this demonstration, I prompted students to make connections between the ideas introduced by HK and IP and their observations of the stream table when the incline increased. Kyle shared that he observed the water moving faster because of the steeper incline, but no students shared a connection between their observations of the steel ball demonstration and the effects of fast-moving water in the stream table. The class demonstration of the steel ball investigation provided students with an introduction to the concept of energy and how their observations of this demonstration could contribute to their understanding of what they observed in their stream table models.

Heavy rain has more energy: The rain model. On Day 19, Ms. White introduced the class to a model of rain using two containers that had different-sized holes drilled into the bases (Figure IV.3). Prior to this, the class had been introduced to the terms, *kinetic energy* and *potential energy* during a whole-class reading. Ms. White introduced the containers as a model and told the students that they would be investigating how rain changes the land (11.22.16 field notes). She conducted this investigation as a class demonstration and invited students to help her conduct the demonstration and provide their observations and ideas. Prior to conducting the demonstration, Ms. White elicited predictions from the class about what may happen. Caleb shared that heavier rain would make a bigger hole in the sand. Ms. White asked the class to indicate if they agreed with him and several students raised their hands. When Ms. White asked the class to provide reasons, one student shared that heavy rain falls faster than light rain (11.22.16 field notes). This comment introduced the idea of speed and its effects on the sand into the class's conversation. Ms. White built on this by prompting the class to think about the speed of the rain. A student shared the observation that the water in their stream table was faster without rocks (11.22.16 field notes). This comment suggests that the student may have made a connection between the speed of the water in the stream table and the speed of the water in rain. There was no further conversation to determine if the student was thinking about the effects of faster rain and how his or her observations from the stream table could also apply to this model. At the conclusion of the demonstration, Ms. White asked students to identify the container of rain with more energy. GL responded that the heavy rain had more energy and Ms. White agreed with him (11.22.16 field notes).

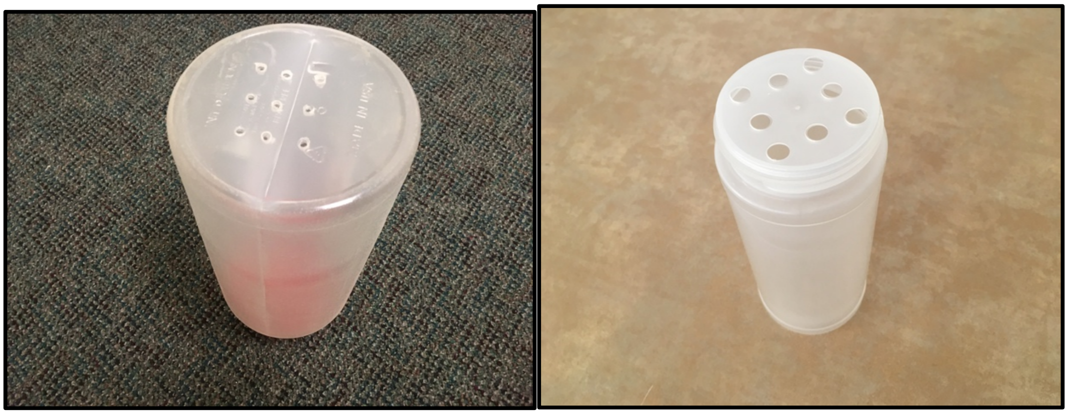


Figure IV.3. The rain model. This model was comprised of two canisters with different-sized holes drilled in the base of each canister to model different intensities of rain – light and heavy rain.

Then, the class moved to constructing a scientific explanation to answer the question, *How does rain affect the land?* During this process, the teacher used revoicing to support students' sense-making about what they observed in the model and how their observations related to energy. The teacher asked students to share their ideas for claims. Caleb shared that "heavy rain had more energy because the potential energy became kinetic energy faster" (11.22.17 field notes). Ms. White revoiced this claim as, "heavy rain will have more energy" when she recorded the claim on the board. Ms. White followed up with Caleb to ask how the heavy rain would affect the land. Caleb shared that it "cut straight through." Ms. White added to the claim on the board, "and will change the land faster." Caleb introduced the idea of energy in the claim, however his use of the terms, potential and kinetic energy, was not correct. Ms. White's revoicing of his claim built on his use of the term, *energy*, and also introduced the idea that the heavy rain would change the land faster, as this was not an idea that Caleb introduced in his response.

As discussed by Clark and Linn (2013), students develop knowledge fragments through their experience with phenomenon, both through formal schooling and their everyday experiences. These fragments are continuously refined, evaluated, and integrated to form coherent understandings. Caleb's response suggests that he was forming knowledge fragments about the different types of energy that the class had previously discussed and how they related to the rain canisters, but his understanding of how potential energy is transferred to kinetic energy was still incomplete. These fragments could eventually be integrated into an explanation of why the heavier rain caused more erosion to the sand.

After students shared their observations that could be included as evidence, Ms. White moved onto the reasoning portion of the claim. I reintroduced the idea of energy into the class's discussion and prompted students to make connections between what they observed and the ideas about energy they had been discussing during the steel ball investigation. I also introduced the idea that the heavier raindrops had more speed and therefore more energy. This statement tied together Caleb's idea that the heavier raindrops had more energy and the observations that students made in the steel ball investigation regarding the speed of the ball and its effect on the movement of the yogurt container. Ms. White wrote on the board, "heavy rain had more energy and it did change the land faster." This statement did not reflect the ideas that I introduced into the conversation, but drew on the ideas that Caleb and Ms. White previously introduced in the discussion.

At the beginning of the next science period (Day 20), students drew on the ideas introduced by Ms. White, Caleb, and me during the previous lesson. While students shared their ideas in small groups, Ms. White circulated to listen to groups' ideas. When she stopped to listen to Kyle's group, he said, "the heavy rain really made the impact on the sand tower because the force was coming down really fast." Ms. White rephrased this as, "so it had more energy because it was faster?" When Ms. White asked for volunteers to share, Kyle shared, "the heavy rain made a bigger impact on the sand tower because it had more energy, so it came down faster than the light rain." Kyle and Ms. White co-constructed this understanding during the small group time of this lesson and his statement reflected the ideas introduced by Caleb and Ms. White during the previous lesson. The exchange between Ms. White and Kyle illustrates how Kyle constructed productive resources regarding the role of speed and energy in the process of erosion from rain and how Ms. White's use of revoicing of ideas supported Kyle to make connections among these different resources (Clark & Linn, 2013). The differences between Kyle's first statement during the small group discussion and his second statement during the large group discussion reflects small, but important, shifts in his understanding regarding the causes of erosion and the role of energy in this process. The interactions with Caleb and Kyle in the context of the class's use of the rainfall model demonstrate how Ms. White used revoicing to support her students to make sense of what they observed in the rainfall model and how their observations related to the ideas about energy that the class had been discussing.

Water is an active agent in changing the land: The wave table model. The third model that students interacted with was a wave table. This model simulated the effect of waves on the shore and was designed to provide opportunities for students to observe the erosion that occurs on coastlines and the shores of lakes. The wave table was assembled using a square cake pan with sand piled on one side to represent a beach. Water was added to the pan and waves could be created by moving a ruler back and forth in the water.

Ms. White requested that the second researcher (Mr. D) assisting in the classroom lead the demonstration, so that she could monitor student behavior. Mr. D introduced the wave table by explaining, “For this particular demonstration we have tried to make a model, we’ve recreated what you saw in the video.” He introduced the idea that models could be recreations of what students saw in the videos of waves that they had watched prior to the demonstration. Throughout the demonstration, he continued to emphasize his attempts to recreate the waves that the students had seen in the videos. Mr. D began by modeling small waves in the wave table and asked the class to share their observations, particularly regarding the amount of energy that was present in the video of the small waves. Caleb responded, “it was less energy because the waves were smaller.” This response provided students with an opportunity to compare how waves with different amounts of energy affected the shoreline at the end of the demonstration. MU and Caleb made specific observations regarding how the water was affecting sand in specific areas of the tray. Caleb shared, “It’s kind of molding the little piece right there.” When Mr. D asked for ideas about why it was “molding” the sand, Serenity responded, “When the water is coming forward it is pushing the sand and when the water goes back it make the sand go back with the water.” These observations introduced the idea that the water was an active agent in changing the land.

Mr. D transitioned to using the wave table to model big waves. He introduced this model by asking students to brainstorm how the beach might be different during a big storm. GL predicted that the rain would be heavy and it would spread the sand, which may have been informed by the use of the rainfall model. Mr. D asked students to think about how the ocean might be different. Kyle shared that the waves would be bigger and another student, BW, agreed by saying, “they would be HUGE [original emphasis].” Caleb added, “since it is going faster, it will make waves faster so they would be closer together.” Serenity agreed with this idea but had different reasoning, explaining that “the amplitude will be higher and the wavelength will be shorter because it's higher so it might not make it as wide apart." Caleb and Serenity drew on the vocabulary that the class had been introduced to in the previous lesson. During the demonstration, several students observed the waves moving faster. Caleb also observed that "they are getting really close because of how fast the waves are going." Mr. D prompted students to think about Serenity's earlier comment regarding how the water moved the sand and asked for additional observations. RM stated that the sand was going into the water. Caleb added that, "it starts falling down slowly. The sand is falling slowly but the erosion is going fast." Serenity added that "the waves are making the sand fall fast" and HK observed that the beach looked flooded. The observations made by Caleb and Serenity reinforced the idea that the faster waves caused more erosion; however, the concept of energy was not included in any of these observations.

After Mr. D finished the demonstration, I reminded the class that the wave table was a model of the ocean and asked them how the wave table was similar to the ocean. TC stated that in the model, the sand moved a lot, and HK observed that "It actually was water to make the waves and the sand was the beach." When I asked for differences, DD responded that we added more water to the model and Serenity observed that the model was smaller and did not use salt water, like the real ocean. This was the first opportunity during the unit in which students were invited to think about the similarities and differences between a target phenomenon and the corresponding model. Differences between models and their corresponding phenomena were briefly discussed during the steel ball investigation when HK observed that the action of the steel ball hitting the yogurt container was similar, but not the same, as water hitting the sand in the stream table because the steel ball and water were different materials. In the context of the wave table, students' answers revealed that they were thinking about the target phenomenon (i.e., salt water, water and sand) when considering the similarities and differences, but the majority of the responses focused on physical features, such as the materials, as opposed to the underlying mechanism that is similar in both the target phenomenon and model. Serenity did suggest that the scale of the model was smaller than the ocean, but this was not elaborated on by other students. Mr. D prompted students to think about deeper differences between the model and the phenomenon, such as the source of the waves. He asked if there was a ruler in the ocean, and this prompted a brief discussion about the role of the moon and wind in generating waves.

This conversation introduced the idea that models can share similarities and differences with the target phenomenon and contributed to the class's ongoing discussion regarding models. The tendency to focus on the physical features may have been supported by the fact that the wave table model and the target phenomenon of waves in the ocean did share many physical similarities. These similarities lower the cognitive overhead of the model, but also may limit students' consideration of invisible or process-oriented similarities because the physical similarities are so obvious (Lehrer & Schauble, 2010; 2012).

Models can help people understand a phenomenon: Student-constructed models. As the unit reached its conclusion, students constructed paper-and-pencil models to explain how water changes the land. On Day 25, the teacher introduced this task using a power point designed by the researchers. This presentation was designed to help the teacher and students reflect what they had learned during the unit and their use of models to prepare students to construct their own models. The power point was not in the curriculum, but was added by the researchers during the enactment in order to support the teacher to feel more prepared to lead a discussion about the characteristics of models.

During this conversation, students shared ideas about the uses of models and the practice of modeling that had been introduced and reinforced throughout the unit. Ms. White followed the power point and allowed students to talk in small groups, as well as invited comments and ideas from the whole class. She first asked students to summarize what they had learned about how water changed the land. Ms. White circulated among the small groups and used revoicing to support students in making sense of what they observed during the wave table demonstration, similar to when students discussed what they observed in the rainfall model demonstration. While visiting one group, Kiara shared, "I think the water moves faster and changes the land." Ms. White pressed her to identify what that caused, and Kiara repeated that it changed the land. Ms. White revoiced Kiara's answer and said, "erosion." This revoicing of Kiara's idea using the terminology that students had been working to develop during the unit emphasized the meaning of the term, erosion, and modeled how Kiara could use it. When the class shared their ideas, Kiara did not share, and it is unclear if she took up the term to explain what she observed. Kyle shared with the class, "that when the - with the waves, in the video about the waves, in the first video of the waves. [Ms. White clarified it is the video with the big waves] The big waves. They were eroding more of the land because they have more energy." Ms. White responded by affirming that the class had been talking about energy and asked Kyle to elaborate on what happens with more energy, "The more energy, the what?" Kyle responded, "the more it moves the land." Kyle and Kiara's responses to the prompt suggest that students were drawing on their experiences throughout the unit and the different ideas that were introduced about the factors that influence to what extent water changes the land. Kyle's observation and Ms. White's response also re-introduced the concept of energy into the class's conversation.

Then, the class transitioned to discussing the use of models in science. Ms. White invited students' ideas about the purposes for using models in science. GL shared, "a model is like you draw the waves, right? Or something like that. You draw the stream." GL identified the diagrams of the different properties of water waves, including wavelength and amplitude, that the students drew on the board after using the wave table. Ms. White replied, "Our stream table was a model that we used. Mr. D had the wave table, that was another physical model that we used." Ms. White's response clarified GL's idea by reframing the different phenomena that GL mentioned (i.e., wave and stream) as the different models the class used and classified all of these as physical models. This introduced a similarity in the types of models that students had engaged with during the unit and that models could be physical objects.

Ms. White moved to the next discussion question and asked the class to talk in small groups about why models are helpful to create. She circulated to different groups and spoke with RO and Alyssa. RO shared that, "it shows us what it does" and Alyssa added, "how the water moves." Ms. White agreed with them and responded, "Yah, instead of just looking at a picture." The idea of models as better tools for understanding something, as opposed to looking at a picture, is one that Ms. White introduced at the beginning and reiterated throughout the unit. Her statement emphasized that models had affordances that looking at pictures or reading about phenomena lacked.

When the class came together to share their ideas, LM explained, "maybe so if they don't understand what it is and it would help them…it can help the person out by drawing a wave or something." The teacher pushed LM to think about other kinds of models. She reminded the class about the wave table demonstration and asked LM to explain why that demonstration was helpful. He replied, "so we could see when it was faster it was knocking down more of the sand

and if was bigger it would free all the sand." LM's response repeated the idea that Ms. White shared with RO and Alyssa and her previous comments about the purpose of models to see things. NK added to the idea of seeing things with models by explaining, "In the introduction when Mr. D did the model, he was pushing the model with the ruler. He was giving us a good example of what it would look like if you were on the beach. [Ms. White: How was that helpful to us?] So we could think about it." NK repeated the idea brought up by LM, but he also added the idea of using models to "think about it." So far in the conversations about the purpose of models, Ms. White and her students had focused on the importance of seeing phenomena and making observations but had not discussed what the observations of a model might reveal about a phenomenon. HK added onto the discussion by introducing the idea of the trustworthiness of models, "If someone is like, studying them like waves and stuff like we were, and they couldn't see like real waves in person, they could make a model of how they think that waves work so they could make a model then trust it and know about waves and stuff." HK's idea builds on NK's idea of using models to think about phenomena and the ability to use models to learn about a phenomenon and trust what you see. These ideas demonstrate how students were extending on the ideas that Ms. White had seeded at the beginning of the unit, as well as building on each other's ideas (Figure IV.1). Many of these ideas had remained relatively untouched as students progressed through using the different models, but the analysis of this conversation suggests that the use of multiple models may have supported student to develop an understanding of the ways in which models can be used to study phenomena. This discussion also contributed to students' understandings of the contexts in which scientific models can be used and the purposes they serve, an important element in the development of meta-representational competence (diSessa, 2004).

After this discussion, Ms. White introduced the 6 characteristics of models (Table IV.2). These characteristics were included in the lesson plan for the teacher to verbally discuss with students, however, the researchers hypothesized that including a visual would better support the class's discussion. After reviewing these characteristics, Ms. White transitioned the students to planning their own model. Students worked individually, or in small groups, to decide on the variables for their model, namely the type of moving water they would include in their model and its effect on the land. Ms. White and the researchers circulated to work with students to identify the variables for their models.

Table IV.2
Six characteristics of models.

1. All models seek to answer a question about why something happens.
2. All models have variables.
3. Models show connections between the variables.
4. Models should provide a cause for what happened. (Cause and effect: if one thing causes another thing to happen, it might explain or predict other events).
5. Models are shared for feedback.
6. Models are revised based on feedback.

Before students advanced to drawing their models, Ms. White reviewed the different ways that water could cause changes to the land and asked students to share the associated effects. Students' responses suggested that they were applying knowledge and ideas that had been developed through the use of the different models. For example, Kyle chose to include waves in his model. When asked by Ms. White to explain how the land would change, he stated, "it pushes the sand because of the energy and it eroded and it carried sand back a little bit." Ms. White also asked for a volunteer to share how the land changed using the rain model and the differences between heavy and light rain. TH described that "…the water rains down to the sand because the land has so much powerful energy, like the … [Ms. White: We had our sand castle and the rain came down and did what to it?] it melted down like with the hard rain and went faster because the sand tower was lower and lower and the light rain… the little rain has a little energy." The beginning of TH's response revealed some confusion, but he corrected himself after Ms. White helped him to begin his explanation. TH's explanation revealed his sense-making of the process of erosion from rain, especially when he described the rain as "melting." This description suggests that TH understands that the heavy rain caused the sand to move and lose its shape. In addition, the confusion revealed at the beginning of TH's answer suggests that he may still be working with multiple, possibly contradictory, ideas regarding where the energy is located in the system. Clark and Linn (2013) suggested that the inclusion of new ideas into knowledge webs requires students to confront their existing ideas and possibly change the connections between ideas in a web. TH's disorganized response suggests that he may still be revising and refining connections between ideas.

Both Kyle and TH incorporated the idea of energy into their responses. TH's response suggested he was thinking about the relationship between the speed of the rain and the amount of energy when he described the little rain as having little energy. Kyle demonstrated how he was thinking about the role of energy in the movement of the sand when he described the water as pushing the sand because of the energy. Both responses demonstrate the productive ideas regarding the role of energy and the factors that contribute to erosion caused by moving water with which students were working and applying to the construction of their drawn models. At the end of the class, Ms. White selected students to share their models with the class. Serenity shared her model and the teacher drew the class's attention to the use of labels as an important feature of models.

During the next class period students exchanged models and provided feedback using a Model Feedback sheet. This sheet included reflective questions designed to help students assess one another's models and provide feedback using the 6 characteristics that students were introduced to the previous class (Table IV.2). In order to introduce students to this sheet and the task, Ms. White and I decided that it would be helpful to provide students with an example model and the class would complete the feedback sheet together. I constructed a model that was purposefully incomplete so that students could identify areas of improvement, but also included components that students had struggled to understand during the previous class, such as labeling components of the model and showing the process of erosion through pieces of land breaking away from the side of the river (Figure IV.4). The teacher led the students through the worksheet and focused on the procedures to fill out the sheet. She primarily accepted one answer per question, which did not provide many opportunities to gauge how students were thinking about the process of erosion explained in the model. When Ms. White asked the class to share constructive comments about what could be changed, students suggested adding features that corresponded with their experiences during the unit, such as adding rocks or rain.

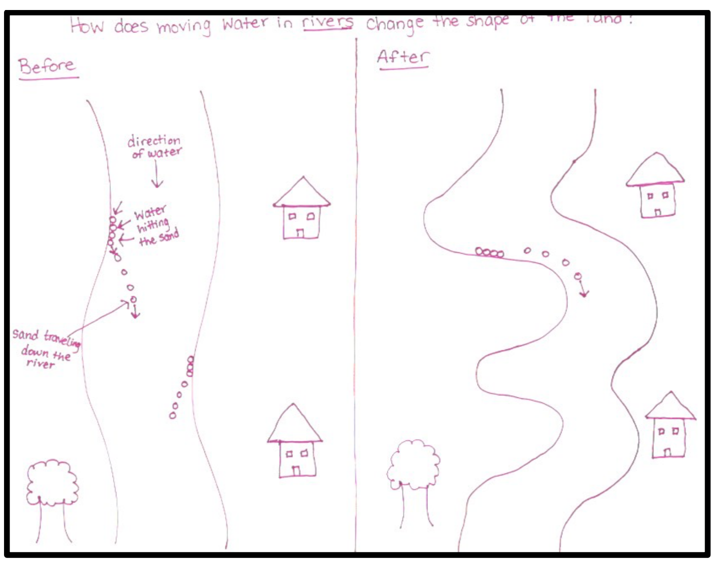


Figure IV.4. Model used an example to introduce students to the feedback protocol.

Observing another model during the introduction to the class and engaging in peer feedback led many students to revise their model. At the beginning of class on Day 27, Ms. White asked for volunteers to share the feedback that they received the previous day. Several students shared that they needed to add labels. GL shared that his partner suggested that he needed to show more connections between the variables in his model. Ms. White used this as an opportunity to remind students to elaborate and be specific in their models. She reminded the class about the example model that she showed the previous day and how there were arrows showing how the sand was being carried (12.15.16 field notes).

Students' drawn models explaining how water shapes the land provided the first opportunity for students to construct models during the curriculum. The class's discussion during the introduction to this task revealed the ideas that the teacher had seeded earlier in the unit regarding the purposes for models and modeling had developed as the unit unfolded.

Summary of the class case. Conceptual ideas that were introduced by both the teacher and the students during class discussions were built upon in subsequent classes, including that the process of erosion causes land to be taken away, the speed of an object influences how far it can push another object, and the amount of energy in the water influences the rate of erosion. Students also referenced the models they had used when discussing conceptual ideas. For example, HK referenced the stream table when explaining what he saw during the steel ball demonstration and TH referenced his observations of the rain model when discussing which type of rain had more energy. These examples also demonstrate how energy was discussed and considered during the unit. Students were able to describe different types of rain or waves as having more or less energy. By the end of Unit 1, energy was a way to characterize moving water and students could explain the effects of water with *more* or *less* energy on the sand; however, there is no evidence from the class discussions that students could discuss these effects using the idea of energy transfer.

Ms. White introduced students to the important epistemological idea that models could be used to represent a phenomenon (Lehrer & Schauble, 2010), and emphasized the importance of models and their usefulness in studying erosion throughout the unit. At the end of Unit 1, students built on this idea to share additional epistemological ideas regarding scientific models, including that: (a) models are trustworthy ways to study a phenomenon, (b) they can provide an example of a phenomenon, and (c) they can be used to study a phenomenon. These ideas suggest that the initial ideas introduced by Ms. White supported students to develop their understandings of the use of models.

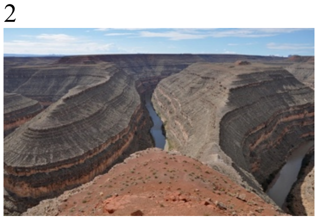
An analysis of the class discussions suggest that students began noticing connections between the models and the target phenomena as the unit progressed. Neither Ms. White nor the students drew connections between their observations of the stream table model and their observations of the stream outside the school, but at the end of the unit students were drawing on their observations of the model as a way to explain the phenomenon of erosion. For example, TH explained how the rain "melted" the sand tower as a way to explain how rain shaped the land and HK suggested that using models was a trustworthy way to learn about how waves change the land. These observations suggest that students may have been using their observations of the models to inform their explanations about the process of erosion.

Focal Students' Sense-Making

Focal students' interviews conducted at the beginning and end of Unit 1 were used to construct sub-cases of their sense-making regarding the process of erosion and epistemological beliefs of models, including the idea that models can be used to observe phenomena. The analysis of these sub-cases provides additional insight into the ways in which models influenced students' sense-making.

Kyle. Kyle demonstrated typical prior knowledge on the unit pre-assessment in relation to his peers. Kyle's sense-making throughout the unit was documented through his contributions to class discussions and shifts in his thinking regarding assessment questions. His answers on the content pre-assessment suggested that he was thinking about how natural processes shaped the land shown in the pictures, but his ideas did not involve how water contributed to these changes. Table IV.3 shows Kyle's written responses to questions 1 and 2 and his elaborated responses during his Unit 1 pre-assessment interview[6].

Table IV.3
Kyle's written and elaborated responses on the Unit 1 content pre-assessment

Question	Written Response on assessment	Elaborated Response in interview
1 	It shaped by an asteroid.	Well I was thinking that, that was kind of like new land that they found…And it got hit by an asteroid before they found out about it.
2 	It got shaped by an earth quack [earthquake].	I thought it would be like an earthquake that formed it because there was so much cracks in it.

These responses on the content pre-assessment and during the interview suggest that Kyle thought the land has been changed, as opposed to always looking like that, and that the changes occurred through natural events (i.e., an asteroid and an earthquake), but that water was not responsible or involved in the changes to the land. Kyle's responses also align with findings in the literature that some students attribute the effects of erosion to catastrophic events (Martinez et al., 2012).

[6] Question 3 from the content assessment was not included in the analyses due to the quality of the image on the assessment.

Kyle's responses on the Unit 1 modeling pre- assessment reflected uncertainty about the use of the stream table as a model of real streams and rivers, but that he did think that the stream table could be used to study the real streams and rivers. Students took this assessment on Day 3 of instruction, one instructional day after they used the stream tables for the first time. Kyle chose "Not much" in response to Question 1, "How much can you learn about the ways water changes the land by using the stream table?" When I asked him to share his thinking about this choice, he responded, "well because I didn't think like before we did the demonstration that the water would change a lot by the water moving the sand…so I didn't think that much would happen to the water and sand." Earlier in the interview, Kyle shared that he recalled completing this assessment prior to seeing the demonstration of the stream table. In reality, students engaged in the class demonstration and interacted with the stream table in small groups on Day 2 of instruction, one day prior to completing the assessment. It is possible that Kyle did not realize that he was working with stream tables on Day 2 and therefore did not recognize the term on the Unit 1 modeling pre-assessment.

Kyle responded "Not sure" to Question 2, "Does a stream table need to look exactly like a real stream or river in order to answer questions about how water changes the land?" His written explanation for this choice was, "Because I don't know if they do or not?" Kyle's responses suggested that he was not confident in the uses of the stream table to learn about how water changes the land because he was unsure about how a stream table worked. However, in response to Question 5, "Can you use the stream table to predict how water will change the land?," Kyle answered "Yes" and wrote, "because it changes land when water flows over the land." This answer suggested Kyle had some prior knowledge about how water changes the land that he was applying to make predictions about what would happen in the stream table. However, given his other answers on the modeling assessment, he may not have been thinking about the ways in which a stream table could show this phenomenon but was instead applying his prior knowledge about the phenomenon itself.

Kyle's thinking about the use of the stream table as a model had already changed by the time of his interview regarding his Unit 1 pre-assessment, which occurred between Days 10 and 11 of science instruction. During the interview, I asked Kyle if he still agreed with his response to Question 1 (How much can you learn about the ways water changes the land by using the stream table?), or if he thought differently now. Kyle shared that he now thought "that it changes a lot", and explained "because when we tried it out, when we did another test, like a lot of the sand moved on to the bottom of the stream table when we moved the water down." Kyle's response suggests that he was already thinking differently about the stream table as a model of how water shapes the land and using his observations from the stream table to inform his understanding about how water shapes the land.

Kyle made contributions during class discussions regarding the use of models that were also reflected in the pre-assessment interview. For example, on Day 10, Kyle shared that one purpose for using models was to test different materials, which Ms. White revoiced as "performing tests" (10.31.16 Field notes). During his interview about his Unit 1 modeling pre-assessment, he used the language of "test" to explain how he knew that the sand in the stream table moved. The use of this vocabulary suggests that he took up the terms that the teacher had introduced, because the interview occurred after Day 10 instruction. When asked about how he might change the stream table so that it could do a better job of predicting how water changes the land, Kyle suggested, "maybe I could like put rocks all over to still see if the water could get through" (Kyle Unit 1 Interview #1). Kyle drew from his own experiences and referenced the investigation that he completed with his group on Day 10. Kyle's explanations during his interview reveal how the class discussions and activities supported his sense-making about the role of the stream table as a model early in the unit.

Kyle's contributions as the unit progressed revealed how his understanding of the process of erosion and the ways in which the stream table could be used as a model developed throughout the unit. After observing the rain model demonstration, Ms. White and Kyle co-constructed an explanation during a turn-and-talk that Kyle shared with the whole class that, "the heavy rain made a bigger impact on the sand tower because it had more energy, so it came down faster than the light rain" (11.28.16 field notes). This was the first time during class that Kyle discussed the idea of energy during recorded class discussions.

Even though Kyle demonstrated that he was thinking about the idea of energy during class discussions, he did not bring up the idea of energy during the post-unit interview regarding his drawn model, nor in his post-unit conceptual and modeling assessments. However, Kyle's interview did further reveal the development of his understanding regarding the process of erosion caused by water and the role of models in science.

Post-unit interview. During the post-unit interview, I asked Kyle to tell me about his model (Figure IV.5). He explained, "so this is the river one that I did and then this one is the sand and rocks getting pushed onto the corners of the river and it kind of made the river, it kind of changed the shape" (Kyle Unit 1 Interview #2). The model that Kyle shared looked very similar to the example model that Ms. White showed the class at the beginning of Day 26 (Figure IV.4), suggesting that he may have been primed to draw a model of erosion in a river as opposed to using the example of erosion caused by waves that he shared with the class on Day 25.

Kyle also created a model that explained how waves changed the shape of the land, but he was unable to find this model on the day of our interview. Kyle constructed this model during class on Day 25, when the class was working to develop their drawn models. Ms. White asked Kyle to share how the waves in his model would change the land and he shared that, "It pushes the sand because of the energy and it eroded and it carried sand back a little bit" (12.8.16 field notes). Kyle applied the idea of energy to his reasoning about how waves change the shoreline, which revealed that he was considering the idea of energy in his sense-making regarding how waves changed the land. These are example of resources that Kyle developed during the unit that he was able to apply to his explanation of why waves change the shape of the land. Kyle's explanation involved productive knowledge fragments regarding the presence of energy that could eventually be applied and integrated into a causal account for why erosion from waves occurs. Kyle's answer also reflects the ways in which students were talking about energy. Kyle was aware that energy was present but was not able to explain *how* energy was involved in the process of erosion (i.e., energy is transferred to the sand, causing the sand to move).

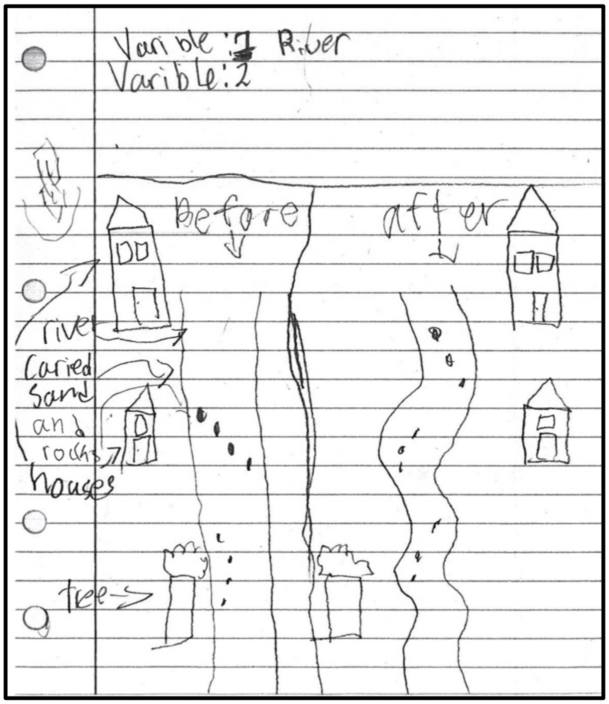


Figure IV.5. Kyle's Unit 1 drawn model showing the effects of erosion on a river.

When I asked Kyle what his model was explaining, his response revealed that he was thinking about the timescale of changes to the shape of the river (Kyle Unit 1 Interview #2).

K(yle) It's explaining that the rocks and sand are hitting the sides of the rivers and after a period of time it makes the river a different shape.

MM Okay so what kind of period of time? How much time are we talking?

K Maybe like three months.

Kyle's responses suggest that he was aware that erosion was an ongoing process, but did not understand the timescale of erosion. Kyle's developing understanding regarding the timescale of erosion was also present in his thinking regarding the items on the post-unit content assessment. Table IV.4 shows his written responses on the post-unit assessment and his elaborated responses during the post-unit interview.

Table IV.4
Kyle's Unit 1 content post-assessment written and elaborated responses

Question	Written Response	Elaborated Response

1	Erosion that happened for a long time.	That it probably took a year or two for [the rocks] to get back that far.
2	Erosian from million years ago	Kyle: Oh, that was an erosion and it kinda reminded me of the Grand Canyon and how it got its shape. MM: So, can you tell me more about that, how did it get its shape? Kyle: Umm the, so there was a stream going right there and then the water carried the sand and it made all curves and from the rain coming down and going down farther. MM: Okay and you said from a million year ago? Kyle: Yah because it probably took a long time to get all the way, way down there.

Kyle's response to Question 1 and his explanation on his drawn model suggested that he was not aware of the timescale over which erosion occurred. However, his response to Question 2 suggests that he applied his understanding about the specific context of the Grand Canyon, which the class had discussed on Day 3. Kyle's reasoning about why it would take a million years to form indicates he was thinking about the long timespan associated with the process of erosion in the specific context of the Grand Canyon, but he did not make connections between this understanding and other forms of erosion. Clark and Linn (2013) suggest that students develop ideas within specific contexts and must distinguish between and connect these ideas together in order to form a coherent understanding of a phenomenon. Kyle's reasoning suggests that he had developed an idea related to the long timespan associated with erosion from water in the context of the canyon, but he had not created a coherent understanding that could be applied to other examples of erosion caused by water, such as the beach in question one.

Kyle's responses and elaborations regarding his answers on the modeling assessment revealed how his experiences and the class discussions supported his sense-making about the role of the stream table model in learning about erosion. In response to Question 1, "How much can you learn about the ways water changes the land by using the stream table?" Kyle selected

“A lot.” When asked to elaborate on his choice, he explained, “because stream tables are basically just, so they help you because you see, so you could see how the water changes the land” (Kyle Unit 1 Interview #2). This response echoed Ms. White’s repeated statements regarding the use of the stream table to see erosion and suggests that Kyle had taken up this idea in his own sense-making about the role of the stream table in studying erosion.

Kyle also drew on his experiences from the unit when explaining what could be changed about the stream table to better predict how water changed the land. He said, “Maybe you could add…well I don’t know because the rocks were the rocks and the green stuff was like the grass.” This response is similar to his explanation regarding what he had already learned about stream tables during the Unit 1 pre-assessment interview. In his answer, Kyle makes reference to the idea that the “green stuff” was standing in for “grass,” suggesting that he was thinking about the role of certain aspects of the stream table as representing aspects of the target phenomenon. He discussed additional ideas about how he could change the stream table when sharing his thinking about Question 5, “Can you use the stream table to predict how water will change the land?” Kyle selected “I don’t know,” which was a change from his response of “Yes” on the Unit 1 pre-assessment. When prompted to share his thinking about his response, Kyle revealed his thinking about the limitations of the stream table model and the features of land that it could model.

K(yle) Well yeah because maybe the stream tables are, like, cause you kind of control it where you put all the land and it might not be the same because you didn’t place the land there in a real stream.

MM Okay. So, is there a way we could change the stream table so that we could make predictions or explain things?

K	Maybe we could try to put the land in the same area of where it is, where it happens.
MM	So you think that would help?
K	Yah.
MM	Anything else?
K	Maybe, because, maybe they aren't the same going down.
MM	What do you mean by going down?
K	So if the stream happened going down a mountain maybe it's not the same with the other stream table because it's not as far down as the mountain would be.
MM	Okay so what would you change then?
K	How, I would change how high the stream table will be.
MM	And so that would make it more like the mountain?
K	Yes.

Kyle's conversation with me revealed several insights into his thinking about the role of models and their predictive power. First, he indicated that physical similarities between the model and the target phenomenon (in this case, a stream) were important for being able to make predictions about how water shapes the land using the stream table. Kyle also observed that, because the stream table is a model, you could design the land in any configuration, which could either enable or limit your ability to make observations about how water shapes the land. Then, Kyle made a connection to the students' investigation with the stream table, in which they investigated the slope of the stream table. He identified the slope as another way in which the stream table model could differ from a real stream. Kyle indicated that changing the slope of the stream table to match the slope of them mountain could increase the predictive power of the model.

Kyle's explanation suggests that he was thinking about the physical similarities between the stream table model and target phenomenon as important for increasing the predictive power of the model. However, Kyle's explanation of slope also alludes to ideas regarding the function of the stream table when he said, "it might not go down the same way." This statement suggests that Kyle may have been considering factors that would influence the model's ability to show the effects of slope on erosion.

Kyle's understanding of erosion developed throughout the unit. By the end of the unit, he explained the images on the content assessment in terms of the process of erosion and his explanations of the images and his model suggested that he was developing an understanding regarding the timescale of erosion. His responses reveal that his understanding of timescale was context-specific and was being developed in the context of the Grand Canyon. Kyle had not yet applied his understanding of the timescale of erosion other contexts, including his model and the images on the post-assessment.

Kyle's understanding about the stream table as a model also developed during the unit. His responses on the Unit 1 modeling post-assessment revealed that his understanding about the role of the stream table as a model had deepened, and he was thinking about the similarities and differences between the model and the target phenomenon. However, the comparisons that Kyle made between the model and target phenomenon were primarily physical comparisons, which is unsurprising given that students new to the practice of scientific modeling can struggle to consider similarities or differences in the underlying mechanism of the model and target phenomenon (Lehrer & Schauble, 2012).

Samuel. Samuel demonstrated low prior knowledge on his Unit 1 content pre-assessment as compared to his peers. Table IV.5 shows his written answers on the pre-unit assessment and his elaborated answers from the pre-unit interview.

Table IV.5
Samuel's Unit 1 content pre-assessment written and elaborated responses

Question	Written response	Elaborated response
1	Jesus made the land.	From the water? From erosion?... That the water made it like that.
2	That turtles made it like this.	The water erosion made it like that.

Samuel's answers changed from the ones that he wrote on his pre-assessment to when I discussed them with him during the Unit 1 pre-assessment interview. Because the interview occurred 11 instructional days after Samuel completed the pre-assessment, his thinking had been influenced by the activities in science. When elaborating on Question 2, Samuel initially struggled with an explanation for how the canyon in the picture was formed, but eventually said "the water erosion made it like that." Samuel's answers during the Unit 1 pre-assessment interview suggest that he had already begun thinking about the role of water played in shaping the land, and was familiar with the word, erosion; however, these ideas were still developing, and he did not apply these ideas to explain how water played a role in erosion and in shaping the land.

Samuel's responses on the modeling pre-assessment also provide insight into his practical epistemological beliefs about science (Sandoval, 2005). In response to Question 1, "How much can you learn about the ways water changes the land by using the stream table?" he responded, "A lot," and shared his thinking about why he chose that answer.

S(amuel) A lot, because every time we do it in science.

MM Because we do it in science?

S Mmhmm.

MM If we didn't do it in science would you change your answer?

S Nothing at all.

MM Oh, nothing at all. So, because we do it in science that is why we can learn a lot?

S Mmhmm.

In this excerpt, Samuel revealed that the use of the stream table in science is the reason he is able to learn from it. Samuel may have believed that learning from the stream table can only occur in the context of "doing science." According to Sandoval (2005), beliefs that students hold about the production of knowledge in the context of school science are their *practical epistemologies*. Samuel's belief that the stream table was useful because it was used in his science class is an example of a practical epistemological belief that he holds.

In response to Question 5, "Can you use the stream table to predict how water will change the land?" Samuel answered, "I don't know" and explained, "I've never seen a stream table before." This rationale was similar to Kyle's response and statement that he had not seen the stream table prior to completing the assessment. Similar to Kyle, Samuel may not have realized that the stream table referred to in the assessment was the same model that they had used in the previous class period. During the Unit 1 pre-assessment interview, I asked Samuel if he would change his answer now that he had used the stream table. He indicated that he would change his answer to, "Yeah because, because the stream table can change the land in different ways, different shapes." His answer suggested that Samuel observed changes in the stream table and related these changes to the changes referred to in the question. In addition, when asked how he would change the stream table so that he could learn even more from it, Samuel responded that he would not change anything. This response suggests that Samuel was not thinking about the limitations of the stream table model or that models could be revised.

Unit 1 post-assessment interview. Samuel's model that he created at the end of Unit 1 revealed his developing understanding about the process of erosion (Figure IV.6). Samuel described his model as, "So there are waves and it's going up the sand and changing the sand to go a little more down and go back" (Samuel Unit 1 Interview #2). Then, when I asked Samuel what his model was explaining, he provided a very similar answer, "The waves are, my model is changing this hill of sand to make it go down, to make it not a hill" (Samuel Unit 1 Interview #2). Both of these answers are almost identical suggesting that Samuel did not distinguish between a literal description of his model and the phenomenon that the model was meant to explain. In addition, he was focused on the literal features of his model, instead of the processes or mechanism of erosion that his model explained. This suggests that Samuel may not have understood that models are used to explain a target phenomenon, which has been reported in the literature as a struggle that students may face when learning about the role of models in science (Baek & Schwarz, 2015; Lehrer & Schauble, 2010; Schwarz et al., 2009).

Despite the similarities in the two responses, his model did include features that contribute to an explanation of the process of erosion, such as arrows showing the movement of water; in addition, his explanation explained the process of erosion in terms of the physical changes to the land. This focus on the visible features of the process of erosion is not surprising, given younger students' proclivity to focus on the visible aspects of phenomena in early experiences with modeling (diSessa, 2004; Lehrer & Schauble, 2000; 2010; 2012).

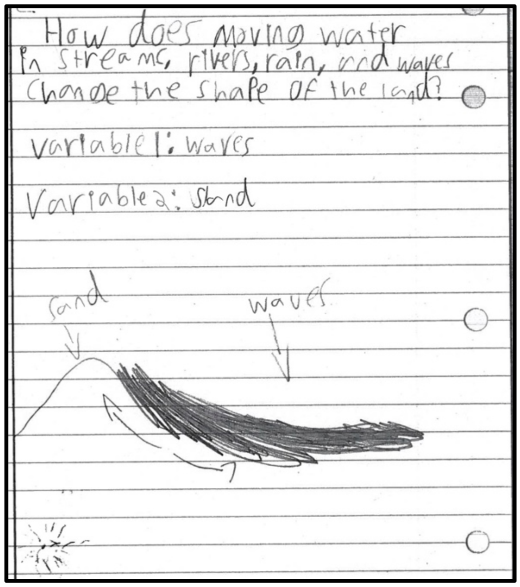


Figure IV.6. Samuel's Unit 1 drawn model showing how wave cause erosion of the sand.

In the Unit 1 post-assessment interview, Samuel demonstrated his developing understanding of the process of erosion and focused on the results of erosion caused by water. His responses suggest that he was still unclear about how erosion worked and did not understand how energy was involved in this process. Table IV.6 shows Samuel's answers on the post-unit content assessment and his elaborated answers during the unit post-assessment interview.

Table IV.6
Samuel's unit 1 post- content assessment written and elaborated responses

Question	Written response	Elaborated response	
1	The water made it like that	S(amuel)	So the water made like a hill so the rock on it get hard and make like a wall like there.
		MM	Okay, like a cliff?
		S	Yes
		MM	So what did the water do?
		S	It e-eroded?
		MM	Okay so what does it mean to erode?
		S	To like go, it means to like to, I forgot.
		MM	Okay do you remember what happened in the stream table when we said the water eroded the sand?
		S	It went all down.
		MM	Okay, so what do you think happened here when the water eroded?
		S	It made it go up like a cliff?
		MM	So it made the land go up?
		S	Yes. Like a cliff.
2	The water made curves.	S	So, the water was it was going fast so it would make, by the mountains it would make curves. It would make curves where the water could go.

	MM	So you said the water went fast. Why does the water have to go fast?
	S	Because I learned umm because it would have to go fast because how would the curves be made from the mountains, and if the curves weren't made, where would the water go?

Samuel attempted to explain his thinking regarding how the cliff was formed in Question 1 and was able to apply the term erosion in his answer; however, he could not explain what erosion is. Interestingly, Samuel revealed that he thought that the land moved upwards as a result of erosion as opposed to moving downwards, like he observed in the stream table. Changes in the land by accumulation, as opposed to degradation, is a documented misconception that some elementary students' hold regarding the process of erosion (Martinez et al., 2012). Samuel's explanation suggests that he was familiar with the term, *erosion*, but had a very context-specific understanding of the results of erosion from his experiences with the stream table and the scenario he constructed in his model. Therefore, he was not able to apply these ideas to the new context of the pictures in the assessment.

Samuel's response to Question 2 revealed additional resources that he developed during the unit regarding the role of the speed of the water in the process of erosion. He accurately identified that fast-moving water would have a larger impact on the erosion of the land and would result in more curves to the path of the river. Samuel also applied the idea of speed to his explanation in the novel task. He explained that the arch in Picture 1 of the novel task was shaped by "…the water got fast and broke in and busted through that hole right there. So, there would be a hole right there." When I asked why the water had to be fast, Samuel responded, "Because if it was slow how would it break that?....It wouldn't be broken, it wouldn't have a hole. It would just be a whole one with no hole." Samuel's response suggested that he was thinking about the role of the speed of the water in causing erosion but had not made the connection between the speed of the water and the role of energy. Samuel's ideas regarding the speed of the water are productive resources that could contribute to an explanation of the process of erosion, once he develops an understanding of the role of energy in the process.

Samuel's responses during the Unit 1 post-assessment interview highlight an interesting response pattern that Samuel used, especially in his discussion about his answers on the Unit 1 modeling pre-assessment. Samuel positioned the phenomena from the photographs (i.e., the arch in the novel task photograph or the canyon in Question 2 of the content assessment) as confirmatory evidence for his explanation. For example, when discussing the arch in the transfer measure photograph, he posed the question, "Because if it was slow how would it break that?" Samuel considered his knowledge as the only explanation for what he observed in the photograph.

Samuel used this same logic when explaining his thinking regarding his responses on the Unit 1 modeling post-assessment. In response to Question 1, he selected *A lot* and explained during the interview, "I said a lot because umm if I said nothing at all then how would I know how a stream table works if I didn't know how the land change, changes the land." Samuel's answer remained consistent from the pre- to post-assessments, but his rationale changed. On the pre-assessment, Samuel cited the fact that the stream tables were used in science as evidence for why he would learn a lot from using them. On the post-assessment, his evidence for why he would learn a lot came from his experiences using the stream table and the fact that he felt that he understood how a stream table worked. Similarly, when responding to Question 5, he answered that you can use the stream table to make predictions and explained, "I said yes because how would you know how water changes the land." Samuel's answers suggest that he considered the model of the stream table to be synonymous with the phenomenon of erosion caused by water, as opposed to a representation of the phenomenon.

Samuel's understanding of erosion was most apparent during the novel task at the end of the unit. He was able to explain that speed was a factor in the formation of the arch in the picture. He also alluded to the idea of speed in his elaboration of Question 2 on the post-assessment, suggesting that Samuel may have developed this understanding during the unit.

Samuel also demonstrated a non-critical stance towards the stream table model during the unit. Both before and after the unit, Samuel's discussions regarding the stream table model during his interviews suggested that he considered the model to be synonymous with the target phenomenon. In addition, when I asked Samuel if there was anything he would change about the stream table to improve it, he did not identify any changes, similar to his response during the Unit 1 pre-assessment interview. Samuel's discussion regarding his thinking about the stream table model suggested that he did not consider the stream table model as something that needed to be improved or revised. Baek and Schwarz (2015) suggest that one epistemological aspect of modeling that students can develop is an understanding of how empirical evidence can be used to justify or refute a model. They suggested a learning progression that includes accepting the accuracy of the model with no evaluation as the lowest level of understanding. Samuel's response on the Unit 1 modeling post-assessment suggests that he accepted the stream table as a model that did not have any limitations.

Sophie. Sophie demonstrated high prior knowledge on the Unit 1 content pre-assessment, as compared to her peers. Her answers made references to different ways in which water could shape the land. Table IV.7 shows her written responses on the Unit 1 pre-assessment and her elaborated responses from her Unit 1 pre-unit interview.

Table IV.7
Sophie's pre-unit content assessment written and elaborated responses

Question	Written response	Elaborated response
1	The land got shaped that way because of the water. The rock wall was actually mad[mud] before It was shaped Into stone.	S(ophie): I think that happen because it looks kind of sharp like sharp edges…and mud it sometimes it kind of looks like that. MM: Okay so the sharp edges along here? Now do you think that happened quickly or do you think that happens slowly? S: Slowly MM: And what do you think it looked like before it looks like this? MM: The land was all flat S: Okay so do you think it looks like up here above or do you think it looked like this down here? [MM points to land where houses are on the cliff and down on the beach] S: I think it looks like this MM: Okay like the stuff above? S: Yeah
2	The land got shaped that way because There used to be water with Islands around It but eventually all of the water dried up.	I thought that the water well it kind of had waves that went up because of the patterns on it."

Sophie's discussion regarding her thinking in Question 1 suggest that she correctly understood that the process of erosion did not occur quickly and that it was the result of degradation to the land, as opposed to accumulation (Martinez et al., 2012).

In response to Question 2, Sophie suggested that there were patterns in the rocks that could have been created by water waves. This led her to say that the land had originally been islands before the water was removed and revealed the rocks in the picture. However, she may not have realized that water was in the bottom of the canyon in Question 2, due to the quality of the image. Sophie's responses to the content assessment questions suggested that she was thinking about the effect that water had on the land, but she only described the process of erosion in response to Question 1. Her explanation of Question 2 suggested that the land remained the same and the water changed. She alluded to the effects of water on the rocks when she identified that the water made patterns on the rocks.

On the modeling assessment, Sophie answered that you can learn a lot from the stream table, "because the sand it was like all flat and then there were some patterns in the sand after we pour the water and then there was a lot of sand in the bucket where the water came out" (Sophie Unit 1 Interview #1). She used her initial experiences with the stream table as her evidence to support her ideas. In response to Question 5, Sophie initially responded that she did not know and wrote, "I'm not sure because some places do not get rained a lot, but it does rain a lot usually when it does rain, but they would not have it erode that much though." During the interview, she changed her answer to yes, but I pressed her to elaborate on the original answer that she wrote on the assessment. Sophie referenced her thinking about a desert and that, "it doesn't usually rain much but when it does rain they get a lot of rain…So the rocks don't really get like that but sometimes it's the sand that erodes the rocks" (Sophie Unit 1 Interview #1). When asked about the use of the stream table to learn about what happens in the desert, Sophie shared her thinking about the model and its limitations.

MM Do you think that this stream table would be a good way to learn about what happens in the desert, or not really?

S(ophie) No, not in the desert.

MM No, why not?

S Because you wouldn't really be able to see it rain there.

MM Okay.

S And when you do it's very rare.

MM Oh, okay.

S Like you have to have a planned-out day to see it rain

[….]

MM So, is there a way we could change the stream table so we could learn about the desert, how water changes the land in the desert?

S Maybe more sand.

Sophie compared the conditions in the stream table with the conditions of the desert. She also identified that the purpose of the stream table was not relevant for the conditions in the desert. When pushed to think about how to change the stream table, she identified the addition of more sand as a variable that could be changed but was not able to explain how she could change the stream table to make the conditions more similar to the desert. This difficulty could have been due to her unfamiliarity with the desert environment. Sophie's discussion indicates that, prior to the start of Unit 1, she was already thinking about the ways in which the stream table model would be able to explain different contexts.

Unit 1 post-assessment interview. Sophie's Unit 1 model provides insight her understanding about the causes of erosion and how water affected the sand in different types of erosion (Figure IV.7). Sophie described, "so the waves are going up on the sand and then carrying the sand back down with it" (Sophie Unit 1 Interview #2). This description is also evident on her model through her use of arrows to show the movement of the water. Sophie also included rain in her model. When I asked her whether the rain was a part of the waves model or a separate model, she was non-committal and suggested that it could be either one model or two separate models. When asked to describe her rain model, she said, "so the rain, the dirt turns into mud and then it like goes up like it splashes and it goes to a different spot from where it was." In both of these descriptions, Sophie identified the water as having a role in the movement of the sand. When asked what her model explained, Sophie replied, "erosion, well how things erode" (Sophie Unit 1 Interview #2). This answer suggests that Sophie did consider her model to be a way to explain the process of erosion. In addition, she used arrows to show movement, suggesting that she was incorporating representations of the process.

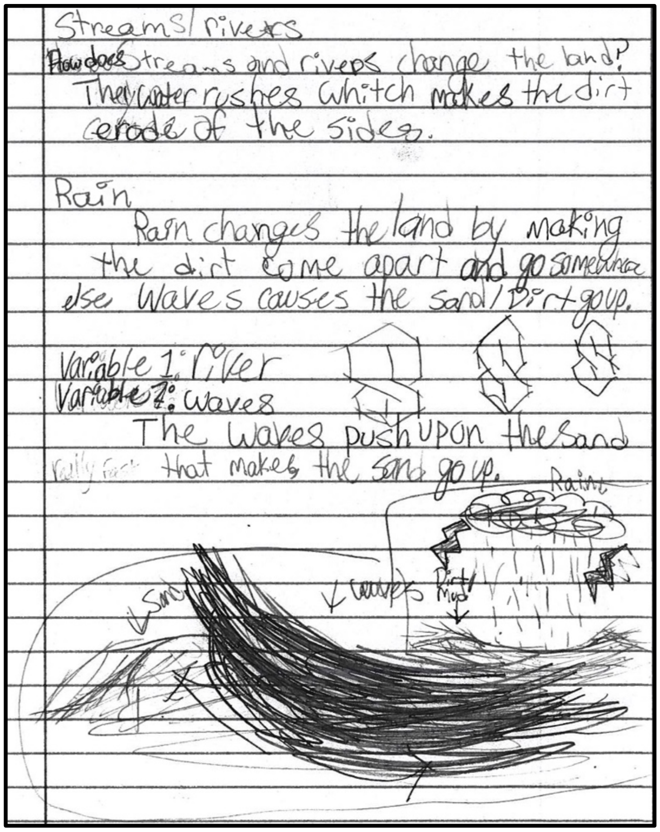


Figure IV.7. Sophie's Unit 1 drawn model explaining how waves and rain cause erosion.

Sophie's written explanation on her model adds additional insight into her thinking about how the process of erosion occurs. She wrote that, "the water rushes whitch makes the dirt erode of the shore." Her use of the word "rushes" suggests that she was thinking about the speed of the water or knew that the water moved quickly when erosion occurred. She also incorporated the idea of speed into her written explanation of her wave model by saying "The waves push upon the sand really fast that makes the sand go up." These two explanations suggest that Sophie was familiar with the speed of water as a factor in erosion. In addition, she describes the degradation process of erosion in her written explanation of her rain model. She described the rain as “making the dirt come apart and go somewhere else…” This description suggests that she thought that the rain changed the dirt and broke it apart.

Sophie continued to discuss the movement of the sand when sharing her thinking about the second photograph in the novel task. She indicated that the “river would get curvier” and explained, “The sand, it hits the sides and then it goes down and it keeps going on” (Sophie Unit 1 Interview #2). She continued to discuss the movement of the sand when she stated that the river would also get deeper “because the sand and water would travel to a different place” (Sophie Unit 1 Interview #2). In both of these ideas, Sophie drew upon her understanding of the effect of erosion on the movement of sand; however, she does not elaborate on what why water moves the sand.

Sophie’s responses on the Unit 1 content post-assessment suggest that she understood some aspects of the process of erosion but could not apply her understanding to certain contexts. Table IV.8 shows her written responses on the Unit 1 content post-assessment and her elaborated responses from her Unit 1 post-unit interview. The exchange between myself and Sophie regarding her thinking about Question 1 suggests that Sophie understood that erosion caused by waves causes the sand to be carried away, but that she was not thinking about the role of energy transfer between the water and sand and, instead, was focusing on the observable phenomenon of the sand moving with the water. In addition, Sophie continued to apply her thinking about erosion caused by waves to Question 2, even though the context in the image did not involve waves. This may have been because Sophie did not have another explanation to explain the picture, other than her understanding about erosion caused by waves. It is also possible that she identified similarities in the contexts of Question 1 and Question 2 and applied the same understanding to both situations (Clark & Linn, 2013).

Table IV.8
Sophie's Unit 1 content post-assessment written and elaborated responses

Question	Written response	Elaborated response
1	Erosion, eroded by the waves hitting the land	S(ophie): Well the waves hit the land and the sand got carried with the waves. MM: What causes the sand to get carried with the waves? S: Mmm, the water hitting the land.
2	Waves that went up and carried sand with it.	The waves, they went up and they carried the sand back into the water.

Sophie's answers on the modeling post-assessment suggest that her experiences in class supported her sense-making of the use of models and that she continued thinking about limitations of the model to generalize to other contexts. In response to Question 1, Sophie selected, "A lot" and explained, "Because a lot of the sand gets carried down and is kind of like actual erosion." When asked to elaborate on her phrase, "actual erosion," Sophie said, "well because it's kind of like an actual like, well, land, area of land but it's not really but it's still helpful." Sophie's responses were reflective of the language that Ms. White used to emphasize students' abilities to see erosion firsthand in the stream table. She also indicated that she was thinking about the land in the stream table as being similar real land, but she was not able to articulate this idea clearly. Sophie used these idea in her explanation, even though she struggled to explain what was meant by the term "actual erosion."

The rest of Sophie's interview regarding her responses on the modeling assessment involved the application of ideas that Sophie shared during the Unit 1 pre-assessment interview. When asked if she would change anything about the stream table in order to make better predictions about how water changes the land, Sophie suggested adding more water to make actual rain. She did not share why she felt this would help her to make better predictions. During the Unit 1 pre-assessment interview, Sophie discussed the use of rain in the stream table when she talked about using the stream table to model a desert. Sophie's answer suggests that she continued to think about the presence of rain in the stream table model. Interestingly, she did not suggest using the rain container model that she engaged with in class as a way to include rain in the stream table model.

Sophie responded, “I don’t know” to Question 5 and explained during her interview that, “because the land isn’t always shaped by water…Well sometimes it’s sand that blows in the desert that makes rocks, they shape it.” Once again, Sophie brought up the idea of using the stream table to study the desert, suggesting that the question, or the stream table model, prompted her to think about the desert. I introduced the idea of erosion in response to Sophie’s answer about the desert and asked her, “do you think that is another example? Do you think we could call what the sand does when it blows around to the rocks, could we call that erosion?” Sophie explained, “well it’s like erosion, it’s erosion just a different way…The sand is hitting the rocks and the rock gets shaped differently.” Sophie’s description revealed that she had developed an understanding of erosion and was able to identify similarities between erosion from water and erosion from sand. Her description also revealed that she was still thinking about the desert as a context in which the stream table would not serve as a good model, but her thinking had developed so that it was more generalized and related to factors that change the land, instead of focusing on the amount of rain in the desert.

When asked if there is anything else she could change about the stream table to make better predictions or explanations, Sophie revealed her sense-making about the role of vegetation in reducing erosion.

S Maybe put like fake trees and fake plants in there.

MM How would that help?

S To see how it would affect the stream table with the plants in it.

MM What do you think would happen?

S There would be less sand or dirt in the bucket where the water comes out of the stream table.

MM Okay, why would that be?

S Because there are plants and well the fake plants would be blocking the water.

This conversation suggests that Sophie considered the stream table to be a way to test ideas and that her prediction reveals that vegetation can be used to block the water and prevent sand and dirt from moving with the water.

Sophie's sense-making regarding the process of erosion centered around the movement of sand in water during erosion and the role of waves and rain in this process. Sophie initially had ideas about the limitation of the stream table model in generalizing to different contexts (i.e., the desert), but her thinking developed over the unit, so that her ideas about the limitation shifted to focus on the model's ability to represent erosion caused by wind, which she considered to be more prevalent in the desert.

Serenity. Serenity was considered to have low prior knowledge based on her answers on the Unit 1 content pre-assessment, as compared to her peers. However, the discussion of her responses to this assessment revealed that she held more prior knowledge about the process of erosion and how water changed the land than was evident in her written responses. Table IV.9 shows her written responses on the Unit 1 pre-assessment and her elaborated responses from her Unit 1 pre-unit interview.

Table IV.9
Serenity's Unit 1 content pre-assessment written and elaborated responses

Question	Written response	Elaborated response
1	The earth used to be all water so when the water evaporated it (had) dirt particles in it so the water took some dirt with it.	I was thinking that this part was water and this part was a little more shallow, so the deeper part of the water took more dirt.
2	There was a lot of rain that made the dirt sink and it made a very big river and when all of the water evaporated	So, I was thinking cause when water evaporates, it doesn't exactly not have a shape of where it was because sometimes the land around it can dry up so the water

	it left the shape of the river.	when it evaporated it just kind of left the shape.

In both of Serenity's answers, she applied her understanding of the water cycle and the process of evaporation to her explanations of the images. In Serenity's explanation of her answer to Question 1, she indicated that the different areas of the picture had different amounts of dirt taken from it when the water evaporated (i.e., the top of the cliff had less dirt removed by the water and below the cliff had more dirt removed by the water). Serenity's explanation suggests that she understood that water could move dirt, but she incorrectly thought that the dirt evaporated with water as opposed to traveling into the ocean. Serenity's response to Question 2 alluded to the process of erosion and that water could be an agent that changed the land and created the shape of the river. Serenity confirmed that she was familiar with erosion during the interview and indicated that she thought erosion occurred in the phenomenon featured in Question 2 when she explained, "Like in this picture because the water was carrying the sand along with it and wherever it went it took it along with it." Serenity was familiar with the concept of erosion and the role of water in carrying sand; however, because the interview took place so long after the start of the unit, it is possible that Serenity developed this understanding of erosion during the unit, as opposed to before the unit began. In Serenity's written and elaborated responses on the Unit 1 pre-assessment, she consistently explained how the evaporation of water affected the land, suggesting that she was drawing on prior knowledge of the water cycle and, perhaps, the context of the images in the content assessment triggered the application of these ideas.

Serenity's responses on the modeling pre-assessment provide insight into her thinking about the use of the stream table model. She was absent from class on the day when the class engaged in the stream table demonstration prior to taking the assessment. Because Serenity was not able to see the stream table used prior to taking the assessment, her written answers and verbal explanations illustrate changes in her understanding between time of the pre-assessment and the interview. In response to Question 1, Serenity answered, *Not much*, and explained during the interview, “Because I know that water changes the land in its own way.” However, when asked if this process is similar or different from what happens in the stream table, Serenity explained, “It’s kind of similar because it’s still changing and making its own path and making its own shape and path and so that’s what happens with the real river.” In her responses, Serenity revealed her thinking about the unpredictability of how water changes the land when she describes the land as changing “in its own way,” but also revealed that she thought the changes in the stream table were ones that can also happen in real rivers. This difference in thinking could be a result of having experiences with the stream table, but also suggests that Serenity could have been developing an understanding regarding the use of the model to represent the target phenomenon.

In response to Question 5, Serenity answered *Yes* and wrote, “Because it helps you think why it’s like that.” She explained, “I mean like, it helps you figure out why it’s like that because you can see it actually happening, because some rivers, it’s not really flowing so you can’t really tell what’s happening.” Her answer and explanation suggest that Serenity considered the stream table model to be a way to show or understand the processes occurring in a river. She also alluded to the concept of studying processes that might be invisible in nature, when she suggested that some rivers do not flow quickly and in the stream table “you can see it actually happening.” In addition, Serenity echoed the theme of the usefulness of models to see phenomena that Ms. White’s introduced to the class.

Serenity's sense-making about the process of erosion and the development of her understanding throughout the unit is evident in her explanation of her model (Figure IV.8).

> I was trying to show how after a long period of time like the stream was kind of curvy and then it was really curvy at the end. By doing that, I was showing how the sand was going down stream with the water by being carried away from the sides. In this part [the After picture], the water was still carrying sand, but I didn't get a chance to finish this part (Serenity Unit 1 Interview #2).

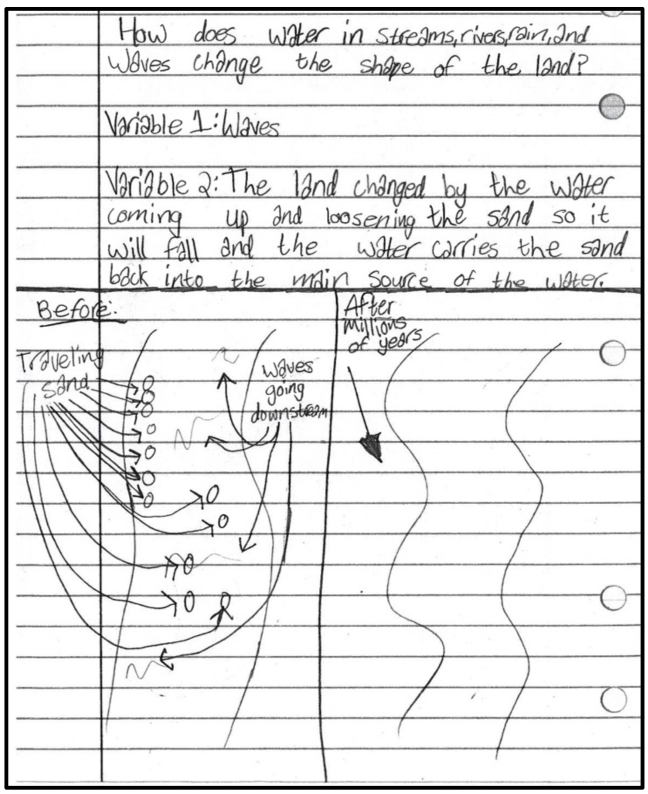


Figure IV.8. Serenity's Unit 1 model explaining the process of erosion from moving water in rivers.

This description of her model reveals several ideas related to the process of erosion that Serenity developed over the unit. Serenity wrote, "After millions of years" on her model and specified that her model showed "a long period of time," suggesting that Serenity was thinking about the long timespan over which erosion occurs and that she understood the timescale of erosion. Serenity also described how the water carried the sand away from the sides. This description was a shift from her statements on the pre-assessment in which she indicated that the water evaporated. Her description suggests that she was thinking about the process of water moving sand from the sides of the river. She also specified in both her model and her explanation that the river would form more curves after millions of years. Serenity also included waves in the "Before" portion of her model but did not discuss what role they played in the movement of the sand or the changing of the shape of the river.

Serenity's model also suggested that she developed an understanding regarding certain features of models and the use of models to explain a process. She included time in her model to show the timescale of the process. She also incorporated observable changes to the river at different levels, including an overall change to the shape of the river and the movement of individual pieces of sand. Serenity also provided ideas about what her model was explaining. "I'm trying to explain how water can change the land and the ways it carries away the sand from the walls of the river or stream" (Serenity Unit 1 Interview #2). These details suggest that Serenity used details in her model, such as how the movement of sand is involved in the changing of the land, to communicate a process. Serenity's model did not include a representation of energy or the role that energy transfer plays in the process of erosion. Her model shows observable changes but stopped short of including invisible entities involved in erosion. She may not have considered the inclusion of energy to be relevant or her understanding if the role of energy was not developed enough for her to apply it to her model.

Serenity did demonstrate that she had developed productive ideas regarding the role of energy when elaborating on her answer to Question 2 on the Unit 1content post-assessment. Table IV.10 reports her written responses on the Unit 1 post-assessment and her elaborated responses from her Unit 1 post-unit interview.

Table IV.10
Serenity's Unit 1 content post-assessment written and elaborated responses

Question	Written response	Elaborated response
1	Their house is by a beach when the wind crashes the water takes dirt back with it.	I said that because it kinda looks like there is a beach along here and when the water hits the sand, it might go back littler further and take this off.
2	After millions of years of eroding the river sunk into the ground a little deeper.	Like when it rains and stuff it makes there be more water and it helps the water in the river have more energy to take off chunks of land.

When elaborating on Question 2, Serenity introduced the idea of energy in the discussion and revealed that she understood that energy was involved in the process of erosion. She also indicated that more water could add more energy but did not specify why this would be the case. Serenity's explanation suggests that she had developed ideas regarding the role of energy in the process of erosion that eventually could be used in an explanation of the process of erosion. Students' abilities to apply ideas to different contexts requires them to identify similarities between contexts and then develop connections between ideas that allow them to apply those ideas to different contexts (Clark & Linn, 2013). Serenity's understanding of the role of energy in erosion may still be closely tied to the context of rain, considering that she did not apply her understanding of energy that she shared when discussing her Unit 1 content post-assessment to her discussion of her Unit 1 model.

In her responses to both questions on the Unit 1 content post-assessment, Serenity demonstrated a change in her thinking from the Unit 1 content pre-assessment regarding how water acts as an agent in erosion. Instead of describing the water as evaporating and changing the land, she described the water as moving and taking sand or land with it. This change in description suggests that Serenity developed an understanding that water is an active agent in the process of erosion.

On the post-unit modeling assessment, Serenity's thinking became more nuanced regarding how the stream table model could be used. In response to Question 1, she answered *A* *lot*, and explained, “I said a lot because I feel like, if you don’t know how water changes the land, you can use a stream table to figure it out…because it’s kind of like a river and you can see it more clearly how it is taking sand particles and taking them down…taking them down with the rest of the water” (Serenity Unit 1 Interview #2). In the Unit 1 pre-assessment interview, Serenity discussed how what happened in the stream table was similar to a real river. Her explanation in the Unit 1 post-assessment interview was more detailed and explained the role that models can play in helping the user figure out a mechanism or process. When asked to share her ideas about what could be changed about the stream table to learn more about how water changes the land, Serenity’s response suggests that she was thinking about the ability of the model to explain other phenomena.

> Building it differently would help me learn more because you could see the different ways it would work. Because when we did the rain unit, it is like the stream table but in a different way because it is with rain instead of a table…maybe I would add rain to it and have it like an actual stream because it always rains on streams and I thought maybe that would help (Serenity Unit 1 Interview #2).

Serenity’s response suggests that she was considering the limitations of the current stream table design and how the integration of additional models with the stream table model could improve the stream table’s ability to model the phenomenon of erosion.

Serenity continued to think about the stream table model as a tool for figuring out the ways that water shapes the land and additional ways to improve the model. In response to Question 5, Serenity explained, “I think so because when you are trying to figure it out, like if you know a little bit and are trying to figure it out even more, you could like try to predict how it would change” (Serenity Unit 1 Interview #2). When I asked how she could change the stream table to help her better predict or explain how water changes the land, she explained, “I would use all the different ways that water could change the land…wind, water, ice, and snow.” Serenity’s explanations suggest that she considered the stream table to be a tool that could be used to study a process and was also aware of the limitations of the stream table in explaining or predicting how water changes the land. She provided examples of other forms of water that might shape the land that could be incorporated into the stream table. These ideas suggest that Serenity understood that models should be able to explain multiple phenomena and that the purpose of models is to explain a process (Lehrer & Schauble, 2010).

Conclusions

A comparison of the sub-cases of the focal students suggests the ways in which the design and enactment of the unit influenced the development of their understandings about the process of erosion from water, as well as epistemological ideas regarding modeling.

All students demonstrated development in their understanding of the process of erosion. For example, Samuel developed familiarity with the term, *erosion*, but still held the misconception that erosion was a process of accumulation as opposed to degradation of material. Kyle, Sophie, and Serenity demonstrated context-specific understandings of the process of erosion. Kyle shared his understanding of the timescale of erosion in the context of the Grand Canyon but was not able to apply this understanding to other examples of erosion. Sophie was able to describe how erosion caused by water and erosion caused by sand were similar and different, suggesting that she was able to apply her understanding of the process of erosion in two contexts. Serenity demonstrated a developing understanding of the role of energy in the process of erosion, in the context of rain. She was the only focal student to discuss energy during the interviews, despite the emphasis placed on energy during whole-class instruction.

An analysis of focal students' interviews suggests that students still struggled to understand the role of energy in the process of erosion. The steel ball investigation was designed to introduce students to the concept of energy in moving objects and the transfer of energy between objects. While one student, HK, made connections between the stream table model and the steel ball investigation, the other students in the class may have missed or not understood this connection. Providing additional prompts and opportunities for students to make connections between the different models may support students to recognize similarities between different models and support students to draw on these connections in developing an explanation of the process of erosion.

Students demonstrated understanding of the use of the stream table to observe a target phenomenon. This idea was continuously reinforced by Ms. White, and focal students adopted a similar way of describing the stream table as a way to see erosion. Focal students also demonstrated a continuum of stances from *the model is synonymous with the phenomenon* (Samuel) to *the model only shows some of the ways that water changes the land* (Serenity, and to a lesser extent, Sophie and Kyle). Samuel used the stream table as his evidence for why he knew how water changed the land. His discussions about the stream table model were phrased as observations about the target phenomenon. In addition, he could not think of ways to change or improve the model and stated that it did not need to be changed. Both Sophie and Kyle suggested ways in which the stream table could be changed and identified limitations of the model to explain erosion. Kyle's suggestions were mostly focused on the physical features of the model (i.e., adding rocks or fake trees), but he did discuss how the slope of the stream table could influence its ability to explain erosion in certain locations, such as mountains. This suggests that he was beginning to think about the process of erosion and how the factor of slope might influence that process. Sophie thought about the ways in which the model was limited in explaining the context of the desert. Her thinking did develop between the Unit 1 pre- and post-interviews regarding this; at the end of the unit, she identified factors that were not in the stream table but were related to the process of erosion (e.g., wind). Finally, Serenity identified multiple different forms of water that were not included in the use of the stream table in the classroom and how incorporation of these forms of water could help the model better explain the process of erosion. In addition, she described how models were a tool for figuring something out, suggesting that she considered the model to be a way to determine a mechanism or process.

Students' ideas regarding the uses and limitations of the stream table model align with the development of children's understandings of the uses of models. Initially, students may not realize that models can be changed, but as students become more familiar with the process of modeling, they may begin to regard models as representations that can be used to study a phenomenon and can be improved based on new data (Baek & Schwarz, 2015). The class did not engage in discussions regarding how they could improve the physical models that they used during the unit. Students did provide feedback to each other about their drawn models; however, greater emphasis could be placed on the evaluation of models and the ways in which they could be improved throughout the unit. This may result in students' abilities to move past physical limitations of models and consider the ways in which they communicate processes. Given the abstract nature of an underlying process or mechanism, this would be best supported in the whole-class setting where the teacher and students can build on each other's ideas.

CHAPTER V

Unit Two: Modeling Energy Transfer from Moving Water and Wind

The second unit of instruction was framed by the driving question, *Where does the energy to light my home come from?* This unit focused on sources of renewable energy and the energy transfers that occur in order to change moving energy of water and wind into electrical energy. The unit was designed to build from students' experiences with the energy of moving water in Unit 1. The unit took place over 25 days of instruction and totaled 19.31 hours.

The curriculum for Unit 2 did not include as many opportunities and scaffolds for using and constructing scientific models as were present in Unit 1. Therefore, I worked with Ms. White and the other researchers present in the classroom to create additional opportunities for students to use models and engage in the practice of scientific modeling throughout the unit.

In order to incorporate additional scientific modeling opportunities into the unit and respond to Ms. White's observations and concerns regarding student learning during the unit, it was necessary to make modifications to the curriculum, both before and during its enactment. Consistent with the design-based research approach, the curriculum and any changes made to the curriculum prior to enactment represented the anticipated trajectory of student learning. As described by Cobb and colleagues (Cobb, Confrey et al., 2003; Cobb, McClain et al., 2003), hypotheses regarding ways in which to support students' sense-making regarding energy transfer and epistemologies related to modeling are embedded within this anticipated trajectory.

In order to study how the enactment unfolded and the ways in which the enactment influenced students' sense-making regarding the concept of energy transfer and epistemologies related to modeling, I used minicycles and macrocycles (Cobb, McClain et al., 2003) to conduct a close study of the enactment and student sense-making during Unit 2. There were two minicycles in this unit, each centered around a different model with which students were engaging. Before each minicycle, I worked with the other researchers and Ms. White to agree on the curriculum that would be used to guide the teacher and students through the lessons in the minicycle and serve as the anticipated learning trajectory. During each minicycle, the research team and Ms. White met to discuss sources of struggle and success in students' sense-making related to the concepts that students were grappling with while engaging with each model, and make adjustments to the activities in which students were engaged or provide additional supports that Ms. White could draw on in her teaching. The modeling events that occurred during Unit 2 are shown Table V.1.

Table V.1
Unit 2 Modeling Events

Day #	Date	Lesson and Activities	Time
2	12.20.16	**Lesson 1.1: What can a turning water wheel do?** ***Activity 4:*** Class plans investigation and discusses variables and fair tests.	36 minutes
7	1.18.17	**Lesson 1.3: What can a turning water wheel do?** ***Activity 1:*** Introduce lesson DQ ***Activity 2:*** Introduce waterwheel video. Revisit claims & evidence. ***Activity 3:*** Waterwheel reading, then update DQ board	45 minutes
8	1.19.17	**Lesson 1.3: What can a turning water wheel do?** ***Activity 3:*** Waterwheel reading – individually. ***Activity 4:*** Revisit written explanations. Students share revisions with class.	45 minutes
12	1.26.17	**Lesson 1.5: How can moving water produce electricity?** ***Activity 3:*** Students use Collabrify to model how water in a dam generates electricity.	60 minutes
13	1.27.17	**Lesson 1.5: How can moving water produce electricity?** ***Activity 3:*** Students use Collabrify to model how water in a dam generates electricity.	60 minutes
18	2.6.17	**Lesson 2.5: Can wind transfer energy to cause a bulb to light?** ***Activity 1:*** Review previous lesson and introduce lesson DQ. ***Activity 2:*** Introduced windmill investigation and students explored materials. ***Activity 3:*** Students discuss windmill design. Teacher supports students to realize that generator needs to be tested before adding windmill.	45 minutes
22	2.10.17	**Lesson 2.5: Can wind transfer energy to cause a bulb to light?** ***Activity 3:*** Students used final designs from testing to create models using flipbook.	45 minutes

23	2.13.17	**2.5 Can wind transfer energy to cause a bulb to light?** ****Alternative lesson plan**** **Students watch videos of how wind turbines work and look at different wind turbine designs**	35 minutes

This chapter will be organized into three sections: (a) the hypothesized starting points of students and anticipated learning trajectory of the unit, (b) the actual learning trajectory of the unit using the analyses of the two minicycles, and (c) a retrospective, macrocycle analysis, focusing on students' sense-making with models across the entire unit. In the analysis of each minicycle, I will indicate when deviations were made from the planned enactment and the reasons motivating the changes. I will also detail: (a) how students engaged with models and the practice of modeling in each minicycle, (b) changes that were made to the enactment of the curriculum in an effort to support students' sense-making, and (c) how the use of models influenced students' sense-making at the class and individual student levels.

Hypothesized Starting Points and Learning Trajectory Specific to Energy Transfer

Two of the *NGSS* performance expectations related to energy for Grade 4 call for students to, "ask questions and predict outcomes about the changes in energy that occur when objects collide (4-PS3-3)" and "apply scientific ideas to design, test, and refine a device that converts energy from one form to another (4-PS3-4)" (NGSS Lead States, 2013). These performance expectations require students to develop an understanding of both the sources and forms of energy, as well as the idea that energy can be transferred from one object to another. These performance expectations guided the design of the curriculum for this unit.

Renewable energy was chosen as a topic that could initiate meaningful inquiry and support students' development of the process of energy transfer. Based on the curriculum in Unit 1, the developers hypothesized that students would be entering Unit 2 with an understanding that kinetic energy is present in moving objects and collisions between moving objects lead to a transfer of energy. Students had also been introduced to the idea that energy was present in moving water and used this understanding to explain how changes in the land occurred. Students built upon these ideas to explore other sources of energy, such as wind, and different examples of energy transfer that are used to generate electricity.

The curriculum was designed around two sources of renewable energy: moving water and wind. Students built physical models of a water wheel and windmill and constructed computer-animated models in *Flipbook* to explain how each of these devices could be used to harness the moving energy of either water or wind to generate electricity. Students also applied their understandings about harnessing energy to produce electricity to make predictions about how the moving energy in waves could be harnessed. Students' sense-making was also supported by the use of a hand-crank generator and a homemade generator to model the components necessary for the conversion of moving energy to electrical energy on a larger scale.

The incorporation of multiple types of models was purposeful to provide students with opportunities to move among different forms of representation and different media for constructing models, as a way to support the development of meta-representational competence (MRC) (diSessa, 2004). One aspect of MRC is recognizing different contexts in which different forms of representation can be used and their functions within those contexts. In addition, the models in this unit were designed to support students to engage with functional analogs and recognize the role of models as an analogy of the target phenomenon (Lehrer & Schauble, 2012).

Actual Learning Trajectory

The sense-making map shown in Figure V.1 illustrates the flow of sense-making ideas that were introduced and discussed by the teacher, students, and researchers during Unit 2. An analysis of this sense-making chart reveals that fewer ideas related to the concept of energy and epistemological aspects of models were introduced and discussed in the whole-class context during Unit 2 as compared to Unit 2; a total of 12 ideas were documented during Unit 2 as compared to the 28 ideas documented during Unit 1. One explanation for the fewer number of ideas documented during Unit 2 may be that students were worked with a fewer number of models during Unit 1 as compared to Unit 1, which limited the number of conversations that students could have related to the use and construction of models.

The ideas documented during this unit were related to epistemological aspects of the construction of models, such as that models can be made of different materials but demonstrate the same function as the target phenomenon and models can be used to explain an abstract phenomenon, the concept of energy, including the effects of energy transfer on spinning wheels, and the process of generating electricity, including the role of a generator is producing electricity.

A comparison of the sense-making charts from Unit 1 (Figure IV.1) and Unit 2 (Figure V.1) provides evidence that students did build off of sense-making ideas related to the purpose of models in Unit 1 during their engagement in Unit 2. For example, Ms. White and her students introduced and repeated ideas related to the role of models to see phenomena and "to study something you cannot see" in Unit 1 (Figure IV.1). These ideas were embedded within the sense-making ideas students shared during Unit 2 related to the use of models to study an abstract phenomenon and the use of models to explain how renewable sources of energy can be harnessed to produce electricity. There were additional ideas introduced during this unit related to the construction of models, such as the use of conventions to improve the explanatory power of the model and that feedback can be used to improve models. The sense-making ideas related to energy were contextualized to the phenomenon of renewable energy as opposed to more generalized ideas regarding energy transfer or different sources of energy, which may have influenced students' abilities to draw connections between the sense-making ideas in Unit 1 and their sense-making in Unit 2.

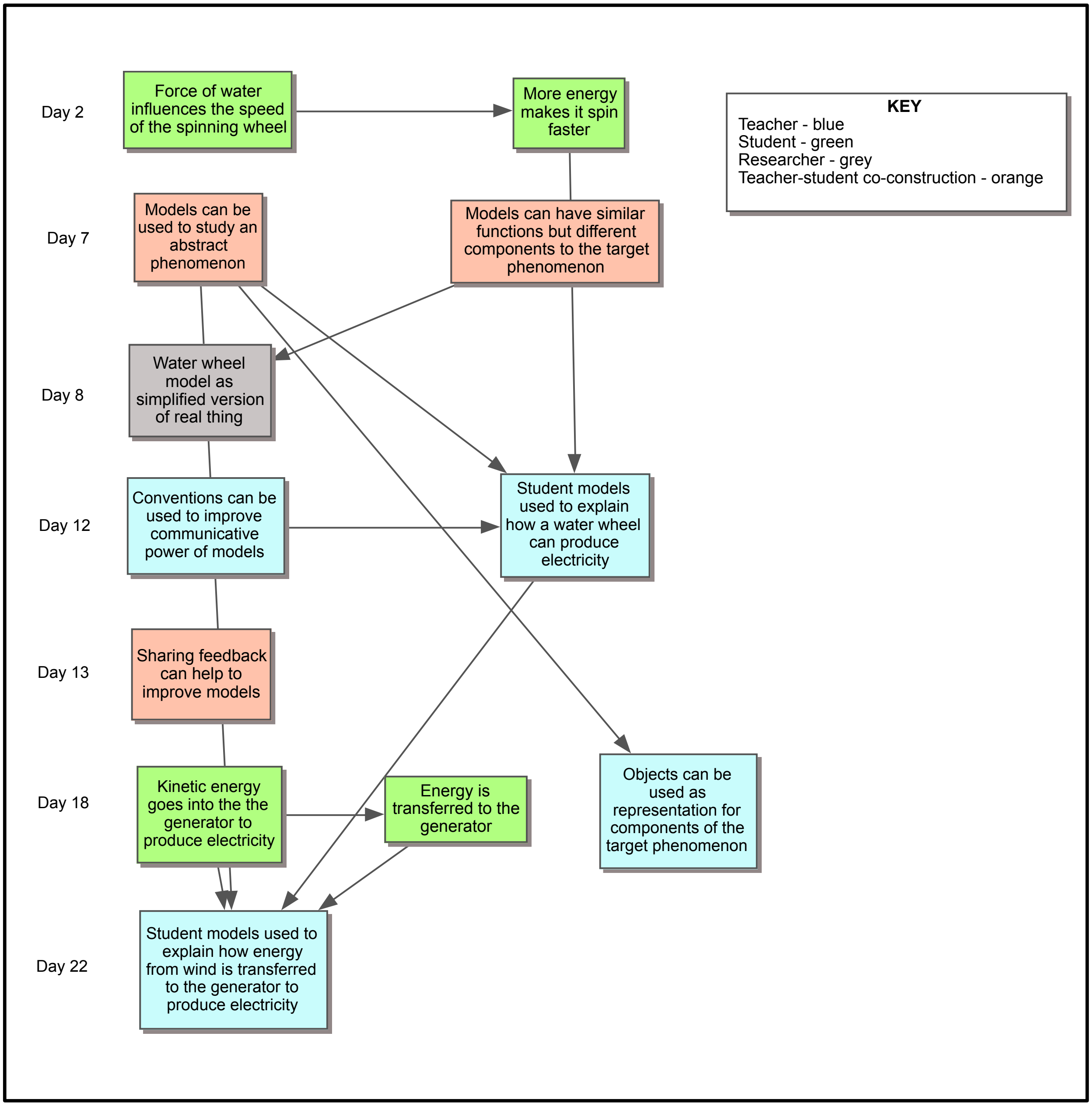


Figure V.1. Unit 2 sense-making map illustrating the flow of ideas introduced and reiterated during whole-class discussions.

Minicycle 1: The Water Wheel Model

In the first minicycle, students investigated how the energy of moving water could be harnessed to generate electricity by constructing and using a model of a water wheel. This minicycle occurred over the first 15 instructional days of unit enactment. On Day 1, students built physical water wheel models following a prescribed set of directions. The teacher did not discuss with students how they would be using the model prior to constructing them. On Day 2, the class worked to collaboratively plan the investigation that students would conduct with their water wheels. The purpose of this investigation was to explore if water could be used to lift objects off the ground and introduce the idea of energy transfer in a system. Students' evidence for energy transfer would be drawn from the height the objects were lifted off the ground (i.e., energy from the water is transferred to the spinning water wheel, which lifts the object). While discussing the plan for the investigation and their predictions, students drew on their experiences with models in Unit 1 to inform their thinking about how to conduct this investigation.

> The teacher asked students to think about how to change the force of the water. [The researcher (MM)] added that students could think about the demos from unit 1. How did we change the force of water before? IP said that we used cups. Teacher asked her what was special about those cups. IP said that had holes in them. [MM] asked if there was a difference between the holes in the cups. IP, then, brought up the rain demo and said we had light rain and heavy rain. She said the size of the holes in the cups was different. The heavy rain had larger holes (Field notes 12.20.16).

In this excerpt of the field notes from Day 2, IP drew on her previous experiences with the rain model to introduce the idea that the class could use cups with different sized holes to change the force of the water. This idea was taken up by both Serenity and Kyle, who added ideas in response to Ms. White's elicitation for predictions regarding how the movement of the water wheel would change if the force of the water changed. Serenity proposed that "having larger holes, the water wheel would spin faster" (Field notes 12.20.16). Ms. White asked how many other students agreed with this statement and several students raised their hands. When Ms. White asked for reasons to explain why this would happen, Kyle said, "with the larger hole, the water has more energy going down to hit it and it will spin faster" (Field notes 12.20.16). Kyle drew on concepts from Unit 1 to explain Serenity's prediction. Kyle's prediction introduced the idea of energy transfer into the class's Unit 2 conversation, but this idea was not taken up by either the teacher or the other students.

After students completed their investigations with their water wheels, they were introduced to the different ways that people use water wheels (Day 7). I stepped in and led the class and, after watching video of working water wheels and looking at pictures, I asked students to draw comparisons between the water wheel models they constructed and the water wheels in video they watched. During this conversation, I added additional discussion prompts to support students to make connections between their use of the water wheel as a model for studying energy transfer and their use of models in Unit 1.

MM	How is this similar to the water wheels we made? How is it kind of the same?
Caleb	The pipe is like making water, it's kinda the same because the cup is putting water on our wheel too.
IP	It's kind of like the water wheel, but the water is going onto the ground.
Serenity	It is the same shape, but they both have the panels that carry the water.
MM	What were the panels on your water wheel? What were they made out of?
Caleb	Plastic.

MM Did they do the same thing with the water wheel?

Class Yeah.

MM We talked about this during Unit 1, you use these to study things, it starts with an M…

Ashley Model.

MM So your water wheel is a model and what are we using these to study?

Serenity Water wheels

MM But we are learning about something bigger than water wheels.

Madison Energy!

This conversation introduced two ideas into the class discussion about modeling: (1) the water wheel model had similar functions to the real water wheel; and (2) the class was using the water wheel model to study energy. Caleb's comparison of the real water wheel and the model included a comparison of function (e.g., "The pipe is like making water, it's kinda the same because the cup is putting water on our wheel too"), but both IP and Serenity's observations focused on the physical appearance of the water wheel. Serenity's observation about the similarity in the presence of panels in both the real and model water wheels prompted my question about a comparison of the function of the panels and re-introducing the idea that the water wheel was a model.

The brief discussion regarding the water wheel as a model also introduced a new idea into the class's on-going conversation about modeling, that models could be made out of different materials from the target phenomenon but serve similar functions. This is a foundational idea to the role of models as analogs (Lehrer & Schauble, 2012). In addition, this conversation reinforced the idea that models could be used to study complex, abstract ideas, such as energy transfer, as opposed to studying the phenomenon itself, which can be a confusing concept for young children (Ero-Tolliver et al., 2013).

The next lesson, on Day 8, introduced students to the role of a generator in the production of electricity through students' exploration of a hand-crank generator and how the speed of the turning crank affected the brightness of the light bulb in the system. The instruction during this lesson followed the proposed curriculum. Then, on Day 9, students used their understanding of a generator and their water wheel investigation to explain how energy from water could be transferred in a system that generated electricity. Students observed a video showing the inner workings of hydropower plant. I was leading science and introduced the important distinction between "making energy" and "transferring energy."

MM How was what we were doing with the crank similar to this?

BC We were turning the crank. It was also making a light.

MM Do we make energy? We use another word. It starts with a "t".

Ashley Transferring energy.

MM We do not make energy. Where does the energy start?

DD The water.

Madison The water wheel.

MM The water wheel spins.

CH The wheel cranks the thing...

The distinction between "making" and "transferring" energy was not included in the curriculum, but was added in response to students' use of the phrase, "making energy." This exchange revealed that students still struggled to think about transfers of energy, especially with respect to the origin of the energy in the system, and when they considered the similarities and differences between their water wheel models and the hydropower plant system. These struggles are consistent with those documented in the literature regarding elementary students' lack of understanding related to conservation of energy and scientific use of the term *energy* (Hammer et al., 2012; Liu & Tang, 2004; Neumann et al., 2013).

During this lesson, I sought to reinforce the ideas that models were simplified versions of phenomena and there were similarities and that models include and exclude different aspects of the target phenomenon by adding additional discussion questions to prompt students to compare their models with the hydropower plant system.

MM We've been focusing on water wheels. These are like super fancy water wheels. What was kind of like your water wheel?

CH When the water was being poured into it, it was spinning a gear.

MM We still have that spinning to generate electricity.

Kyle They both use water to make energy.

MM They both use water to produce energy. So, I want you to think about your water wheel as a simple version of the way we use water to produce energy. We're going to watch a second video, this one is more about how the generator works.

[Class begins watching video]

MM So, when you did your investigation, this pipe, the penstock, is similar to what?

Caleb The cup.

MM The cup. It is spinning a turbine that is similar to a...

Class Water wheel.

MM What else was spinning?

Student What was going through the wheel?

KH Energy?

DK Water?

Ashley The dowel?

MM The dowel is like this big thing here that is spinning, the shaft that goes to the gear here that... If we made some changes, we could have generated some electricity.

I proposed these questions to the class to reinforce that there were similarities between the model and target systems. In addition, the questions were meant to prompt students to think about the construction of their water wheel and how they could use what they knew about that to inform their sense-making of how hydropower works. This conversation also reinforced the idea that models could be used to learn about a target phenomenon, even though the model and the phenomenon may appear different from each other.

On Day 12 of instruction, students began constructing a model to explain how energy from water can be used to generate electricity. There were several design changes made to this lesson based on students' modeling experiences in Unit 1. The lesson called for students to construct a model to explain how a hydropower plant could harness the power of moving water to generate electricity. The researchers decided to change the focus of the model to how a water wheel could harness the power of moving water to generate electricity, because students had engaged in more sense-making experiences with water wheels and this modeling opportunity would provide additional information to the teacher and the researchers regarding students' sense-making. When Ms. White introduced the phenomenon that students would be modeling, she reiterated the importance of including a question and told the students, "you are going to show us how a water wheel produces electricity. You are going to be drawing that out…don't forget to label. You're going to need to label, you could add arrows." These directions reinforced different conventions that students could draw upon in their models, including labels and arrows. In addition, Ms. White reinforced the purpose of models to explain a process or mechanism.

Recall that students had access to a computer applications, *Collabrify Flipbook,* in which they could create animated models. For this model, students used *Collabrify Flipbook* for the first time. Students were instructed to use this application instead of paper to construct their model in order to allow them to use the animation feature and to decrease the number of lost or misplaced models.

Ms. White and my observations of students' struggles and decisions informed additional supports for the modeling process. While students were completing their initial models, many figured out how to import pictures from the internet to serve as background images for their models. Some images were tangentially related to the student's model (i.e., a picture of a river), but many images were not related at all (e.g., pop culture references). Students' interest in adding pictures that were related to the target phenomenon, such as pictures of a river or a house, reinforced that they were considering ways to make their models similar to the target phenomenon. Lehrer and colleagues (2008) refer to models as functional analogs that communicate the underlying mechanism or process in a phenomenon as opposed to literal representation. Students' discovery and enthusiasm for importing images into their models provided opportunities to discuss the role of models as analogs to the target phenomenon and the importance of choosing components that were central to the explanation of the process.

During a weekly meeting with Ms. White, she and I discussed how to address this issue and decided that she would review the six characteristics of models with the class that were introduced in Unit 1 (Table IV.2). After reviewing these characteristics, Ms. White would project a few student models on the board and the class would discuss the necessity of the components in each model (Teacher meeting 1.30.17). During this class discussion, students indicated that background images were not necessary and made models appear cluttered (Field notes 01.31.17). While this class discussion resulted in some students removing images from their models, others continued to import unrelated images.

The teacher and researchers decided to include the feedback activity that was originally piloted at the end of Unit 1. These feedback activities were designed to provide opportunities for students to provide constructive comments to their peers and engage in the process of critiquing models. When Ms. White introduced the feedback activity, she connected it to the established peer review procedure that the class used in writing. She told the class, “We’ve been talking about revisions in writing. We’ve been revising all year. Why would we have a partner look at our models?” Serenity answered, “To make it better.” Ms. White agreed and replied, “To improve! And we know that is even part of our STEM, that improvement piece” (01.26.17 Video). Ms. White identified other opportunities in which students provided feedback and made improvements, which may have allowed students to draw on their own experiences when engaging in the feedback activity. This activity provided students with a structured way to provide feedback to each other and reinforced the idea that providing feedback and making revisions is an important aspect of scientific sense-making (Ford, 2012), and the practice of scientific modeling (Louca & Zacharia, 2015).

After students provided feedback and revised their models, I added an additional component to this modeling experience by providing students the opportunity to write explanations of their models. The explanation sheet included the prompt, *Pretend you are* *showing your model to a group of third graders who have not studied how water wheels work. Explain what your model shows so that a third grader can understand it.* This prompt was included to give students an authentic audience and purpose for explaining their models. In addition, 3rd graders were chosen to be the audience for this activity because it was an audience that the 4th grade students would not expect to know about water wheels, but was close enough in age to the 4th graders that the audience would be meaningful to them.

During the enactment of Minicycle #1, several ideas related to the concept of energy transfer were introduced and reinforced. There was also evidence that students struggled with some of these ideas. At the beginning of the unit, Serenity and Kyle introduced the ideas of the amount of energy and force of water as factors that influenced the speed of the spinning water wheel. As the class continued to discuss the role of energy in the water wheel, students often referred to the water wheel as "making energy," suggesting that students either did not understand or did not differentiate between the language of "making" and "transferring" energy. Students may have been drawing on their everyday experiences with the term "energy," where it is used in many different contexts (Hammer et al., 2012).

There were also several ideas regarding the epistemological aspects of models and modeling introduced and reinforced during Minicycle #1. Building on Ms. White's emphasis in Unit 1 that models can be used to show how something works, the class co-constructed the ideas that models can be used to study abstract phenomena, such as energy, and they can have similar functions, but different construction, as compared to the target phenomenon. Students were able to identify aspects of their water wheel models that were similar and different to the real-life water wheels. Many of these comparisons focused on the physical features, but some comparisons referenced the purpose or function of the water wheels. In addition, Ms. White introduced students to the idea of using different conventions to communicate ideas in their models.

Focal Student Sense-Making During Minicycle #1

To explore the extent to which these changes to the curriculum and the ways in which the ideas were introduced and reinforced in class discussions influenced students' sense-making regarding concept of energy transfer and epistemological ideas related to modeling, I will provide an analysis of data from individual students' interviews about their water wheel model and their experiences using the water wheel. In order to provide an orientation of each focal student's starting point in the curriculum, I will share an analysis of students' pre-Unit 2 interviews followed by their water wheel interviews.

Samuel. Samuel was considered to have high prior knowledge about the use of renewable energy sources to generate electricity as compared to his peers based on his responses on the Unit 2 pre-assessment. When explaining his model, Samuel shared "When the solar pan--power--the solar panel gets power from the--from the sun, which makes power, which is renewable." However, Samuel did not have an accurate understanding of what makes an energy source a renewable source of energy. He described renewable energy as, "So, the solar panel--it, like, it's renewable. You can--so, you can get it again. You can buy another one." Samuel's Unit 2 pre-assessment and interview revealed that he was familiar with one kind of renewable energy and the associated materials that were used to harness it, but did not understand the concept of renewable energy (Figure V.2).

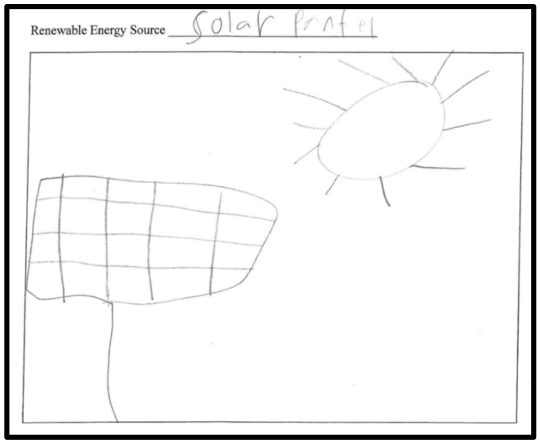


Figure V.2. Samuel's Unit 2 pre-assessment model explaining how a source of renewable energy can be used to power a home.

In Samuel's interview regarding his water wheel model (Figure V.3), he revealed his sense-making regarding the mechanism of the water wheel to harness energy, but also the limitations in his understanding about the role of energy and the process of electricity generation. His answers revealed that he had not made connections between the water wheel and the hand crank generator to explain the how the water wheel could be used to generate electricity.

When Samuel explained his water wheel model, he described how electricity moved from the water wheel to the light bulb.

S(amuel) This is the water wheel.

MM Okay.

S And this is the wire where the electricity goes through wire into the light.

MM Okay. What else is on your model?

S A hand pouring water on the water wheel. Electricity is going through--electricity is going through the--going through the wire and going to the light.

MM Okay. And then, the electricity is coming from where?

S The water wheel.

MM Okay. And what's on the third slide?

S The light turning on.

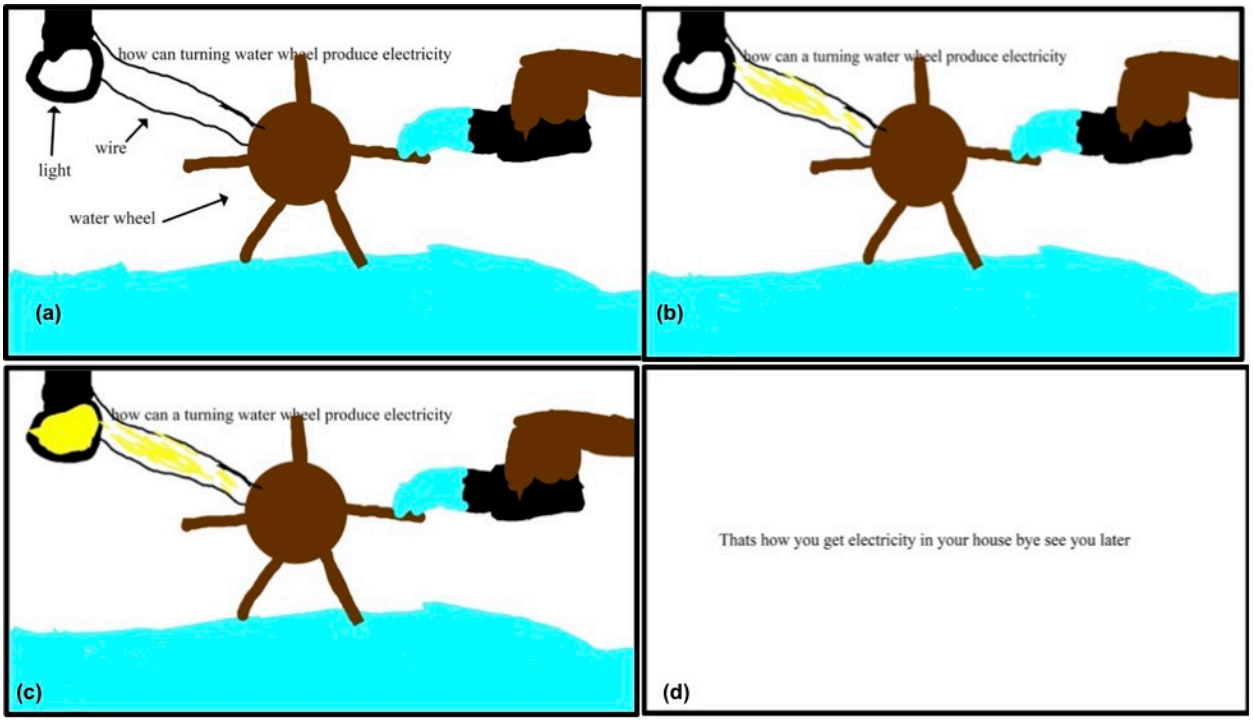


Figure V.3. Samuel's *Flipbook* model explaining how a turning water wheel can produce electricity.

Samuel's explanation of his model demonstrated his sense-making of how a water wheel produced electricity and revealed a misconception regarding the generation of electricity. Samuel showed the water going onto the water wheel, but that a wire was directly connected to the water wheel and electricity was traveling directly from the water wheel to the lightbulb. His written explanation of his final model was consistent with his verbal explanations. He wrote, "The water wheel is making electricity and a wire is on the water wheel. electricity is going through a wire to the lightbulb and lighting up the lightbulb." Neither Samuel's model nor his written or verbal explanations drew on the concepts of energy transfer or the role of a generator in producing electricity. This could suggest that Samuel may not have understood that energy was present in the moving water. Previous research suggests that students must understand that energy can be present in different forms and come from different sources (Neumann et al., 2013). Samuel's understanding that energy was present in the water may have not yet developed, despite the ideas that were discussed in class.

When asked how he changed his model after receiving feedback from his partner, Samuel reported that he was told "just only add labels." The labels that Samuel added to his model only included the physical components of his model (i.e., wires, water wheel, and light) and none of the processes or invisible components (i.e., energy or movement of the wheel). The emphasis on labels was also consistent with Ms. White's reminders about labeling during the modeling process in class. The labels that Samuel added suggest that his sense-making was limited to the observable elements of the phenomenon of electricity generation.

Finally, when asked how he showed energy in his model, Samuel revealed his thinking about the use of conventions in models and the limitations of his sense-making regarding the role of energy in electricity.

MM Can you tell me where the energy is in your model?

S The energy is in the wire.

MM Okay. So, what did you use to show energy?

S Yellow.

MM Okay. So, did you--why did you use yellow?

S Because yellow--because energy--because yellow kind of looks like energy.

Samuel's decision to use the color yellow to denote energy suggests that he was conflating energy and electricity. In addition, his decision to use yellow was based on his familiarity with how electricity is usually shown in pictures and suggests that he was thinking about the conventions of different components within his model, but was not considering how the use of these conventions would influence the ability of others to understand his model.

Samuel's water wheel model and interview suggest that he was still developing an understanding that energy is present in different forms and comes from different sources. Samuel only referenced energy in the form of electricity, as opposed to energy that was present in the moving water.

Nick. Nick was considered to have low prior knowledge relative to his peers regarding sources of renewable energy to generate electricity. On the Unit 2 pre-assessment, Nick drew a lighter and wrote, "I put like a lighter. A lighter because you could turn it on and off again and again." When asked to explain his model, Nick said, "Well it basically explains it causes friction, it causes fire to come out right here and you can use the fire." This response suggests that Nick was not familiar with sources of renewable energy, but that he may have had an emergent understanding that renewable energy could be reused, because a lighter can produce fire again and again (Figure V.4). In addition, Nick's explanation revealed that he understood the role of friction in creating fire and was applying this idea to the context of the question.

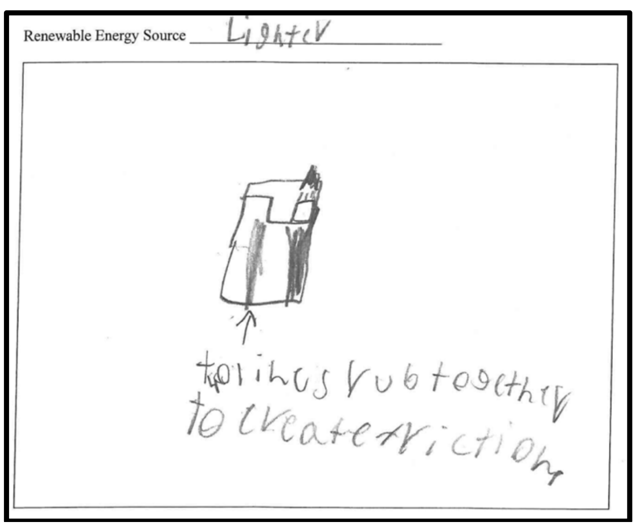


Figure V.4. Nick's Unit 2 pre-assessment model explaining how a source of renewable energy can be used to power a home.

Nick's explanation of his water wheel model revealed that his experiences in class with the physical water wheel model and hand crank generator influenced his sense-making about how energy from moving water could be harnessed to produce electricity (Figure V.5).

N(ick) Alright this one, I put the water pouring down and slowly the electricity through the wire and going to the generator.

MM Okay so the electricity is going through, what?

N The wire

MM The wire, oh ok, and to the generator.

N Yah

MM Anything else you want to explain about your model?

N No that's basically it.

Similar to Samuel, Nick described the electricity as emerging from the water wheel and traveling through the wire to the generator. However, unlike Samuel, Nick demonstrated an emergent understanding of the role of the generator in electricity generation. When asked about how he showed energy in his model, Nick described, "Well, as the water wheel is getting water poured on it, it [electricity] is slowly going through the water as the slides go on" (Nick Unit 2 Interview #2). This description reveals the misconception that both Samuel and Nick shared about the generation of electricity. They both described the electricity as being created in the water wheel.

In addition, Nick further revealed his thinking about the generator later in the interview by referring to it as "the mini water wheel" that he saw in a video in class. The interviewer told Nick that the generator in his model was in the wrong part of the process and that its role was to turn energy into electricity, as opposed to receiving the electricity. Nick explained that he could change his model and “put the generator right there so that it explains where the generator is supposed to be and I could put a light down there” (Nick Unit 2 Interview #2). Nick’s reasoning for the changes to his model suggests that he understood that the model could be used to explain how the water wheel system works, though it is not clear from his explanation if he understood the path of energy from the water to the generator.

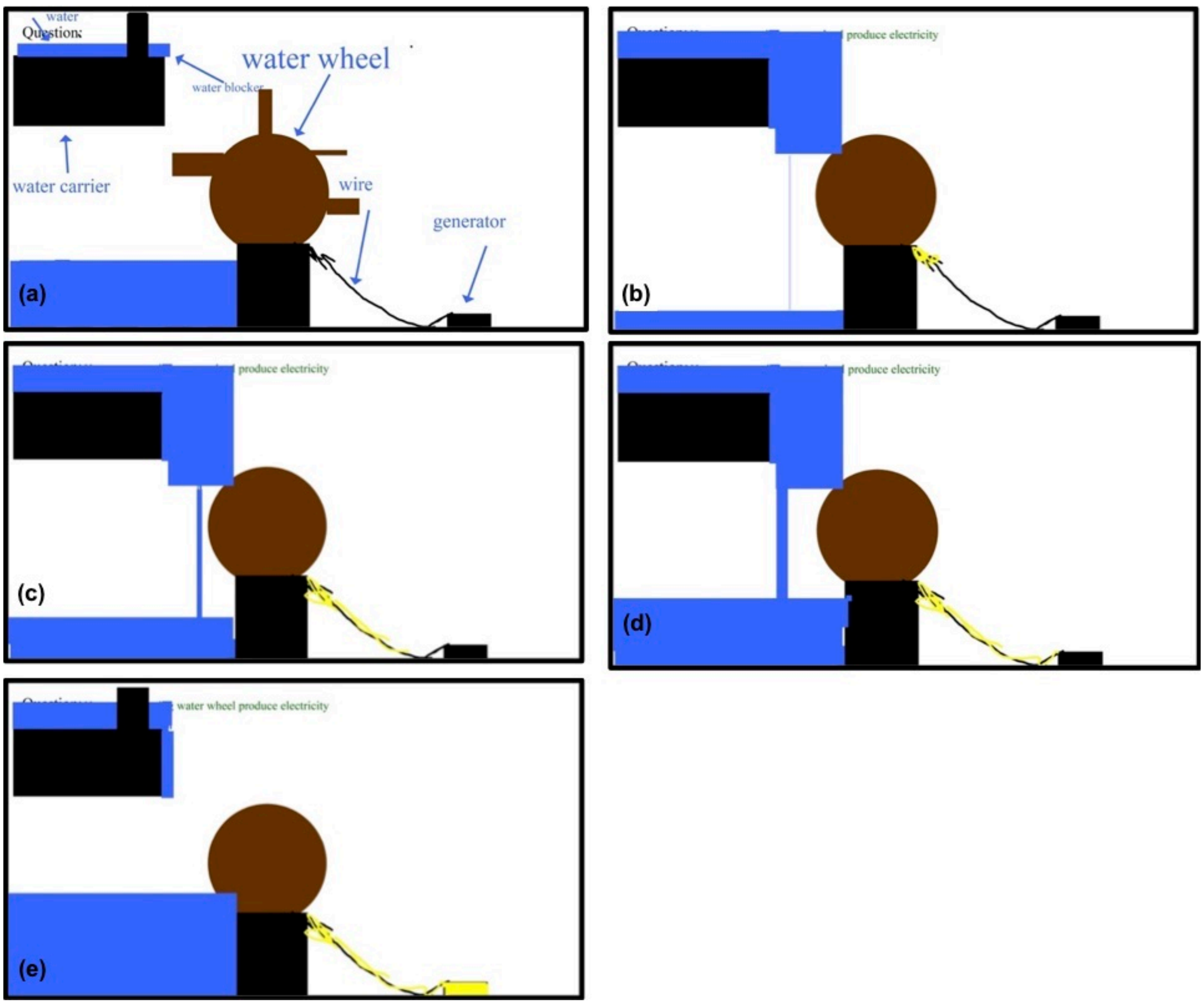


Figure V.5. Nick’s *Flipbook* model explaining how a turning water wheel can generate electricity.

Similar to Samuel, Nick’s revisions to his model were also focused on observable components. He shared that he added “sticks” to the water wheel on slide 1 (Figure V.5a) and he changed the appearance of the water drains “because they looked really bad” (Nick Unit 2 Interview #2). These changes suggest that the appearance of the water wheel system and its similarities with the phenomenon of the water wheel were important to Nick. The emphasis on physical appearance in their drawn models is common for younger children who are newer to the practice of scientific model; considering the invisible processes and components can be very abstract and challenging (Lehrer & Schauble, 2000).

Nick's reasoning for his decisions regarding how to represent energy suggests that he was considering the use of conventions for other people to understand the components of the model and he incorporated an invisible entity. He explained that he used yellow, "cause yellow is the general color of electricity, that's how people see it" (Nick Unit 2 Interview #2). This reasoning suggests that Nick was considering ways to strengthen the explanatory power of his model by using a color that others associate with electricity. Baek and Schwarz (2015) identified the incorporation of invisible entities as one aspect of the use of models to provide explanations of phenomena. They consider this function of models to be an example of students' epistemologies in modeling and provided a learning progression in which the incorporation of invisible entities in the model scored a 2.5 out 3. Using Baek and Schwarz's (2015) rationale, Nick's inclusion of electricity indicates that he understood that this component was important for the explanation of the phenomenon. Nick's rationale for including electricity also supports this interpretation. In addition, Nick demonstrated that he was thinking about the process of generating electricity through the use of the animation feature of *Flipbook*. These are important epistemological aspects of using models to provide an explanation of a target phenomenon (Baek & Schwarz, 2015).

Nick demonstrated an emergent understanding of the process for harnessing energy from water to generate electricity. His sense-making was supported by the use of the physical water wheel model and hand-crank generator; however, it was limited by his misunderstanding about the role of the generator in the process and omission of the ideas of energy transfer in his drawn model.

Caleb. Caleb was considered to have typical prior knowledge relative to his peers regarding sources of renewable energy and the mechanisms by which they generate electricity. Caleb's explanation for his model of fire (his example of renewable energy) was, "it explains kind of how the energy comes from the fire. It's showing this is bigger and then you see it getting smaller because it is hotter when you are closer to it but then once you get further it gets less hot." While his choice of renewable energy is incorrect, he did include a depiction of energy in his model and also explained how the temperature of the fire would impact the amount of energy. Caleb's model and explanation suggest that he had prior knowledge related to the concept of energy and had resources upon which he might be able to draw productively during the unit (Figure V.6).

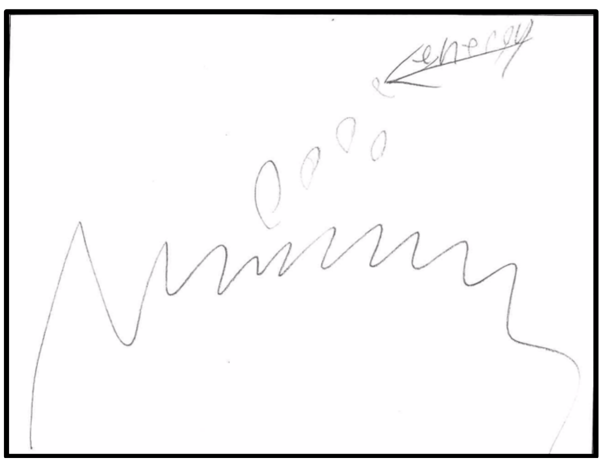


Figure V.6. Caleb's Unit 2 pre-assessment model explaining how a source of renewable energy can be used to power a home.

Caleb's explanation of his water wheel model suggests that the class's experiences with the physical water wheel model and hand-crank generator supported his sense-making and helped him to understand the process of generating electricity.

C(aleb) So it is showing the water wheel and its producing electricity to light up the lightbulb. The electricity is getting further and getting to the light bulb, the electricity got to the light bulb and lights it up, the rest just shows what everything is.

MM I noticed that you have a generator.

C The generator, um, when this moves the generator is getting power from it and its turning and making the electricity to light up the light bulb.

Caleb's explanation of his model suggests that he understood that the turning of the water wheel caused the generator to turn. This idea could serve as a foundation for understanding energy transfer. Furthermore, he specified that the turning of the generator is what produces the electricity. Caleb used the term "producing electricity" when describing his model, as opposed to conflating electricity and energy or referring to the process as "making energy" like other students did. Caleb also identified that his model explained "how the water wheel is turning and making the electricity go to the lightbulb" (Caleb Unit 2 Interview #2). Caleb's specificity in the language he used to describe and explain his model provides insight into his sense-making regarding the phenomenon of harnessing energy from moving water to generate electricity.

When I asked Caleb how he revised his model, he shared that, "I had pictures and my partner [Esther] said that the pictures were distracting so I took them away…She said that my generator was confusing, but I didn't think it was so I kept it" (Caleb Unit 2 Interview #2). Later in the interview, Caleb elaborated further on the feedback his partner gave regarding the generator and shared, "because the generator, she said the generator was confusing and I didn't know why at first but then I found out. The lightbulb is the same color as the generator" (Caleb Unit 2 Interview #2). Caleb's assessment of the feedback he received from his partner suggests that he considered feedback about his model to be optional. He indicated that he considered the feedback, but did not agree with all of it and did not choose to accept every piece of feedback. Receiving and evaluating feedback is an important step in scientific sense-making and in the modeling process (Ford, 2012; Louca & Zacharia, 2015). Caleb's discussion suggests that he thought critically about the feedback and whether or not he wanted to incorporate the feedback in his model.

Caleb also demonstrated that he was thinking about the ways in which he was communicating ideas through the design of his model. When asked why he used yellow to show electricity, he explained, "because usually yellow is not the color of electricity but most people know electricity as yellow" (Caleb Unit 2 Interview #2). Caleb's response suggests that he understood that electricity does not have a color but the color that people associate with electricity is yellow, and this could be used to communicate the path of electricity in his model. Caleb's response demonstrated that he was differentiating between the appearance of components in his model and the appearance of components in the target phenomenon, and was incorporating the invisible component of electricity in his model in order to strengthen its explanatory power. Similar to Nick, Caleb demonstrated the same epistemology in modeling related to explanation. Caleb also specified that he used the color yellow because it was usually associated with electricity, but Caleb went further to distinguish the representation of electricity in the model and the actual appearance of electricity. This distinction suggests that Caleb's sense-making was developing with respect to the use of conventions to communicate in models and how these can differ from the target phenomenon (Figure V.7).

Caleb's model and associated interview suggest that he was developing an emergent understanding of the process of generating electricity from moving water. He was able to discuss how the movement of one component in the system influenced the movement of other components and was able to explain how the generator was involved in electricity production. These ideas could serve as resources for an eventual construction of a complete understanding of energy transfer.

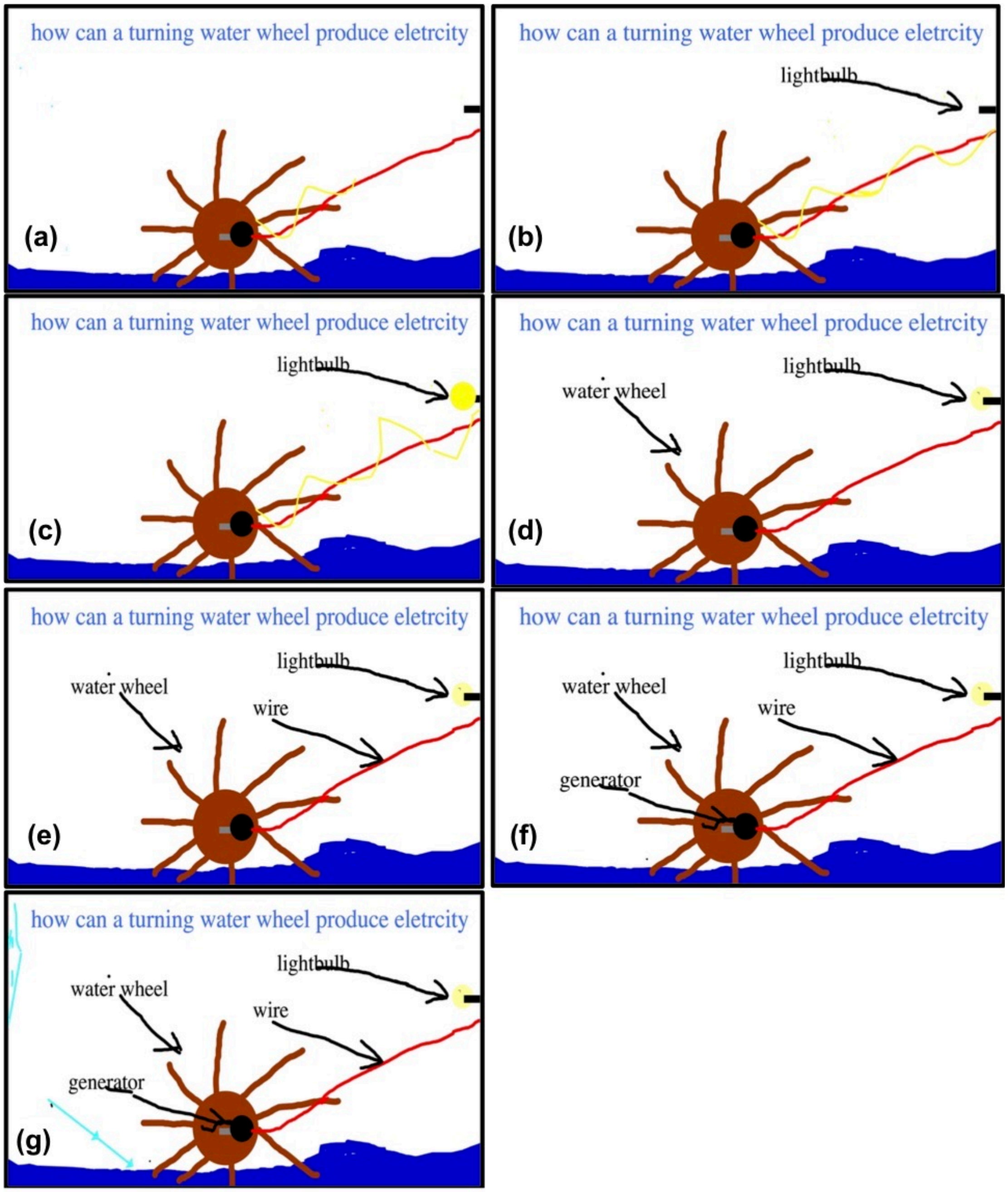


Figure V.7. Caleb's *Flipbook* model explaining how a turning water wheel can be used to generate electricity.

Alyssa. Alyssa was considered to have typical prior knowledge relative to her peers regarding the use of renewable resources to generate electricity. On the Unit 2 pre-assessment, Alyssa indicated that she was aware of water as a renewable energy source but did not know how it could be used to generate electricity (Figure V.8).

A(lyssa): I drew a cup with water in it and for the energy to go to the battery to make the light lit up.

MM Okay is there anything special that the water does to go to the battery?

A It has a little tube.

MM It has a tube? Is the water going through the tube?

A Yeah, to the battery.

Alyssa also indicated that water had to move through a tube to power the battery, suggesting that she may have known that the movement of water was involved in the process. Alyssa mentioned the presence of energy and its role in "mak[ing] the light lit up" (Alyssa Unit 2 Interview #1), which may have indicated that she was aware of the necessity of energy in the process of lighting the bulb or she may have been to referring to electricity necessary for lighting the bulb.

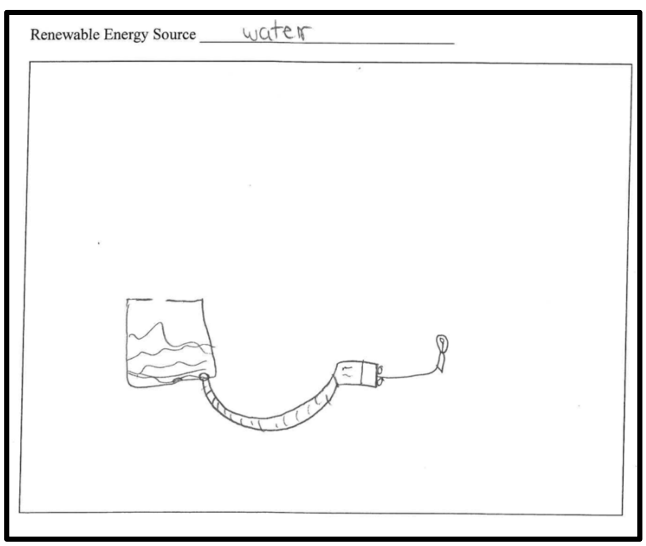


Figure V.8. Alyssa's Unit 2 pre-assessment model explaining how a source of renewable energy can be used to power a home.

Alyssa's discussion regarding her water wheel model further revealed Alyssa's understanding of the role of energy in the process of generating electricity from moving water (Figure V.9).

A(lyssa) So the water bottle is making, so when you tip the water bottle the water is coming out and the water wheel is moving to make the energy.

MM Okay. So how is it moving to make the energy?

A Umm the water is pushing it.

MM Pushing what?

A The water wheel.

MM So how does the water wheel move, if you had to describe how it moves?

A It moves by, so like the water goes on the little pegs it has and it pushes it.

MM Okay. So, can you tell me a little more about the energy? How do we know that energy is being produced?

A Well there's cords connected to the water wheel and there's light bulbs and when the water is turning the water wheel it turns on the lights.

Alyssa's explanation of her model was centered around the role of energy in her model. Alyssa identified that the water was acting on the water wheel and causing it to move. This idea is an important resource that Alyssa might eventually be able to draw upon in an explanation of energy transfer in the water wheel system. Similar to Samuel and Nick, Alyssa explained that electricity emerged from the water wheel. In addition, she used the same language of "making energy" that was used intermittently by students during class discussions. Alyssa also may have conflated the terms energy and electricity in her explanation. She referred to energy during her discussion of her model, but she referenced the cords and the light bulbs in her model as evidence that energy is being produced, which are more commonly associated with electricity.

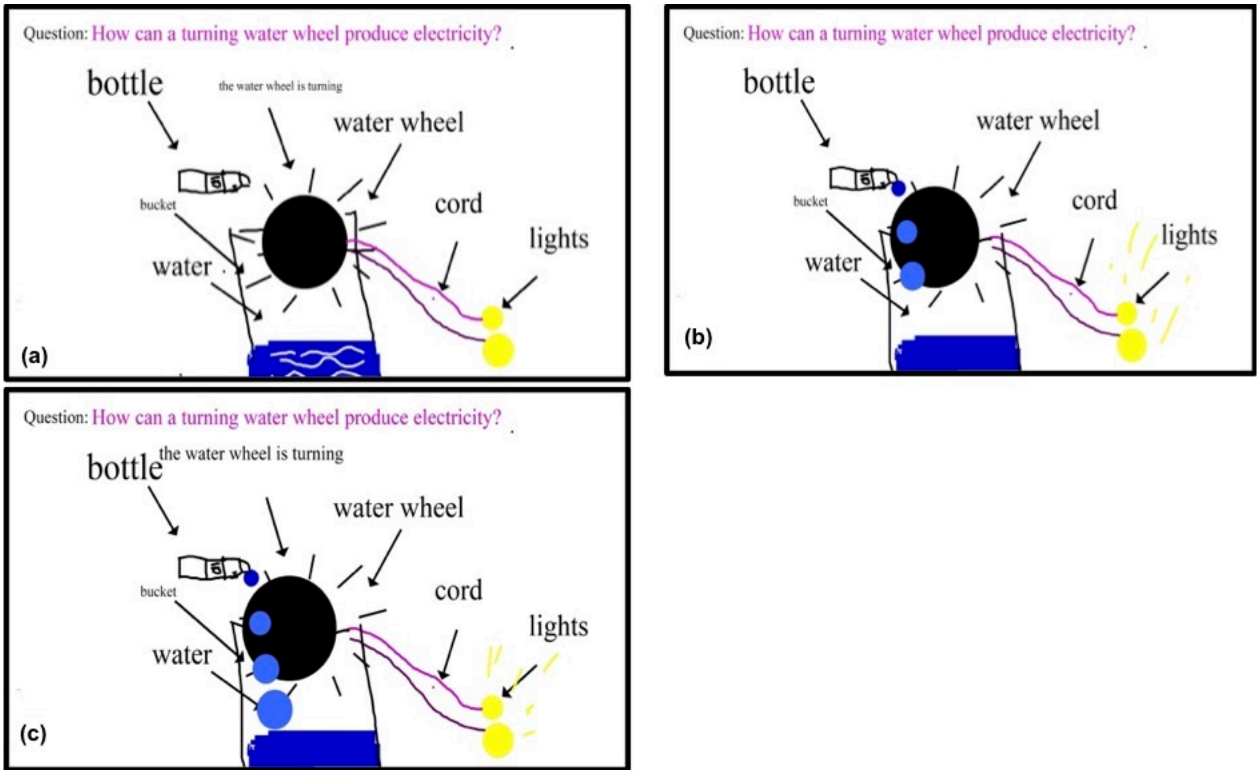


Figure V.9. Alyssa's *Flipbook* model explaining how a turning water wheel can generate electricity.

Later in the interview, Alyssa continued to reveal her sense-making regarding the concept of energy transfer in the water wheel system. When asked what her model explains, Alyssa replied, "it's explaining how you can make energy with using a water wheel." I took that opportunity to discuss the idea of energy transfer in order to gain more insight into her sense-making.

MM Okay, so when we talk about energy, do you remember last week Ms. White saying, we don't ever make energy, we do something else to it? It starts with a t.

A Transfer?

MM Mmhmm, we transfer energy. So, can you explain to me the path the energy is taking in your model? Where does it start from?

A It starts from, umm, from the water wheel, and then it goes to the cord and then it goes to the light.

MM Okay, but even before the water wheel, what causes the water wheel to turn?

A The water?

MM The water. So, the energy starts—where does the energy start?

A When the water is turning the water wheel?

Alyssa's uncertainty about the path of the energy within the water wheel system suggests that her understanding of the concept of energy transfer in this context was still fragmented and her ideas had not been connected into a coherent understanding as characterized by Clark and Linn (2013). Once again, she drew on the presence of the cord to suggest that the energy was lighting the light bulb directly from the water wheel, without the presence of a generator to convert it to electricity. Alyssa shared the same limited understanding of how the water wheel produces electricity as Samuel and Nick. All three children identified that electricity originated in the water wheel and conflated the terms *energy* and *electricity*.

Unlike Samuel, Nick, and Caleb, Alyssa did not include a convention to show electricity moving to the light. When I asked how energy was represented in her model, she first said, "the lights are lit up" and then suggested that she, "could add something showing the energy going to the lights" (Alyssa Unit 2 Interview #2). However, Alyssa's model does include animation that helps to understand her thinking about the process of harnessing energy from moving water. She included the movement of the water wheel, moving water, and beams of light in her model. While all of these components are observable components, they begin to address the process by which a turning water wheel can produce electricity.

Esther. Esther demonstrated high prior knowledge relative to her peers regarding the use of renewable energy sources to generate electricity (Figure V.10). In her Unit 2 pre-assessment interview, she revealed that she already had a basic understanding of how solar panels worked and the concept of energy transfer. She described her model as, “it’s the sun and these are solar panels and the solar panels are absorbing the energy from the sun. The solar panels then transfer energy to a house or something.” In addition, she identified that her model explained, “how you can get energy from the sun.”

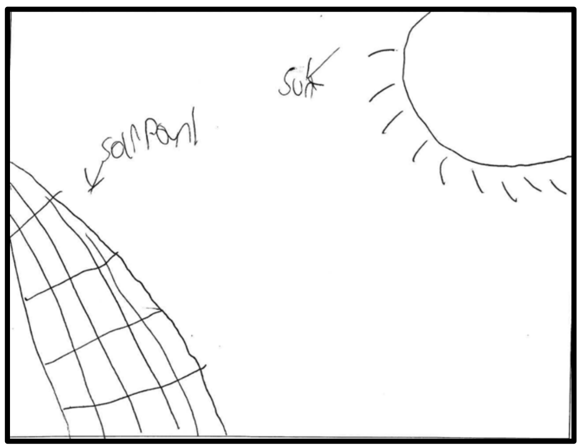


Figure V.10. Esther’s Unit 2 pre-assessment model explaining how a source of renewable energy can be used to power a home.

Esther’s water wheel model provided insight into her sense-making about the transfer of energy (Figure V.11). Esther described her model as, “it’s the water wheel and its transferring energy to a house…I made a tunnel that energy can go through in the ground.” Esther’s description suggests that she continued to think about energy transfer. Esther’s model also showed the path of electricity that includes arrows showing the direction that the energy is moving. During parts of the interview, Esther used the term energy to refer to electricity in her model. However, when asked what her model explains, she responded that, “It’s explaining how energy, or electricity, gets to the house” (Esther Unit 2 Interview #2). This response suggests that Esther understood that there is a difference between energy and electricity, but may not understand the contexts in which it is appropriate to use each term.

When asked how she would revise her model, Esther shared that her partner, Caleb, suggested that she “should add a generator, but I didn’t really want to” (Esther Unit 2 Interview #2). Her reasoning was “because I don’t know how to make a generator” (Esther Unit 2 Interview #2). Esther’s response reveals that one limitation of the feedback protocol was that students may not have been supported to learn more about the suggestions they received. Esther’s lack of understanding regarding the appearance of the generator stopped her from including it in her model. If she had been supported, either by the use of follow-up questions that she could have asked Caleb or through speaking with the teacher, Esther may have found a way to include the generator in her model. Caleb’s suggestion for revision also provided insight into his sense-making regarding the process of harnessing energy from moving water to generate electricity, because the role of the generator was central to his thinking during his interview and in his model.

Interestingly, Esther appeared to have included a generator in her model, though she referred to it as a propeller. The placement of the grey circle in the model, description of its role, and how she could revise that component to reflect her sense-making regarding the hand crank investigation suggested that she may have considered the propeller to act like a generator. When describing Slide 1, she said, “this is the propeller and this is supposed to be spinning [grey circle], and then the energy goes underground. I was going to try and make it move but it wouldn’t work. And then it goes to here to the house, but I didn’t finish that part” (Esther Unit 2 Interview #2). Esther further elaborated on the role of grey circle when she described how she could change her model to incorporate what she had observed from the hand-crank investigation by suggesting, “maybe I could add that the propeller might be moving like the crank so that it lights up the house" (Esther Unit 2 Interview #2). Esther's suggestion illustrates how she made sense of her observations regarding the effect that moving the crank had on the brightness of the light bulb and was supported to apply this idea to her model. In addition, she specified that the crank could be added to the propeller (the grey circle) as opposed to the water wheel, suggesting that she was differentiating between the two components of her model and considered the propeller to be more similar to the hand-crank than the water wheel. However, neither her model nor her interview provide insight into whether she thinks the electricity originates in the water wheel or the propeller.

Esther's discussion about the representation of energy in her model suggests that she was thinking about conventions and ways to communicate movement in her model. She used arrows and dots to represent energy and included directionality of the movement of energy with arrows, Esther explained that she "wanted to make the arrows move" to show "that the energy is moving through the pipe" (Esther Unit 2 Interview #2). This description suggests that she was thinking about the ways in which the animation feature of *Flipbook* could be used as to support the explanatory role of her model and the ways in which she could use invisible components to support her explanation of the process of electricity generation.

Similar to Nick and Caleb, Esther's depiction of energy and her rationale for her design demonstrate the use of invisible entities in the model, which aid in the model's explanation; however, Esther's model demonstrates a different dimension her epistemology in modeling related to explanation related to explanation. Baek and Schwarz (2015) distinguished between the use of invisible entities that are not parsimonious or scientifically accurate and invisible entities that "make use of microscopic/theoretical entities that are scientifically valid or at least parsimonious" (p. 222). Esther's use of dots in her model suggest that she may have been considering the microscopic nature of electricity, but she does not identify these dots as microscopic and therefore they do not contribute to a mechanistic explanation. Given the emphasis on the macroscopic properties of electricity in this minicycle, Esther may have been applying prior knowledge regarding her understanding of electricity and she was not supported during the unit to further develop her understanding of the microscopic nature of electricity.

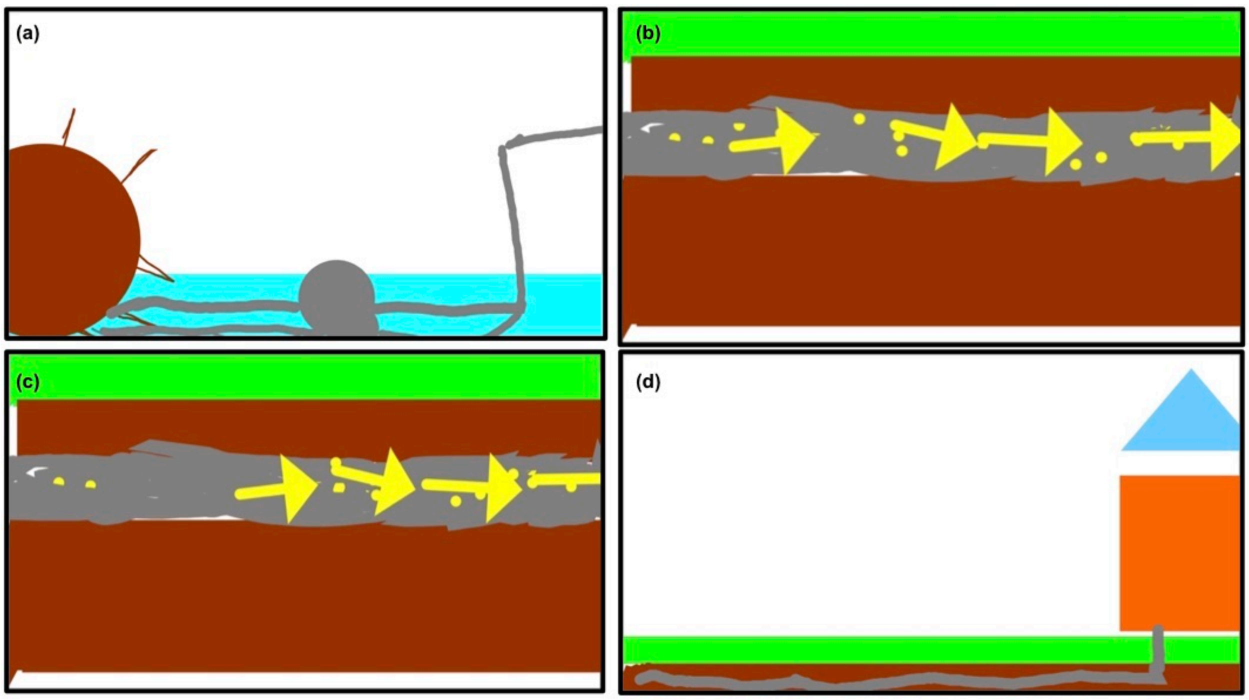


Figure V.11. Esther's *Flipbook* model explaining how a turning water wheel can be used to generate electricity.

Kiara. Kiara was considered to have low prior knowledge relative to her peers regarding the use of renewable energy sources to generate electricity (Figure V.12). In her interview regarding the pre-Unit 2 assessment, Kiara described renewable energy as, "you can use it a lot of times. It really never gets broken." For her model, she drew a pencil sharpener and explained, "Well I drew from the one like in our classroom. It's explaining how first you know you sharpen your pencil for a while and then it is sharp" (Kiara Unit 2 Interview #1).

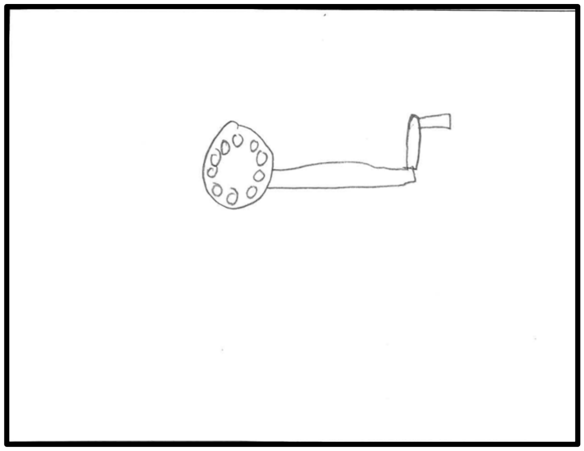


Figure V.12. Kiara's Unit 2 pre-assessment model explaining how a source of renewable energy can be used to power a home.

In Kiara's interview regarding her water wheel model, she revealed how her experiences with the hand crank generator influenced the construction of her model.

K(iara)	Well the crank is turning and its connected to, I forgot what it was-
MM	This thing? The water wheel?
K	No, the water wheel is connected to this thing that is connected to the house
MM	Okay just to make sure I understand, this is the crank, and you turn the crank?
K	Mmhmm.
MM	What happens when you turn the crank?
K	The water wheel turns and emits electricity.
MM	So, what causes the water wheel to turn?
K	The water.
MM	So, not the crank?
K	No.
MM	So, what is slide 3 showing?
K	The house got — bright.

Kiara's inclusion of the crank is very similar to the crank used on the hand-crank generator. While students were constructing their models, I demonstrated the hand-crank generator again for Kiara to remind her how it worked. I sought to support Kiara to recognize the need to include a generator in her model, however she added the crank to her model (Figure V.13). In addition, her explanation suggests she did not understand the role of the generator and how it was related to the crank handle. Kiara did exhibit fragmented understanding of the role of water in causing the water wheel to turn and the presence of energy in the system. This was evident later in the interview when she shared that her model was explaining, "how the water wheel has energy when it turns and stuff and it makes energy and the house lights up" (Kiara Unit 2 Interview #2). Kiara was aware that energy was involved in the system and that the movement of water wheel indicated that it "has energy." However, Kiara shared the same incomplete understanding as Samuel, Nick, and Alyssa that electricity is created inside the water wheel, as opposed to the generator. In addition, she refers to "making energy" as opposed to generating or producing electricity.

When asked how she revised her model, she indicated that her partner suggested that "maybe I should show how it gets light to the house" and she "added a crank and a house" (Kiara Unit 2 Interview #2), but did not provide reasoning regarding how they improved the model. She also did not share reasons for the ways in which she represented energy in the model.

MM So that yellow is the energy?

K(iara) Yah.

MM Is there a reason why you made it look like that?

K That way if its connected, that way it can get energy.

MM Can you tell me about the shape of it? Did you draw it that way for a reason?

K I don't know.

MM Is it important that it looks like this?

K No.

Overall, Kiara's model and verbal explanation suggest that she has a fragile understanding of the beginning ideas of the presence of energy in the water wheel system, but did not make sense of how energy is transferred from moving water to the water wheel and how this process could be used to generate electricity. In addition, she was not considering how her model could be used as an explanatory tool and how different features of the model (i.e., animation or color) could be used to strengthen the explanatory or communicative power of the model.

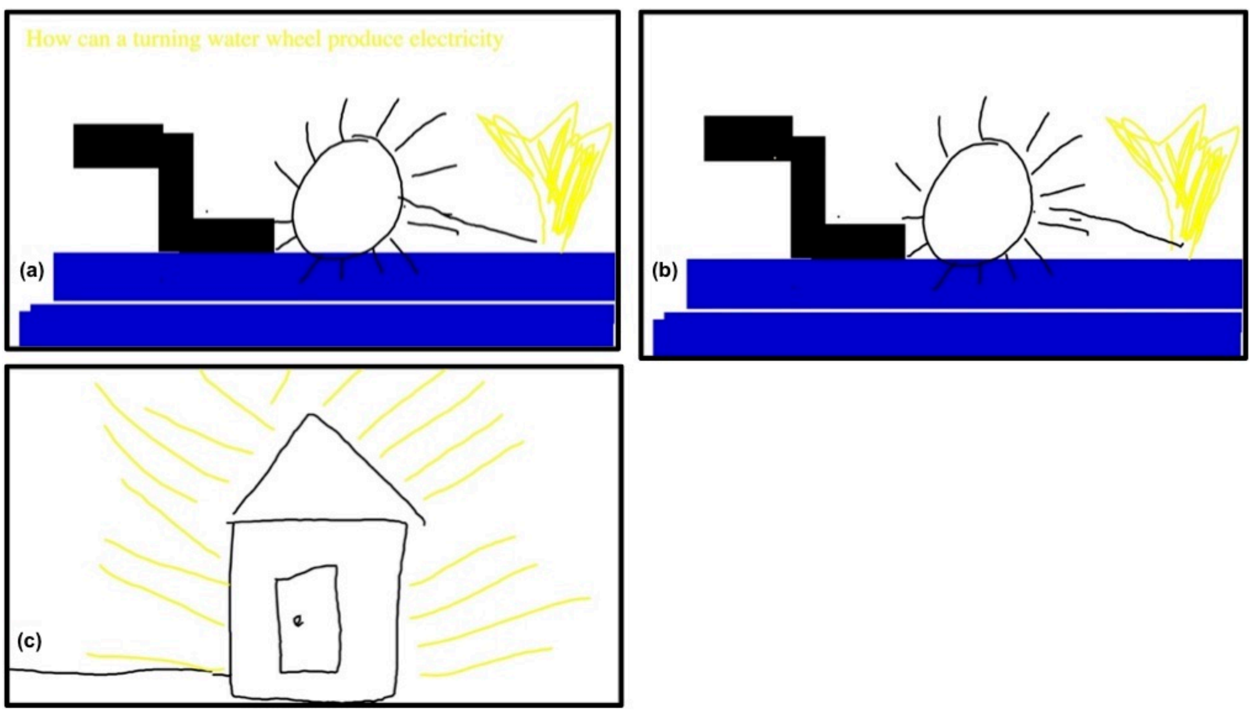


Figure V.13. Kiara's *Flipbook* model explaining how a turning water wheel can be used to generate electricity.

Conclusions from Minicycle #1. Students' individual models and interviews revealed insight into their sense-making related to how the energy in moving water can be harnessed and used to generate electricity. Students' responses suggest that the process of energy transfer between moving water and the water wheel was mysterious for students. Similarly, students did not understand how the mechanical energy in the turning water wheel was transferred to the spinning generator. For example, Samuel, Nick, Alyssa, Esther, and Kiara included electrical energy as a product of the turning water wheel without the presence of a generator. Caleb was the only focal student to include and discuss the generator in his model and interview. Previous research on the development of students' understandings regarding energy suggest that students must first understand that there are many different forms and sources of energy, before they can understand energy transfer (Hammer et al., 2012; Neumann et al., 2013).

While Unit 1 was designed to introduce students to the idea that energy was present in moving water and could cause changes to the land around it, students may not have developed a coherent understanding of this idea, which may have prevented them from to apply it to the new context of the water wheel. Another explanation could be that students' discussions regarding energy were contextualized to the phenomenon of each unit and this prevented students from recognizing similarities between the contexts of Units 1 and 2.

In addition to not discussing the process of energy transfer, students did not include representations of energy transfer in their models. This could have been due to the fact that energy is an invisible component and students were struggling to think about the presence of energy throughout the entire system. Baek and Schwarz (2015) provided a useful learning progression that could be used to compare students' models with respect to their use in an explanation. They identify the desired goal of the learning progression related to explanation as "students offer a hidden mechanism to explain a phenomenon" (p. 222). Several students did include representations of electricity, an invisible component, which fell short of achieving the goal of a hidden mechanism, but contributed to students' emerging understanding of the phenomenon of electricity generation and the development of their epistemological understanding regarding the use of a model to show an underlying process or mechanism. A complete explanation of the hidden mechanism in the case of this model must include a depiction of the process of energy transfer. In Minicycle 2, the researchers made design decisions to try to address students' struggles with the process of energy transfer.

Students also interchanged the terms *energy* and *electricity* during their interviews regarding the water wheel model. The term *energy* is used in everyday contexts to describe a wide range of phenomena (Hammer et al., 2012). Students' inconsistent use of *energy* and *electricity* could have been due to their exposure to the conflation of these two words in their everyday experiences. There were also times during class that the teacher or researchers would interchange these two terms, which may have reinforced students use of both terms interchangeably. Students also struggled with the concept that energy was *generated* by the energy, not *made by* the generator. Students' difficulty differentiating between *energy* and *electricity*, as well as between *generating electricity* and *making energy*, suggested that they also did not understand the difference between the concepts of energy and electricity and the process of using moving energy to produce electricity. More emphasis on the difference between energy (or more specifically, moving energy) and electricity, and how these two ideas are related to each other, could be included in the instruction to support students to understand the differences and communicate their ideas using more precise language.

Many of the focal students demonstrated that they were considering the conventions in their models and how they could use conventions to improve their models' communicative power. All focal students used yellow to denote electricity. Several students provided reasons for this choice related to the common convention of using yellow to show electricity. In addition, Esther included arrows to show the direction of the movement of energy. These elements of students' models suggest that students were developing understandings regarding how to use their models as explanatory tools and the ways in which components within the models could increase their explanatory power. This is in contrast to Unit 1, in which there was no evidence that students were thinking about how components in the model could be used to increase its explanatory power. The development of this understanding may have been supported through class discussions that introduced and reiterated sense-making ideas related to the use of conventions, such as labels and arrows, and that students were constructing models to explain the phenomenon of harnessing the energy of moving water to produce electricity.

The use of *Flipbook* also provided students the opportunity to use animation, which they did not have access to during Unit 1. All students created multiple slides for their models, but not all students used animation in purposeful ways to increase the explanatory power of their models. For example, Kiara created three slides, however, slides 1 and 2 were exactly the same and slide 3 was a different scene. In contrast, Alyssa used animation to show how the water moved down the water wheel and Esther showed the path of electricity traveling to the house. These examples also demonstrate how the use of animation may have supported some students to show a process, which is a pre-requisite for showing the hidden mechanism, referred to by Baek and Schwarz (2015). The use of animation provided the opportunity to demonstrate their sense-making with respect to the process through which energy from moving water was transferred to the water wheel and harnessed to generate electricity, as well as supported their abilities to construct models to explain a target phenomenon.

Minicycle #2: The Windmill

In Minicycle #2, students investigated how the energy from wind could be harnessed to spin the generator and generate electricity. Students continued to engage with the concept of energy transfer, however instead of energy transferring from moving water to a spinning wheel, they explored how energy was transferred from moving air to a spinning wheel. In the design of the curriculum, these two types of renewable energy sources were chosen due to the overlap in the mechanisms through which energy was transferred and electricity was generated as a way to continue to introduce students to different renewable energy sources while simultaneously reinforcing the concept of energy transfer.

This minicycle began on Day 18 of Unit 2 and lasted for six days of instruction. In the curriculum, the teacher had the option of asking students to draw their ideas for how to make a generator spin using wind, or to construct a wind turbine as a class. I changed the curriculum to a combination of these options. Students worked in small groups to design, build, test, and revise, physical models of a windmill and then drew models in *Collabrify Flipbook* to explain how their design could light a bulb. These changes provided students the opportunity to engage in the entire modeling process as suggested by Louca and Zacharia (2015) and with multiple forms of models, including physical, drawn, and animated, for the first time. On Day 18 of Unit 2, Day 1 of this mini-cycle, students were introduced to the problem that they would be working to solve and the materials available. The class began by summarizing the ideas they had been exploring related to energy, including what they knew about the role of the generator in the process of generating electricity. Four students shared ideas related to energy that the class had previously discussed.

RM Water wheels. They force energy, kinetic energy, into a generator and it produces electricity.

GL There's so much energy.

DD Inside generators. How they move. How energy transfers to generators.

BW Generators, they can move.

For their windmill model, students used an empty thread spool as a representation of the generator. They were tasked with the challenge of making the thread spool spin, similar to how a generator would need to spin to generate electricity. The teacher introduced the question, "The question we are going to be working on is this, how can wind transfer energy to light a light bulb? We've been talking about water and now we are switching to wind energy." Ms. White reminded students that their exploration with the water wheel was related to water energy and now students would be exploring wind energy. In addition, Ms. White and I prompted students to think about the role of the generator and the use of the spool to represent the generator.

Ms. W [The generators] won't actually work, but you have to find a way to have your wind turbine hook up to this generator. You're also going to be testing your designs. It will be similar to what we did with our water wheels... This spool will be a stand-in for our generator. You will have a bucket and a dowel rod.

MM You will have to figure out how to attach your wind turbine to this dowel. What motion does the spool need to make?

TH The generator!

MM Yes, but what motion does it need to make?

KH It has to spin.

MM You are going to have to figure out when you make your design, you are going to have figure out how to make that rod and that spool spin.

During this conversation, students provided ideas about the motion of the thread spool using what they had already observed and learned about the function of a generator. The use of the thread spool was intended to support students' sense-making about the function of the generator and the motion of the generator. This idea was reinforced by the researcher before students began planning their designs.

MM	Who can summarize what problem you are trying to solve? What are you trying to do?
GL	You are trying to make the windmill connect with the thing.
MM	You have to make sure it connects to the wooden piece.
Student	You have to transfer energy.
MM	The wind is going to transfer energy, so that what will happen? What do we need to have happen?
Serenity	The light bulb to light up.

Students had a variety of materials available, including craft sticks, foam disks, appetizer forks, pipe cleaners, cardboard, and plastic utensils, etc. Students worked for 3 days to plan and build their windmills. Unlike the water wheel minicycle, Ms. White did not conduct whole class instruction during this time. Instead, she circulated around the classroom and supported students in building, testing, and revising their windmill models. While circulating, Ms. White asked students about the materials that they planned to use to build the wind turbine and how they planned to attach their turbine to the thread spool.

The use of the materials and the thread spool to serve as the generator resulted in physical models that had fewer similarities in their physical appearance to actual wind turbines, as compared to the number of similarities between the water wheel model and actual water wheels. This provided an opportunity for students to pursue epistemological ideas about modeling related to the importance in similarities of *function* between the model and target phenomenon, but not necessarily similarities in *appearance*.

Many groups drew on their experiences with the water wheel and made initial windmill models that looked very similar to the water wheel models. Many of students' original designs did not address the ways in which the turbine would turn the generator. During a conversation with Ms. White on Day 20, she shared her observations about a point of struggle that students were experiencing with their models.

> She commented that she thought the students did not make the connection between the model of the generator with the thread spool and the real box generator. She thought they were understanding how it worked and the connection to how it produces electricity before the windmill lesson, but that understanding seems to have gone away while working on their windmills (Teacher-Researcher Phone Call Memo 2.8.17).

Ms. White's observations regarding student understanding emphasized the challenge of abstraction often associated with models, especially since students' previous experiences with models had included models with multiple physical similarities between the model and the target phenomenon. The class had previously established that the generator was a necessary component and that it needed to spin. They had also seen a homemade generator and how it could be powered by a hand spinning the magnets to light a light bulb. However, Lehrer and Schauble (2012) found that models with fewer similarities to the target phenomenon result in higher cognitive overhead, which suggests that students may have experienced greater challenges when applying what they knew about the actual generator to the thread spool due to the lack of remnants between the phenomenon and the representation.

I worked to address Ms. White's concern on Day 22 of instruction, when the class was discussing the components needed for their drawn models to explain how their windmill designs could be used to light a lightbulb. Before this, students had revised their initial designs and tested again. Now, students were asked to draw a model in *Collabrify Flipbook* to explain how their design could be used to light a light bulb. I reminded the class of the question that Ms. White introduced at the beginning of the minicycle and supported students to think about the elements that should be included in their models.

MM You are going to draw a model of your final design on Flipbook. You will draw a model about how it works. What are some things that you need to include in your model?

Kyle How is it producing the -, or how is it making the generator spin?

MM What was the generator in our tests? What took the place of the generator?

Madison The spoons?

MM No, good guess.

Madison The spool. The thread thing.

MM You have to show how your windmill made the generator spin.

MM What other pieces, that we call components, what other components do you need in your model?

Madison Some kind of fan or a hair dryer.

MM What was the fan or the blow dryer supposed to represent?

DD The wind.

MM Okay, you want to make sure you wind. You could add a fan or a hair dryer. What's one very important piece we need in our model?

Serenity The windmill.

MM Can I just draw a circle and call it my windmill?

Class No

MM What else could we include?

NK Add spoons or pipe cleaners.

MM So, if you included spoons or pipe cleaners, you could add them. You need to put materials.

MM Why do you think we made windmills? We are missing one key thing here. Why are we even talking about windmills?

Student How energy...

HK How energy...

MM How energy from... blank.

Madison From electricity?

DD How does wind make energy?

Class WIND!

MM "...get transferred to..." what? Where is the energy from the wind get transferred to?

TH The generator!

MM Good, the generator. And what is the generator doing? The generator is producing what?

Student Energy.

MM Not energy, electricity. This is the question you are trying to answer. How does energy from the wind get transferred to the generator to produce electricity? Your model needs to answer this question using that design you made, using that windmill that you made. Who can summarize what you are doing in Flipbook?

GL You are creating a windmill that produces electricity to power a generator.

MM Whose windmill are you using?

GH The windmill you made.

Prompts for this discussion were not included in the original lesson plan. During this discussion, I sought to support students to make connections between the generator and the spool, as well as support students' sense-making regarding the components necessary to include in the model. Construction of their drawn windmill models required students to consider the representational aspects of the model in relation to the target phenomenon and how the components worked together to present a causal account of how energy from wind could be transferred to the generator to produce electricity. I worked to support students to identify the representative features that they used during the modeling cycle (i.e., the spool and hair dryers) and what the features represented in the phenomenon of how energy from wind can be used to generate electricity.

After students completed their drawn models, the class viewed an online animation that showed the inner workings of a wind turbine and a wind farm system that showed the path of electricity from the wind turbine to the houses (Figure V.14). The animation included an intermediate step, the sub-station that receives and distributes the electricity. Ms. White asked students to consider how their drawn models were similar and different to the animated model explaining how electricity from wind energy is distributed to homes. This animation was considered a model, because it was a simplified explanation of how energy from wind can be harnessed to produce electricity to light homes. It served as a point of comparison for students to consider different ways to represent the process that they were attempting to model and supported the class's discussion regarding different ways to model this phenomenon.

Ms. W	Take a look at that. Think about your pictures in collabrify and what you were doing. What do you notice?
Madison	So, it works when the wind farm, the light thing goes by the turbines. When this thing goes up, it goes up to the subtation (substation) and goes through the grid into to the house.
Ms. W	What is going through there?
Madison	The light? The electricity?
Ms. W	How does that compare to what you drew?
Madison	It's the same because the light, the energy goes to the house. It's different because I didn't draw the subtation (substation) and the grid.
Kyle	The wind turbines are kind of like the same as my model.
Ms. W	Ah, so the wind turbine shape is the same? Did you make the connection with the electricity?
Kyle	Uh, no.
Ms. W	Okay, some of us didn't get to that.
GL	So the wind comes, the arrows like that, it spins the turbines then when the turbine's spinning it creates electricity. I didn't draw the house being lit up.
MM	Did anyone's design look different?
GL	Mine only had one turbine. I don't have a power line and a house.
Serenity	My wind turbine had more stuff on it than in the picture.
Ms. W	Than in this picture?
Serenity	Ours had more blades.

Madison Mine was different because I didn't draw the wires or the light, the energy going through the wires.

Ms. W Okay so you didn't make that connection with the wires?

Madison And I didn't draw the subtation (substation).

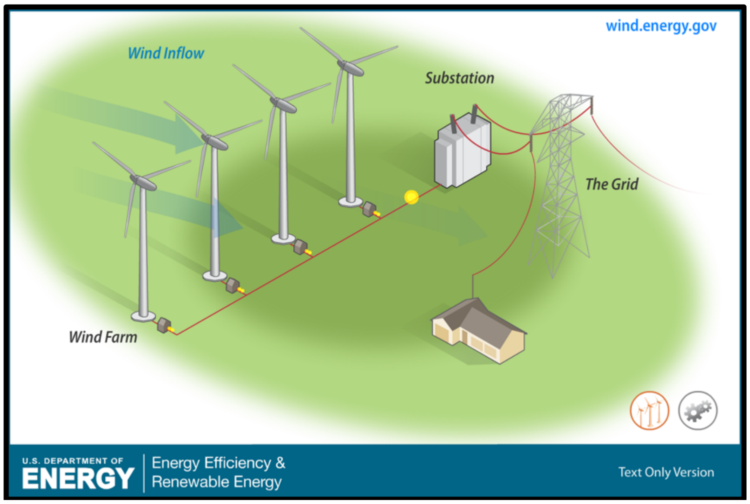


Figure V.14. Still image of energy animation that students observed on Day 23.

During this conversation, three students shared their observations regarding the animated model and how their drawn models compared to it. Similar to their comparisons with real water wheels, students' comparisons focused on the physical features in the two models. However, during this discussion both GL and Madison made interpretations regarding processes being explained in the animation. GL interpreted the arrows and explained how the wind was moving the turbine and Madison identified that electricity was moving through the wires to the house. Students did not explicitly discuss energy transfer, mirroring their discussions of the water wheel, but both GL and Madison made references to electricity and energy interchangeably during this conversation, suggesting that the animated model was prompting them to think about the role of electricity in the process of generating electricity from wind energy. In addition, Ms. White emphasized the idea of making connections to generating electricity and asking students if they had done this in their models. While the students who answered had not made these connections, prompting students to think about this could have reinforced the idea that these kinds of connections were necessary. Ms. White's questions also suggest that she was mindful about the struggle she felt that students were experiencing regarding making connections between the movement of wind turbine and the generator.

Minicycle #2 was designed to support students to extend what they had learned about energy transfer during their exploration with water wheels to another energy source. Students' contributions during whole class discussions suggested that some students were thinking about energy, but similar to the conversations regarding the water wheel, there were no sustained discussions involving energy transfer. The lesson was also designed to engage students in the entire modeling process – planning, testing, evaluation, and revision. Because of the materials students were using, there were fewer remnants than when students engaged with the water wheel model, resulting in higher cognitive overhead for students to make sense of this model, and their first experience with a syntactic model, or a model that only maintains functional similarities and not physical similarities with the target phenomenon (Lehrer & Schauble, 2012). Students also engaged with multiple forms of models during this minicycle, including physical, drawn, and animated models. diSessa (2004) argued that students must be familiar with the purposes of different forms of representation before they are able to evaluate them. Therefore, multiple forms of modeling were intentionally included to introduce students to different forms of models as a way to support the development of meta-representational competence.

Focal Students Sense-Making in Minicycle #2

Interviews with individual focal students provides additional insight into how the changes made in Minicycle #2 supported students to continue to make sense of energy transfer in the context of wind and use and construct different types of models with different levels of representational abstraction.

Samuel. Samuel was not present in class on Day 22 of instruction when students created their windmill models in *Flipbook.* Because he did not have a model to share during his interview, I asked him about the animated model that the class viewed on Day 23 of instruction. Samuel had also been absent for this day as well, which provided an opportunity to gain insight into his initial sense-making about this model. Samuel's observations of the animated model focused on the observable components.

S(amuel) So, the windmill is making electricity. It's going through the substation.

MM Substation.

S Yeah, substation. And both--one of them is going to the grid. The other one is going to a house.

MM Okay. So, how do you know it's making electricity?

S Because the windmill is blowing, which is making electricity.

Samuel's explanation regarding how he knows that that the windmill is making electricity did not refer to the electricity traveling through the wires, but instead references the movement of the windmill, suggesting that he understood that the "blowing" windmill is necessary for making electricity. Samuel did not elaborate on this idea or other aspects of the windmill that are necessary for the generation of electricity. Similar his model of the water wheel in which Samuel described electricity as emerging from the water wheel without explanation for how the electricity was generated, Samuel describes the movement of the windmill as being responsible for making electricity. The similarities in Samuel's answers suggest that his sense-making regarding the process of energy transfer and the use of a generator in producing electricity had not evolved. However, he did specify that the movement of the windmill was responsible for producing electricity, which suggests that he understands that this movement is a part of the process, and was a shift from his explanation of how the water wheel was used to produce electricity. When explaining the water wheel model, he did not specify that the water wheel needed to move in order for electricity to be produced.

Nick. Nick's interview regarding his windmill model revealed that the construction and testing of his physical windmill model supported his sense-making of the role of the generator; however, he did not include any mention of energy transfer during the discussion of his model (Figure V.15). In describing his model, he said: "So here is the fan that is blowing air onto the windmill and there's a generator right here, here's the book that's holding it, here's the wire going to the light." When I asked about the origin of the wire in his model, he explained, that it started from "the generator. And basically, it's slowly, the electricity is slowly going through the wire [Nick was clicking through slides as he spoke]." This explanation regarding the generator demonstrated a change in his sense-making from his understanding of the path of electricity when he made his drawn water wheel model. In his water wheel model, Nick drew and explained that electricity originated in the water wheel and traveled to the generator. Nick's explanation of his drawn windmill model suggests that he recognized the importance of the generator in the windmill system and he understood that the electricity originated in the generator.

His model also shows wind moving from the fan to the windmill. The inclusion of wind suggests that Nick was considering the invisible components in the system, similar to how he included the invisible component of electricity in his water wheel model. In addition, Nick used animation in his model to show the process. Both the use of invisible components that had observable effects and the use of animation were also present in his water wheel model.

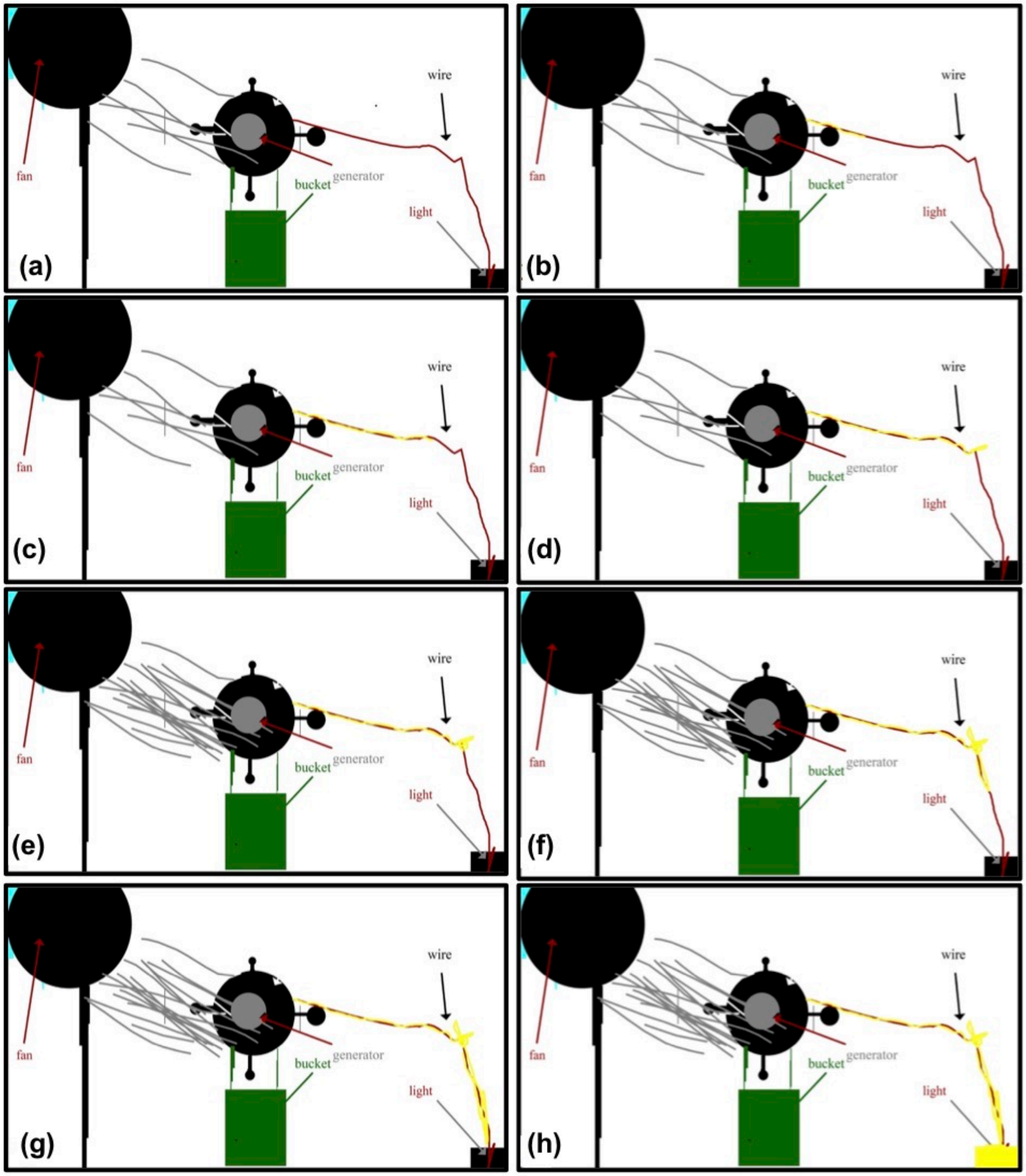


Figure V.15. Nick's *Flipbook* model explaining how his windmill design could be used to light a lightbulb.

The difficulty of considering how energy was transferred from wind to another object was evident in Nick's discussion regarding the role of energy in the process of lighting the light in his model. He identified that, "the energy is going through the wire" and "It's [energy] in the wind" (Nick Unit 2 Interview #4), but did not identify any other places that energy was present in the model. Nick's responses suggest that he understood that energy was present in the wind, but did not understand that it was transferred to the windmill.

Caleb. Caleb's discussion regarding his windmill model revealed that his developing understanding regarding the (a) importance of the generator in the production of electricity, (b) use of conventions in modeling, and (c) the concept of energy transfer. Caleb explained his model as, "we made our windmill where it was a Styrofoam circle in the middle and then there were spoons for the windmill spinner and then this piece right here is a pipe cleaner because that is what we connected to the generator." When asked about the role of the pipe cleaner, Caleb shared that it made the generator spin. Caleb's model that is shown in Figure V.16 is a recovered version, and was not his final version. [Due to technical difficulties, his final model was deleted from the storage site.] Caleb's discussion and the older version of the model suggest that he continued to apply his understanding of the generator that he developed during the water wheel minicycle. In addition, Caleb included wind in his model suggesting that he was thinking about the invisible components necessary to the process of spinning the windmill.

When I asked Caleb how energy was represented in his model, he shared his thinking regarding what was missing in his model.

Caleb I was going to add the generator and [the pipe cleaner] was going to be connected to it. And then I was going to show yellow for the electricity and it was going to light up the lightbulb.

MM How is energy involved in that?

Caleb The generator turns the wind into energy so it can light the light bulb.

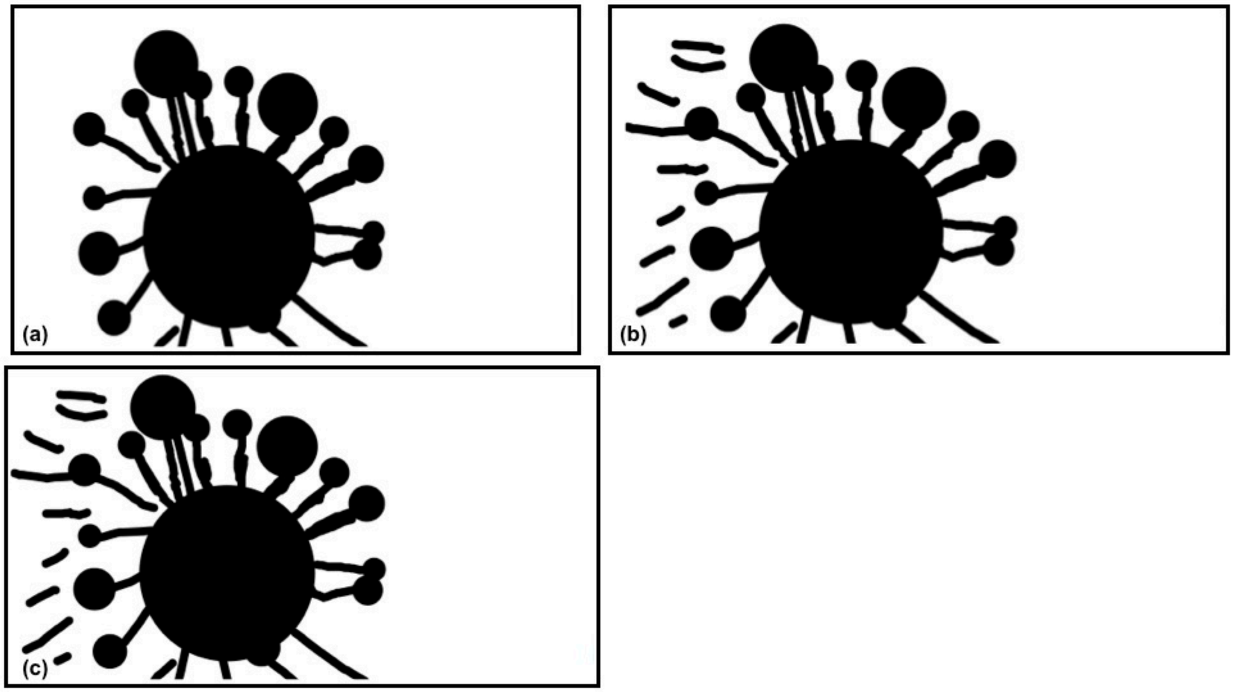


Figure V.16. Caleb's *Flipbook* model explaining his windmill design.

Caleb's description of what he wanted to add to his model revealed that he was considering the conventions for representing electricity. He also demonstrated that he understood that the generator was involved in the transformation of wind into electricity. However, Caleb used both *energy* and *electricity* when discussing the process of generating electricity, suggesting that he may have been referring to electricity colloquially as energy not have understood that energy was also present in the wind, or that he considered energy and wind to be separate ideas. Caleb's discussions earlier in his windmill interview and in his previous his water wheel interview suggested that he was able to differentiate between energy and electricity, but this may have been a developing understanding that was not fully formed. Caleb demonstrated ideas regarding energy transfer that could serve as resources for a future complete explanation of how energy is transferred from the wind. Caleb's responses also illustrate how his developing understanding involved constructing or revising connections between ideas in his repertoire, because Caleb was able to apply ideas related to energy transfer in the context of specific questions, but not others. Clark and Linn (2013) describe the refinement and construction of connections of ideas within students' repertoire as the process of learning.

Alyssa. Alyssa's discussion about her windmill model suggests that she was developing an emergent understanding about the role of energy transfer in the generation of electricity using wind.

A(lyssa) I drew the wind, so it's coming from the fan that we use. Its, well I didn't really show that it is moving the windmill, but it is. There is a pipe cleaner connected to the string and connected to the – [pause]

MM Over here? Are you trying to say that word? Do you remember how to say it? Generator?

A Generator.

MM Okay, what else is going on in your model?

A Umm

MM What are those things on the bottom?

A Buckets, so that it can stand up.

MM Great. You have a lot of stuff in your model. What question were you answering when you drew your model?

A Umm, I forgot.

MM So, if you had to write a question, if you had to tell someone the question your model is answering, what do you think you could say?

A How a windmill spins a generator?

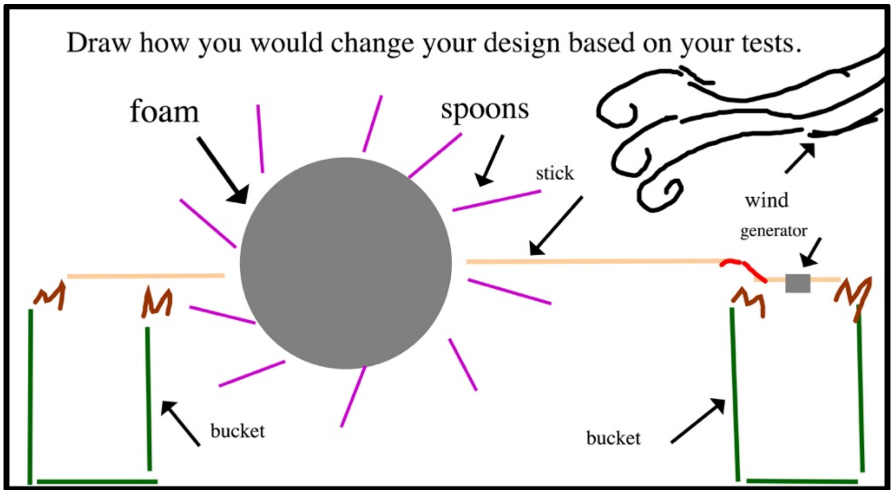


Figure V.17. Alyssa's *Flipbook* model explaining his windmill design.

Alyssa's explanation of her model indicated that she was considering both invisible components, such as the wind, and the mechanism to explain how the system works, such as the movement of the windmill. She also alluded to mechanism when she suggests that the question that her model could answer is, "How [does] a windmill spin a generator?" This question implies that the design challenge was to make the generator spin. However, Alyssa did not mention the reason why the generator needs to spin, suggesting that she may not have understood what the windmill model system was representing (i.e., how the energy from wind can be harnessed to generate electricity). Alyssa's model and her explanation also did not include a representation of electricity, further suggesting that she was focused on the design problem of making the generator spin, as opposed to the phenomenon of using wind to generate electricity (Figure V.17). Her focus on the design problem also suggests that Alyssa may not have understood the role of models as an explanatory tool. Louca and Zacharia (2015) and Schwarz and colleagues (2009) define models as a simplified version of a phenomenon used to explain an underlying mechanism or process in the system. Alyssa's model suggests that she was not able to consider the physical model of the windmill in the context of the target phenomenon it represented and therefore did not consider the pieces of the phenomenon that were absent from the physical model (i.e., the wires and light bulb) when she constructed her drawn model.

When I asked Alyssa to explain how energy is involved in the process of spinning the generator in her model, she revealed her emergent understanding about the process of energy transfer.

A When the wind is spinning the windmill, it's going, well it's not technically going through the stick but I'm like imagining, it goes through the stick and then it goes to the pipe cleaner that is connected to the other stick that has the generator and makes it spin.

MM What is going through the stick?

A Energy

MM Do you remember that word that we used? Because I know what you are saying about it kind of goes through the stick. Do you know that word? It starts with a "t".

A Transformed?

MM Close. Transferred.

A Transferred.

Alyssa's explanation suggests that she understood that the motion of the windmill involves energy and that energy made the generator spin. She provided an interesting insight into a limitation of her understanding when she specified that energy did not travel through the stick, but that she was imagining that it did to reach the pipe cleaner. Her qualification of her statement regarding how energy travels through the windmill system suggests that she may not have realized that energy was also being transferred through the spinning motion of the stick. Her comment that she imagined that the energy traveled through the stick also suggested that she did not know how energy would travel from the spinning windmill to the pipe cleaners in her model without traveling through the stick.

This conversation between Alyssa and myself regarding energy transfer also occurred during the water wheel interview. During the water wheel interview, I spoke with Alyssa about the difference between making energy and transferring energy. While she did not remember the term "energy transfer," Alyssa's understanding of energy transfer had developed from the water wheel model to the windmill model. When discussing her water wheel model, Alyssa suggested that electricity emerged from the water wheel without mention to the role of the generator, while in the windmill model interview, she discussed how the generator was used energy from the wind to spin. She did not indicate what resulted from the spinning of the generator, but her description of energy going to the generator suggests that she did not think that electricity emerged from the windmill.

Alyssa further revealed her understanding about energy transfer when she described the animated model that the class had viewed. Alyssa was not present on this day of instruction and looked at this model for the first time during the interview (Figure V.14). She identified that the model was explaining, "how energy is being transferred from the wind turbines to the generators and then it's going to that power tower and then it's going to houses." Similar to her discussions during the water wheel interview, Alyssa did not differentiate between energy and electricity, however she accurately described energy as being transferred from the wind turbine to the generator. Alyssa's discussion with the interviewer regarding her windmill model suggest that her experiences with the physical windmill model supported her sense-making regarding the presence and role of the generator in the windmill system.

Esther. Esther's explanation of her windmill revealed the development in her understanding about the role of models to explain phenomena. Even though students were tasked with drawing a model to explain how their windmill design could be used to light a bulb, Esther's explanation of her model focused on the broader phenomenon of harnessing wind to generate electricity. Esther explained, "the wind is blowing and its spinning around and the electricity goes and lights up the light bulb… that [the windmill] spins and the electricity from that spinning goes through the wire." Esther stated that the question her modeled answered was, "How does electricity get to somewhere else?" Esther's explanation and question for her model suggest that she did not consider her model to be an explanation of her windmill design, but instead focused on the process of generating electricity. In addition, she revealed her understanding that the spinning of the windmill was involved in the generation of electricity.

Esther did not include the generator in her model, despite the prominent role that the representation of the generator played during students' testing of their windmill designs and Esther's inclusion of a generator in her water wheel model (Figure V.18). However, she did include representations of wind and electricity in her model, suggesting that she was also considering the invisible components that were important to answering her model's question.

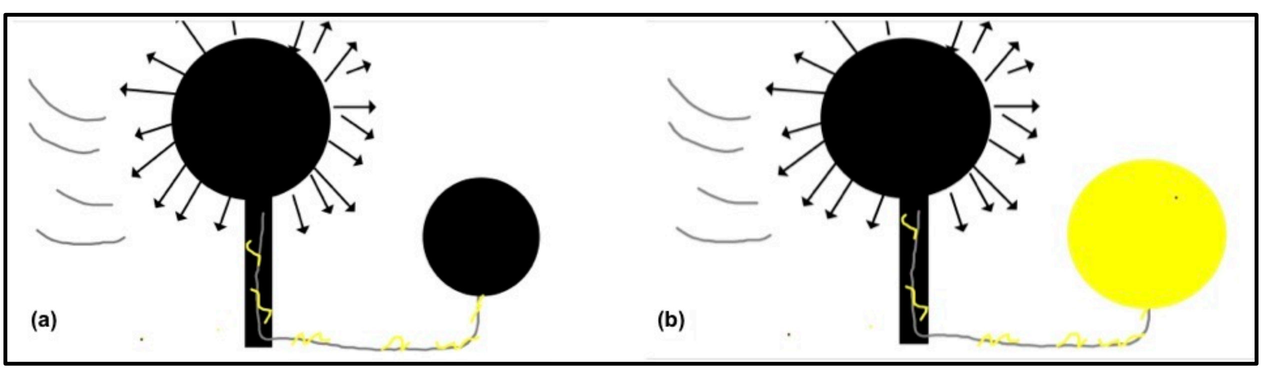


Figure V.18. Esther's *Flipbook* model explaining how his windmill design could be used to light a lightbulb.

Esther demonstrated an emergent understanding of energy transfer when asked how energy was involved in the process of lighting the bulb. She stated, "The energy from the wind goes to here [the windmill] and this [the wire] carries energy that turns into electricity" (Esther Unit 2 Interview #5). Her answer suggests that Esther understood that energy is present in the wind and is transferred to the windmill. In addition, she differentiated between energy and electricity and that "energy is turned into electricity." She does not elaborate on that process, but this distinction demonstrated a shift from the water wheel interview, when Esther was referring to electricity as energy.

Despite not including a generator in her model, Esther demonstrated that she was familiar with the generator and its role in producing electricity when she evaluated the model of the wind farm that the class had viewed. When I asked her if she had suggestions for ways in which this model could be improved, she suggested, "maybe you could show how it makes electricity" and that the model should "show what is going on [inside the turbine], like the generator spinning" (Esther Unit 2 Interview #4). Esther response provides insight into her sense-making regarding the role of the spinning generator in producing electricity, suggesting that she had developed an understanding that the spinning generator was important in the process.

Kiara. Kiara's interview regarding her windmill model revealed that she struggled to make sense of the process of energy transfer from wind through the construction of physical and drawn windmill models. During Kiara's interview, she was continuing to reference the water wheel instead of this windmill. In her initial description of her model (Figure V.19), she described, "Well it's turning in the water and it's making electricity" (Kiara Unit 2 Interview #4). While other students did not demonstrate this same confusion, it is not surprising that Kiara saw many similarities between the water wheel and windmill models, given the similarities in their appearances. In addition, many students initially constructed windmills that looked very similar to the water wheels, and it is possible that Kiara did not fully understand the difference between these two models.

When I asked her if we used water with our windmill model, Kiara immediately corrected herself and remembered that she was planning to change her model to show a windmill. Kiara did not have time to finish her model. The model she presented during her windmill interview was incomplete and reflected her thinking about the water wheel, as opposed to her windmill design. I asked her how she would change her model and she stated that she would add a fan and "take out the water and some stuff I drew," but that she would leave the wheel (Kiara Unit 2 Interview #4). This discussion suggests that Kiara did not understand the phenomenon that was supposed to be modeled and this prevented her from identifying the parts of the model that would have helped her explain how wind could be used to generate electricity. The one aspect the windmill context that she identified to add to her model was the fan. This could be due to the centrality of the fan in the testing of the windmills and my question cued her to think about that experience.

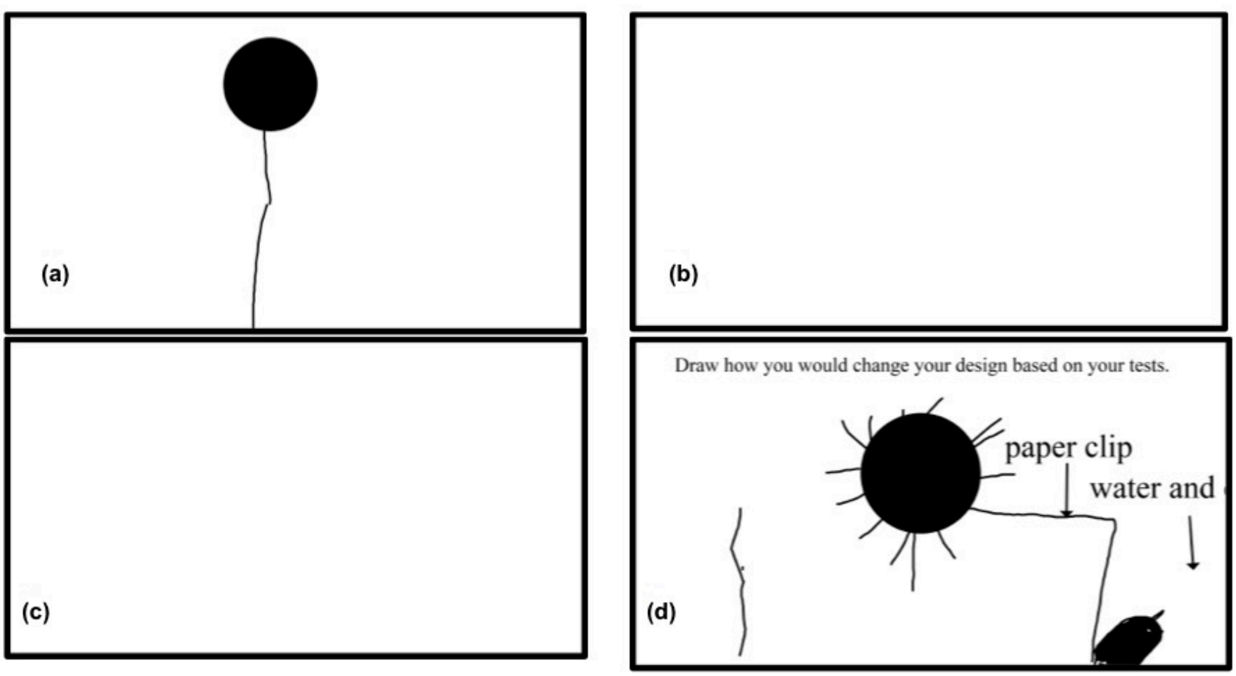


Figure V.19. Kiara's Flipbook model explaining how her windmill design could be used to light a lightbulb.

When I asked Kiara how energy was involved her model, she referenced the observable effects of energy transfer. Kiara explained, "like when the fan is on and is going really fast, it can spin it… Because when the water wheel turns, it makes light." Kiara confused the water wheel with the windmill, but when I asked her if she was referring to the windmill, she said yes, which was consistent with the first part of her answer. Kiara response suggests that she drew a connection between the spinning fan with the spinning wheel and that the spinning wheel is involved in producing electricity. However, Kiara was still confusing the two modeling contexts of the windmill and the water wheel, which was limited her sense-making regarding the phenomenon of energy transfer from wind.

Conclusions from Minicycle #2. The analysis of Minicycle #2 revealed the ways in which students continued to develop understandings and experienced challenges related to the concept of energy transfer and the ways they could draw on their own investigations and experiences to inform the construction of models which represent a larger or more abstract phenomenon. All focal students, except Kiara and Samuel (who did not have a model), included wind as a component in their models. While people feel wind, and can observe the effects of its movement, it is impossible to see wind itself, unlike being able to observe the movement of water and the moment of impact when water collides with another object, such as a water wheel. The invisibility of wind was another aspect that made the phenomenon of the transfer of energy from wind more challenging for students to make sense of when compared with the transfer of energy from water.

The concept of a generator and its role in the process of energy transfer and electricity production remained a difficult concept for focal students to make sense of, despite the prominent role that the generator played in the physical windmill models that students constructed and tested. The number of students who incorporated the generator into their model remained consistent from the water wheel models. Caleb, Nick, and Alyssa incorporated the generator into their models or their discussions about what they would add to their models, while other focal students continued to reference electricity as emerging from the windmill. In the water wheel models, Caleb, Esther, and Nick were the only focal students to include a generator in their models or in their discussions during their interviews, and Caleb was the only focal student to correctly incorporate and explain the role of the generator in the process of producing electricity during the water wheel interviews. The other focal students indicated that electricity emerged directly from the water wheel.

During the windmill interviews, Esther suggested that energy was changed to electricity and indicated that a spinning generator was important for the process, but did not provide an explanation of how this occurred. Caleb, Nick, and Alyssa, included generators in their models, but demonstrated different levels of understanding regarding the role of the generator. For example, Alyssa was able to explain that the generator needed to spin, but did not include a representation of the electricity that resulted from the spinning generator in her model. Caleb and Nick both included representations of electricity emerging from the generator and were able to explain how the spinning motion of the generator generated electricity. Kiara's struggle to differentiate between the water wheel and windmill models limited her sense-making and she did not identify the generator as a component of her model.

Overall, students were more comfortable with the spinning motion of the wind turbine causing something to change, which turned energy into electricity, however several students continued to struggle to understand the role of the generator in this process. These continued challenges underscore the difficulty of this concept. Consistent with Lui and McKeough (2005), I found evidence that the idea of energy was difficult for these 4th grade students to engage with, because it is invisible and can only be measured when it is transferred.

Despite these challenges, students did demonstrate development in their understandings about energy transfer. All focal students referenced either the process – or the effects of – energy in the wind being transferred to the windmill. For example, Alyssa described how energy is transferred from the spinning windmill to the spinning generator and Kiara described how a fan blowing at high speed makes the windmill spin. These two examples illustrate different points on a continuum of sense-making regarding energy transfer in the windmill system. In addition, only Nick and Esther referenced energy in the wind during their interviews. As stated above, the invisible nature of both wind and energy could account for students' difficulty in understanding that energy was present in the wind and is transferred to the windmill. While these ideas alone do not satisfy a complete explanation for energy transfer, they are productive resources and fragments that students could eventually draw upon to develop a coherent understanding of energy transfer (Clark & Linn, 2013; Hammer et al., 2012).

Students' *Flipbook* models also reflected different levels of abstraction in relation to the target phenomenon of harnessing the energy of wind to produce electricity. Some focal students, such as Kiara and Alyssa, created models that reflected their designs and did not include any additional components. In Kiara's case, she created a model of the water wheel, but shared how she would revise the model to reflect the windmill design in her interview. Caleb and Nick's models incorporated some specific components from their windmill designs, but also included components that referenced the target phenomenon. Caleb's interview suggested that he was thinking about ways to revise his model to reflect the target phenomenon (i.e., the inclusion of a generator and representations of electricity). Esther's model and her explanation did not reference her specific design, but instead referenced the target phenomenon. Despite missing components, such as a generator, Esther's explanation and the question that she felt her model (How does electricity get to somewhere else?) suggest that she was using her model to explain her understanding of how energy from the wind can be harnessed to produce electricity, as opposed to only explaining her windmill design. These examples illustrate different levels of students' understanding regarding how models can be informed by data and experience to explain a larger, more abstract phenomenon.

During students' interviews regarding their windmill models, there were still instances of students interchanging "energy" and "electricity." However, there was also evidence that some students who interchanged these terms during the water wheel interview were beginning to make distinctions between these terms. For example, Kiara shifted from saying "making energy" during the water wheel interview to "making electricity" during her windmill interview.

Endpoints

A retrospective analysis of the unit, informed by the minicycles, can be used to inform revisions to the next iteration of the curriculum, as well as the development and refinement of domain-specific theories of learning and instruction (Cobb, Confrey, et al., 2003). In order to inform the retrospective analysis, it is important to document the endpoints for students in this unit. After they completed the Unit 2 post-assessments, focal students participated in interviews regarding their assessments. These interviews provided insight into students' endpoints in the unit. These interviews also included a novel task, in which students were asked to apply the concept of energy transfer to a novel context. Recall that the novel task for Unit 2 was comprised of a video showing billiard balls colliding with each other and a model drawn by an anonymous student that was meant to explain this phenomenon. Focal students were asked to explain why the billiard balls moved in the video and to evaluate the student model (see Chapter 3, page 57-58 for more details).

First, I will report findings from focal students' Unit 2 post-assessment interviews and a characterization of individual students' sense-making across Unit 2. Then, I will compare across student cases to identify themes in student sense-making in order to provide an analysis of the ways in which students were supported or limited in their sense-making with models in Unit 2.

Samuel. In Samuel's post-Unit 2 model, he identified air as a renewable energy source and drew a windmill to explain how the renewable energy source could be used to generate electricity (Figure V.20).

S(amuel) So, the air is going through the windmill. And electricity is coming out of the windmill, and it's going to the house.

MM Okay. And so, what is your model explaining?

S That air can--that air can make electricity too.

Samuel included air, an invisible component in the system, in his model. His explanation that electricity is coming out of the windmill could suggest that Samuel did not understand the role of the generator in the process of generating electricity or Samuel was recalling the animated model students observed in which the generator is located inside the wind turbine and electricity is generated inside the windmill. Samuel elaborated on his ideas related to air making electricity later in the interview when I asked him to share what he had learned that helped him to answer the unit driving question, *Where does the energy to light my house come from?*

S I learned that wind, windmills can, can use air and go to houses to make electricity.

MM Okay. Does the air itself make the electricity?

S No. Air is to--air to the windmill.

MM Okay.

S And then, it makes electricity.

MM Okay.

S And going to the house.

Samuel's elaboration on the answer that he gave in explaining his model suggests that he understood that the windmill uses the wind to make electricity, but he did not mention the role of the generator suggesting that he may not understand its role in the process of generating electricity from wind. This explanation is similar to when he discussed the emergence of electricity from the water wheel in the water wheel model, as he made no reference to the generator or the concept of energy transfer in either explanation and identified electricity as emerging from both the water wheel and the windmill. In addition, his focus on the windmill during his discussion of how he could answer the driving question, as opposed to the water wheel, may have been the result of a recency effect, given that the windmill was the last phenomenon in the unit with which students engaged.

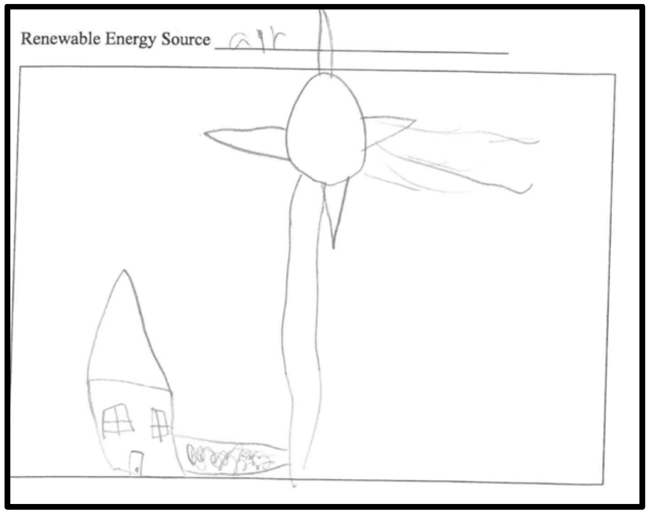


Figure V.20. Samuel's Unit 2 post-assessment model explaining how a source of renewable energy can be used to power a home.

Samuel's responses to the billiard ball novel task provided further evidence that Samuel may not have developed an understanding of energy transfer. When I asked him to use what he knew about energy to describe why the ball rolled into the hole, Samuel responded, "Because the person has--because the person, when he's using the pool stick, and he's pushing the ball to the other ball, which is making it go forward" (Samuel Unit 2 Interview #5). Samuel's response accurately identified the path of the energy transfer from the pool stick to ball #1, then to ball #2. He also referenced how the pool stick pushed ball #1, which then made ball #2 move; however, he was unable to apply the term energy to his explanation. When I asked again if he could use energy to talk about what he was seeing, he answered, "I don't know."

Samuel's Unit 2 post-assessment interview suggests that his understanding regarding the role of air in contributing to the process of generating electricity was the same as his understanding regarding the role of moving water in contributing to the process of generating electricity. In addition, Samuel did not appear to have developed an understanding regarding the role of the generator or the role of energy transfer in producing electricity. In his explanation on the pre-assessment, Samuel was able to identify that solar panels absorb sunlight and use that to generate electricity. This was the same level of detail that Samuel was able to give regarding the role of wind on the post-unit assessment. In addition, in his water wheel model and associated interview, Samuel described electricity as originating inside the water wheel, as opposed to in the generator. This description was similar to the one he gave about the windmill. These similarities suggest that Samuel may have continued to hold the misconception that the spinning wheel generated electricity, as opposed to transferring its energy to a generator and causing it to spin to produce electricity.

Nick. Nick's interview revealed the continued development of his emergent understanding of energy transfer that he had begun to demonstrate during his windmill interview (Figure V.21). He drew a model of a windmill on his Unit 2 post-assessment and described, "so the wind is hitting the turbine and the turbine is spinning and it's creating, well transferring energy… The mechanisms inside are moving around and transferring it through and making it usable." Nick's response suggested that he had an emergent understanding of the process of energy transfer from the wind to the turbine and that a process occurs to "make it useable." In addition, he referenced the animated model that students observed showing how the inner workings of the wind turbine amplified the mechanical energy so that the generator could spin fast enough to generate electricity when he explained, "the mechanisms inside are moving around and transferring it through and making it useable." This suggests that the use of the animated model supported Nick's sense-making regarding the process of electricity generation.

When I asked him what he would call “useable energy,” he correctly identified it as electricity. Nick’s classification of electricity as “useable energy” was a new idea that he had not previously shared. Nick’s written explanation of his model also provided evidence that he had developed a greater understanding of the process of energy transfer within the windmill system. He wrote, “the wind is flowing into the windmill and the blades are spinning the generator to produce electricity.” Nick’s verbal and written explanations suggested that he understood that energy from the wind is transferred to the windmill and then transferred to the spinning generator.

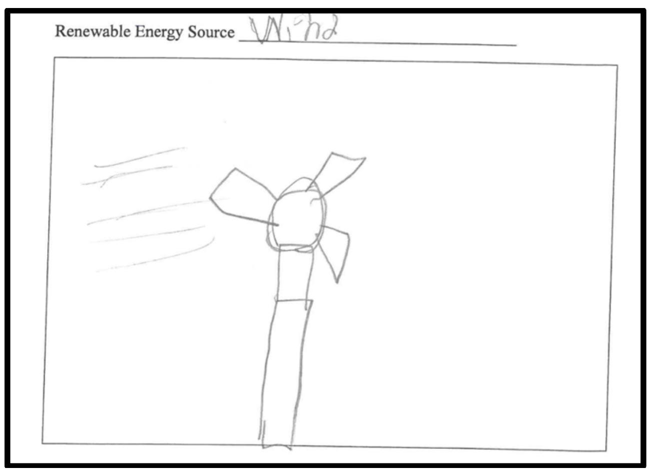


Figure V.21. Nick’s Unit 2 post-assessment model explaining how a source of renewable energy can be used to power a home.

There was further evidence that Nick’s understanding of energy transfer from wind was developing when I asked him where the energy started. He answered that the energy started in the windmill and then goes to “The turbine, no wait it turns into electricity.” Nick’s responses in both the interview about his windmill model and his Unit 2 post-assessment suggest that he had an emergent understanding of certain ideas regarding energy transfer from wind, including that there is energy in the wind, the spinning turbine is transferring energy to generate electricity, and that a generator is a necessary component where the electricity is generated. These knowledge fragments are necessary for developing a coherent explanation for the process of energy transfer.

Nick also referenced ideas related to energy during the interviews about the windmill and post-Unit 2 assessment that he did not reference during the water wheel interview. This shift suggests that Nick was considering the role of energy more in the windmill model than in the water wheel model. However, Nick was still struggling to make sense of the path of the energy from the wind through the wind turbine system.

Despite demonstrating an understanding of the way in which windmills are used to produce electricity through his written and verbal explanations, Nick's model does not contain many of the components he discussed. His model did include a representation of the wind, but did not include representations of the internal components that he referred to in his explanation. One explanation could be that Nick did not know how to represent these features or did not consider them necessary to model because they are not observable when looking at a wind turbine. This also suggests that Nick may not have understood the role of models in providing a causal explanation of a mechanism or process.

Nick further demonstrated his emergent understanding of energy transfer when responding to the Unit 2 novel task.

N(ick) Well he's pushing the white ball with the pool stick and he's hitting the different colored balls with the force of energy with the ball hitting the other balls into the hole.

MM Okay, you already brought up energy, so can you tell me why those balls move, using what you know about energy?

N Well because when he hits the balls, the ball starts moving and the force of the ball crashes into the ball and the ball starts moving and energy is transferred from that ball that was hit by the pool stick to the ball that the ball hit.

Nick’s explanation suggested that he understood that energy is transferred when the moving pool ball hits the stationary pool ball. Interestingly, he did not identify a transfer of energy occurring between the pool stick and the first pool ball. Nick’s responses on the novel task suggest that he has an emergent understanding of the concept of energy transfer and he was able to apply his understanding to the context of the novel task.

Caleb. Caleb’s Unit 2 post-assessment model demonstrated what he understood about the process of harnessing solar energy to generate electricity (Figure V.22). He explained that his model showed “the heat waves going to the solar panel and the solar panel is making electricity” (Caleb Unit 2 Interview #5). Students did not engage with solar panels during this unit, but may have already been familiar with this source of renewable energy due the fact that solar energy is one of the most readily available sources of renewable energy for use on a smaller scale. In addition, the class was preparing to construct solar ovens as an activity outside of the science curriculum, which led to the discussion of solar panels and their use and could have influenced students’ choices on the pre- and post-assessments. His selection of solar power as the topic for his model made it difficult for him to share his understanding of energy transfer, as the class did not discuss the mechanisms through which solar energy is harnessed to generate electricity. However, he did describe the sun’s energy as “heat waves going to the solar panel” suggesting that he understood that heat travels in waves and is involved in the process of generating electricity. This interpretation is further supported by Caleb’s written explanation, in which he wrote that, “the sun is shining and the solar panel is turning the ray of sunshine into electricity.” Caleb also included a representation of the heat waves traveling in his model, suggesting that he was thinking about ways to communicate the movement of an invisible component of the model.

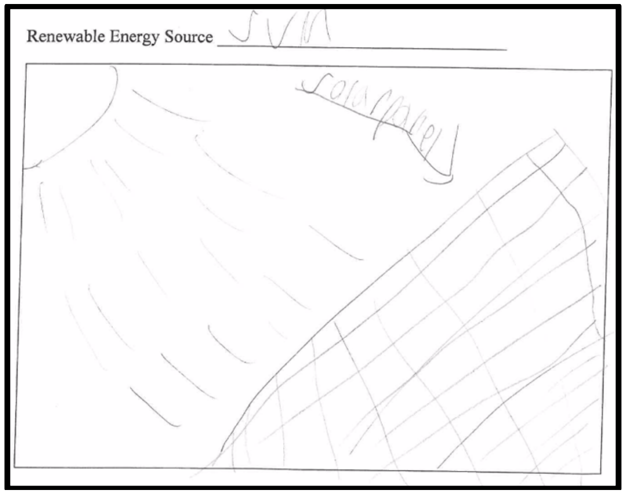


Figure V.22. Caleb’s Unit 2 post-assessment model explaining how a source of renewable energy can be used to power a home.

Caleb demonstrated how the use and construction of models supported his sense-making about the driving question when he was asked to share what he had learned that could help him answer the driving question. He stated, “like, when we made those ocean turbine things and how we showed that the ocean can help light up people’s houses. Or like when we did the water wheel one. That, like, the water wheel spins and it's, like, the water wheel speed, like the crank generator, is making electricity” (Caleb Unit 2 Interview #5). Caleb referenced three different models that students used or constructed during the unit – the water wheel, students’ drawn models of ways to harness the energy of waves to spin a turbine and produce electricity, and the hand crank generator. In addition, he shared how the function of the water wheel was similar to the crank generator and that both could be used to explain how the water wheel “is making electricity.” Caleb’s responses suggest that the use and construction of models supported his sense-making regarding how energy from renewable sources could be harnessed to generate electricity.

During his Unit 2 post-assessment interview, Caleb did not reference the ideas of energy or energy transfer when discussing his model or what he had learned in the unit. The limitations of his understanding regarding energy transfer were revealed during his completion of the novel task. When asked how he could use the idea of energy to explain why the pool balls move, he drew on his previous experiences again and referenced what he observed in the video and the steel ball investigation that students conducted during Unit 1. He explained, “Like with the little launcher thing with the tiny ball and the cup. When the tiny ball went fast enough and made it move.” Caleb’s response references the role that speed played in the collision. However, he was not able to use the word “energy” in his explanations of the video, even after explicit prompting. Caleb’s observation about speed is an example of an idea that was developed during the context of the steel ball investigation that could eventually be applied to an explanation regarding the transfer of energy between two objects.

Caleb’s interviews and models suggest that the use and construction of models supported his sense-making regarding the ways in which electricity can be generated from renewable energy sources. He also included invisible components in his Unit 2 pre- and post-assessment models, suggesting that between Unit 1 and Unit 2, he had developed an understanding for including both visible and invisible representations of components.

Caleb did not demonstrate an understanding about energy transfer in either his windmill or Unit 2 post-assessment models. During his interview regarding his water wheel model, Caleb shared ideas that could serve as a foundation for an understanding of energy transfer, specifically that the turning of the water wheel caused the turning of the generator. He also alluded to these ideas when he discussed what he learned in Unit 2, but his understanding does not appear to have advanced beyond the connection he made between the spinning water wheel and generator, and he did not offer these ideas in reference to his windmill or post-Unit 2 models. Caleb’s numerous references to the experiences during Units 1 and 2 suggest that the use of models was influential in this thinking and sense-making.

Alyssa. Alyssa's Unit 2 post-assessment model and interview revealed her sense-making about energy transfer during the unit (Figure V.23).

A So there's like a windmill like we did in science and so I drew some wind, well actually I drew something to represent what makes wind and I have it connected to a battery that is connected to a light bulb that is lighting it out.

MM Okay, so what does the battery do?

A It has the power to light up the lightbulb.

MM And where does it get its power from?

A From the wind.

MM Okay so what is your model explaining?

A How moving energy can light up a light bulb?

MM Okay so where is the moving energy?

A Going from the windmill going through the cord to the battery and then to the light bulb to light it up.

Alyssa's explanation of her model suggested that she drew on her experiences with the windmill model to draw this model and revealed that she understood that models could include representations of phenomena. She began her explanation of her model by identifying the wind, but then changed her response to specify that she included something that makes wind. It is not clear if she was referring to the windmill in her model as something that makes wind (e.g., a fan) or if the wind in her model represented something that could make wind. Prior to constructing their windmill models, the class discussed how components in models could serve as representations for elements of the target phenomenon (see pages 179-181 for the excerpt from class discussion). Alyssa could have been drawing on this discussion when considering the wind as a representation of another object. The language that she used was very similar to the language I used when discussing this idea with the class, suggesting that she may have drawn from that experience. Another possible explanation is that she was thinking of the fan that was used to create wind when students tested their windmill models and considered the windmill to be the fan.

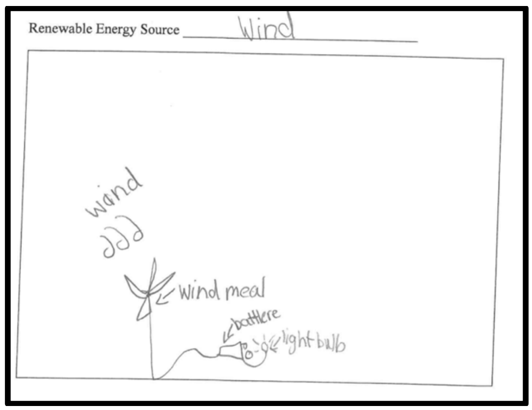


Figure V.23. Alyssa's Unit 2 post-assessment model explaining how a source of renewable energy can be used to power a home.

Despite focusing on the generator in her windmill model and talking about the generator during the windmill interview, Alyssa included a battery in her Unit 2 post-assessment model. Alyssa accurately identified that the battery is used to power the light bulb and received its power from the wind. She also identified the process of using moving energy to light a light bulb as the phenomenon that her model explains and accurately traced the path of energy from the windmill to the battery to the light bulb. One possibility for why Alyssa included a battery, as opposed to a generator, could be because the question may have prompted her to think about a battery. Alyssa also included a battery in her Unit 2 pre-assessment model, but could not describe how the battery received energy to light the bulb. The Unit 2 post-assessment asked students to draw a model to explain how a source of renewable energy could be used to power a house. Alyssa accurately identified wind as a renewable source of energy and included the correct collection apparatus in her model, but the assessment question may not have prompted her to draw on her windmill model, and instead prompted her knowledge of batteries and the role they play in lighting a bulb.

Alyssa's responses on the Unit 2 post-assessment suggest that she developed an emergent understanding of the concept of energy transfer throughout the unit. At the beginning of the unit in the Unit 2 pre-assessment and water wheel models, Alyssa struggled to identify the path of energy and was unable to describe how energy was involved in the process of lighting the light bulb. At the end of the unit, she was able to identify that energy is present in the windmill in both her windmill and Unit 2 model post-assessment models.

Alyssa further demonstrated her emergent understanding of energy transfer during the novel task. She described the action of the pool balls moving as a force, because "he's pushing the ball and the other balls, they're rolling." When I asked her to use what she knew about energy to explain why the balls roll, she explained, "because he has energy with the stick and the ball and so he pushes it with the force and makes energy." She was also able to demonstrate her understanding regarding the transfer of energy by explanation the path of energy through the objects in the video.

MM Okay, let's walk through it again. So, you said the stick has energy?

A Mmhmm.

MM What happens next?

A When he pushes the other ball and it makes the other ball roll, it makes the energy, it makes it roll together to make the other ball roll.

MM Okay, so does the blue ball have energy?

A Yah because it has to roll. So, when the white ball gives the blue ball energy it rolls.

Alyssa identified that the balls need energy to roll and that the collision of Ball #1 into Ball #2 gives Ball #2 energy. Her explanation also revealed the limitations of her understanding. Instead of describing a transfer of energy, she described the pool stick hitting Ball #1 and the collision of the two balls as “making energy.” Despite using the term “making energy” for much of her explanation, Alyssa did identify that the model corresponding to the video needed to show “how the energy is being transferred” and suggested that the modeler could use arrows to show this. This suggestion revealed that Alyssa was thinking about energy transfer during the novel task and had developed resources that could be used in an explanation of energy transfer. Alyssa’s responses also demonstrate how students’ knowledge can be fragmented before it has been integrated into a coherent understanding (Clark & Linn, 2013). Throughout the interviews during Unit 2, she struggled with the terminology of energy transfer, but did demonstrate her developing understanding of the concept.

Esther. Esther’s Unit 2 post-assessment model included the same renewable energy source that her Unit 2 pre-assessment model showed (Figure V.24). Her explanation of her Unit 2 post-assessment model was also very similar to her explanation of her Unit 2 pre-assessment model. For her Unit 2 post-assessment model, she explained, “this is absorbing the energy and sunlight from the sun and then it goes through this wire and goes to the house.” In both her Unit 2 pre- and post-assessment interviews, Esther referenced energy from the sun as a renewable energy source. Similar to Caleb, this may have been because the class was preparing to build solar ovens and were discussing solar energy.

Esther’s Unit 2 post-assessment model included more components than her pre-assessment model. She included a wire leading from the solar panel and a house with lines around it to show that it was illuminated in her post-assessment model. These additional features suggest that the presence of electricity and representations of how the electricity got from the solar panel to the house were more prominent in her thinking after Unit 2 was completed than before it began. In her verbal explanation of her post-assessment model, she mentioned that the energy went to the house, but did not specify how it got there.

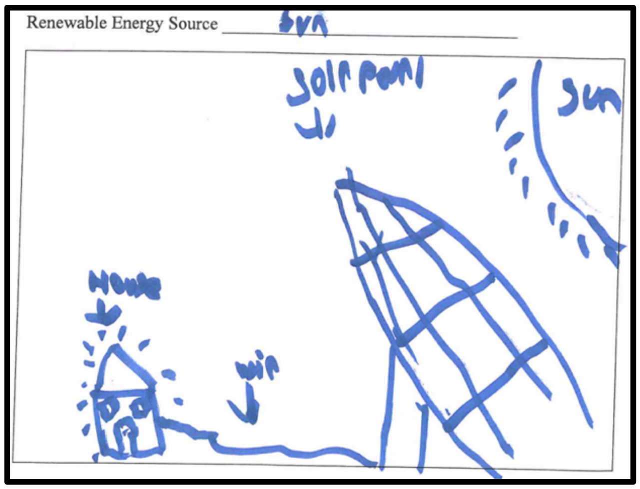


Figure V.24. Esther's Unit 2 post-assessment model explaining how a source of renewable energy can be used to power a home.

Esther demonstrated her understanding of energy transfer during the novel task. When I initially asked her how energy was involved in the moving of the billiard balls, she said, "Because it has energy. The ball. Because it's round." These responses did not provide much insight into her thinking; however, when I asked her to lead me through each step of the process she observed in the video, she was able to identify instances of energy transfer.

MM Can you explain to me which ball has energy?

Esther The white one.

MM How did the white ball get energy?

Esther From the person hitting it from the stick. And the energy from the person goes to the stick and when the stick hits the ball the energy from the ball goes to the ball that it hits.

MM And what happens to the ball that it hits?

Esther It falls into the hole.

Esther's explanation suggests that she understood that the energy originated with the person holding the pool cue. She was the only focal student that made this connection. She also referenced energy traveling from one object to another, suggesting that she understood that, in the moment of impact, energy transferred from one object to another. Despite demonstrating a basic understanding of the concept of energy transfer in the context of the novel task, this understanding was not evident during Esther's windmill model interview. During that interview, she said that the windmill "carries the energy that turns into electricity" as opposed to transferring energy from the wind to the generator. This difference suggests that Esther may not have been able to apply her understanding of energy transfer to the context of the windmill model.

Esther's models throughout the unit became more precise and included more components. In both the Unit 2 pre-assessment and water wheel interviews, Esther repeatedly referenced "transferring energy to a house" when discussing how the house would light up, but she did not include a house as a component in her pre-assessment model. She was more specific in her windmill and post-assessment interviews regarding how electricity traveled through wires. In both models, she included a wire and made reference to it in her explanations of her models. She also included representations of electricity in both her water wheel and windmill drawn models, but not her pre- or post-assessment models. One explanation for this difference was that students were reminded to include representations of important components, such as electricity, during instruction and were using *Flipbook* where they had access to color and other artistic elements. On the assessments, students were constructing models on a different medium than during instruction and this may not have prompted the same considerations as during instruction. These changes in Esther's models across the unit reflect changes in sense-making about the important components of the system she was modeling and ways to show relationships between the components in the system (i.e., water wheel system or windmill system).

Kiara. Kiara's Unit 2 post-assessment model and interview revealed that her sense-making regarding the sources of renewable energy had developed and she had an emergent understanding about the role generators play in producing electricity. However, she did not develop an understanding of energy transfer or that energy is present in sources of renewable energy (Figure V.25). When explaining her model, Kiara noted, “Well, the wind turbines are turning and it’s making electricity and the power cord is connected from the wind turbines to the house and its making electricity” (Kiara Unit 2 Interview #5). Kiara’s explanation accurately identified that the spinning motion of wind turbines was involved in generating electricity. She also said that the wind caused the wind turbines to turn when I asked what caused the turbines to turn. However, Kiara did not include anything related to energy or a generator in her explanation or her model. Despite this, Kiara demonstrated increased understanding regarding the process of using wind to produce electricity from her windmill model interview.

Kiara revealed her emergent understanding regarding how a generator works when she discussed what she had learned during the unit to help her answer the driving question. Initially, Kiara stated she did not know how she could answer the DQ, but recalled her experience with the crank generator and her understanding of what caused the light bulb to light. “When you spin it fast, it makes light…Because of the magnets. And the crank” (Kiara Unit 2 Interview #5). Kiara recalled the magnets as an important aspect of the crank generator, but when I asked what the magnets did, she was not able to describe that they spun and contributed to the process of generating electricity. Kiara’s answer also suggests that her understanding of the generator may have been specific to the context of the crank generator.

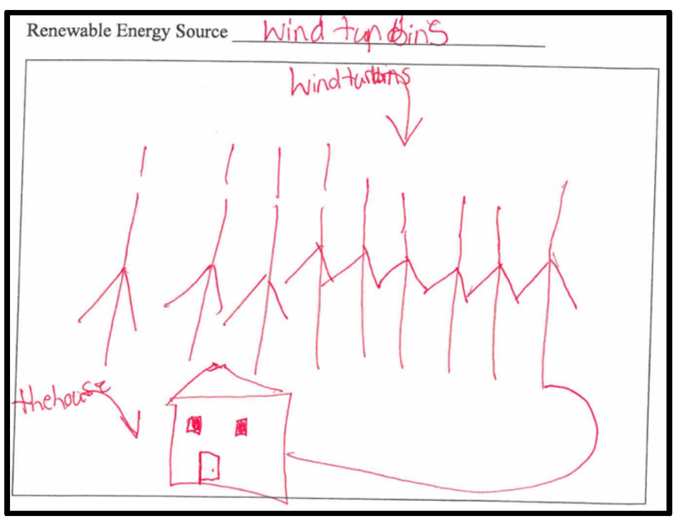


Figure V.25. Kiara’s Unit 2 post-assessment model explaining how a source of renewable energy can be used to power a home.

Kiara struggled to explain apply the concept of energy transfer in the novel task. When asked how energy was involved in the movement of the pool balls, she initially stated, “I don’t know,” but changed her answer to, “Like, it’s rolling?” When I asked her if the ball had energy when it was rolling, she replied “yes.” During her water wheel model interview, she did comment that the movement of the water wheel indicated that it had energy – suggesting that she began developed this understanding early in the unit, but it had not developed further as the unit progressed. Her incorporation of the crank generator in both her water wheel model and her post-Unit 2 interview suggest that the crank generator model supported her sense-making about the components of a generator, specifically the magnets. She did not draw upon her experiences with other models, suggesting that her sense-making was not supported by these interactions.

Kiara demonstrated a developing understanding regarding sources of energy and the idea that moving objects have energy. These ideas align with the literature on the development of students’ understanding of energy and serve as foundational ideas upon which students can develop an understanding of energy transfer (Hammer et al., 2012; Liu & McKeough, 2005; Neumann et al., 2013).

Macrocycle Analysis

The analyses of students’ interviews across the entire unit provide insight into different trajectories of sense-making regarding the concept of energy transfer and the construction of models to explain the process of energy transfer. A comparison of the two minicycles revealed that more whole class discussions regarding the ideas related to energy transfer occurred during Minicycle #1 as compared to Minicycle #2. One reason for this was that Minicycle #1 was longer than Minicycle #2, and therefore provided more opportunities for whole class discussions. Despite a greater number of whole class discussions in Minicycle #1, there were no sustained conversations about energy transfer during either minicycle. This can also be observed in the Unit 2 sense-making chart, which only included one idea on Day 18 of the unit enactment related to the concept of energy transfer (Figure V.1). The lack of opportunities for the class to introduce and build on each other’s ideas related to energy transfer may have limited the development of students’ sense-making regarding this concept. These comparisons suggest that more prompts for whole class discussions should be integrated into the curriculum to support teachers to initiate conversation regarding the concept of energy transfer as it relates to the modeling tasks in which students are engaged. In addition, providing opportunities for teachers to develop their content knowledge regarding the concept of energy transfer during professional development could allow them to better support students' sense-making about energy transfer through class discussion and the use of models, as many elementary school teachers hold inaccurate ideas of energy (Trumper, 1997).

Five of six focal students identified that energy was present in the renewable source of energy that they chose to model during the post-unit assessment. For example, Alyssa, Nick, and Samuel drew models of windmills and identified that the wind provided energy for the spinning windmill, while Esther and Caleb drew solar panels and identified the sun as providing energy to the solar panels. Kiara was the only focal student who did not include a representation of the energy source or provide insight into where the energy came from in her post-unit model of a windmill. These five students also included representations of wind or solar energy in their models, suggesting that they had developed ways of including invisible components and felt they were important to include in their models. This finding suggests that the computer-animated models supported several students to develop their own representations of components. The development of students' understanding of the use of invisible components can be observed across the two minicycles and in a comparison of the pre- and post-unit models. Specifically, focal students included invisible components that had visible effects (e.g., wind and electricity). The visible effects of wind on the turning turbine and electricity in lighting a bulb may have prompted students to include them in their models. The inclusion of these invisible components was more common on the water wheel and windmill models and less common on the pre- and post-assessment models, suggesting that students may have been supported through the prompts regarding using their models to answer questions provided by Ms. White and myself prompts and the sharing of students' models with the class. Another explanation is that the question on the pre- and post-assessment may have not prompted students to draw a model that was used to explain the process of energy transfer or electricity generation. The question specified that the students explain how a form of renewable energy could be used to light their home, which may have prompted students to think about the observable components that are necessary for lighting a house, as opposed to the underlying mechanism of energy transfer.

Students also demonstrated a range of understandings regarding energy transfer in the novel task during the post-assessment interview. For example, Nick demonstrated the most complete understanding of energy transfer of all the focal students. Esther was able to describe, in detail, the path of energy to explain why the pool balls move, but unlike Nick did not use the vocabulary of energy transfer. Caleb was not able to use apply the word “energy” in the novel task and, instead, drew comparisons between what he observed in the video and a previous investigation students had conducted using rubber bands to launch steel balls and observed the effects of their collisions with a container as an introduction to energy transfer. Caleb’s comparison suggests that he saw similarities between the two contexts, but was not able to apply the concepts he used to analyze his data from the investigation to the novel context of the billiard ball task. Finally, Kiara indicated that the motion of the ball was related to the idea of energy but could not elaborate.

The range of understanding regarding energy transfer and renewable energy sources demonstrated by the focal students suggest that prior knowledge may have been one factor that influenced students’ sense-making. Both Nick and Kiara were considered to have low prior knowledge regarding renewable energy in relation to their peers. However, their trajectories of sense-making throughout the unit were very different. In addition, while they both were considered to have low prior knowledge, their responses on the pre-assessment were very different and suggest that Nick was considering sources of energy, while Kiara was not. In addition, the remaining focal students that were considered to have either typical or high prior knowledge with respect to their peers did not demonstrate more sense-making than Nick with respect to energy transfer and renewable energy sources, and in some cases, demonstrated less sophisticated sense-making as compared to Nick. These data suggest that there may be a threshold of prior knowledge that influences students’ ability to engage in sense-making regarding renewable energy through the construction of models. Nick’s prior knowledge was low, but was still related to the topic of energy sources, which allowed him to engage with the ideas of the unit. Kiara's prior knowledge was not related to the topic of energy sources and her lack of prior knowledge may have limited her ability to make sense of the concepts related to renewable energy and energy transfer.

Students continued to experience challenges in understanding the role and function of the generator. Despite the emphasis placed on the generator during Minicycle #2, not all focal students included generators in their *Flipbook* models at the end of Minicycle #2. Three students included generators and two students did not (Samuel did not construct a windmill model). In addition, on the Unit 2 post-assessments, no focal student included a generator in their model. This could have been due to the prompt, but also suggests that students still did not consider the generator to be a necessary component in an explanation of generating electricity. Another possibility is that concept of energy transfer, as it relates to the role of a generator in electricity production, may have been too challenging for 4th grade students (Lui & McKeough, 2005).

The use of the thread spool to represent the generator in the physical windmill model was designed to support students to understand the centrality of the generator to the process of generating electricity and to understand the energy transfer necessary to make the generator spin. While some students did include generators in their models or discussed generators during the interviews regarding their models, this was not true for all students. The thread spool did not share any resemblance with a generator that students had observed and instead served as an analog to the generator. The abstractness of this representation may have limited students' abilities to make connections between the process of spinning the generator and spinning the thread spool. Providing additional supports in the curriculum that teachers could draw upon to help students identify similarities between the processes of the thread spool and the generator, as opposed to literal similarities, could support students to incorporate the role of the generator in their models and explanations.

The students in Ms. White's class demonstrated similar difficulties with the use of the term, *energy*, as has been documented in the literature (Driver et al., 1994). During whole-class discussions and student interviews, students referred to *making energy* as opposed to *transferring energy*, and *force* to describe the collision of one object into another. The teacher and researchers made some attempts to correct students' language, however there were times when both the teachers and researchers also used incorrect terms when talking about energy. The concept of energy is extremely complex and numerous uses of energy in everyday language further complicates the development of students' understandings regarding scientific uses of the term energy. Professional development could support teachers to continue to develop their understandings regarding scientific uses of the term, *energy*, and better prepare them to respond when students use the term in colloquial ways (Hammer et al., 2012).

The use of *Collabrify Flipbook* supported students to demonstrate their sense-making regarding the harnessing of energy from water or wind to generate electricity. In both models, multiple focal students used animation in their models to show the process of water or wind moving and the resulting movement of either the water wheel or windmill. The use of *Flipbook* also provided opportunities for students to create their own representations of the process, including ways to show electricity that others would understand and the incorporation of invisible components (e.g., wind). These features supported students' sense-making regarding both conceptual ideas related to energy transfer and epistemological ideas related to the practice of scientific modeling.

CHAPTER VI

Unit Three: Modeling Sound

The third, and final, unit of science for the year in Ms. White's class was framed by the driving question, *How can we design and use technology tools to improve communication and help others?* During this unit, students engaged in the development of a tool to improve communication using sight or hearing. In order to support their engagement in the engineering process, this unit introduced students to concepts regarding the nature of light and sound energy, light and sound waves, and different forms of human and non-human communications.

I continued my role as a participant-observer during this science unit. Ms. White conducted more of the whole-class instruction than she did during Unit 2, but I continued to provide additional prompts and discussion questions to support students' sense-making during whole-class instruction. Due to the large number of students in Ms. White's class for science, I also worked with smaller groups in the class to conduct investigations or other activities to ease the logistics.

Students spent 27 instructional days and 18.51 hours engaging with ideas related to the transfer of energy from sound and 15 instructional days and 14.05 hours engaging with the ideas related to the transfer of energy from light. Given that the class spent the majority of their time during the unit exploring ideas related to sound, the findings reported in this chapter will only draw on modeling opportunities related to the transfer of energy from sound.

Hypothesized Starting Points and Learning Trajectory Related to Sound

Research on children's understandings of light is more plentiful than children's understandings of sound (Boyes & Stanisstreet, 1991; Eshach & Schwartz, 2006). In their study of children's conceptions of light and sound, Boyes and Stanisstreet (1991) found that 40% of children ages 11 and 12 demonstrated a canonical understanding of the path of sound from the source to the receiver (i.e., sound traveled from the source to the receiver). One possible reason that children may hold a more canonical understanding related to sound is because they can act as sources of sound, but not as a source of light (Boyes & Stanisstreet, 1991). Eshach and Schwartz (2006) interviewed eighth-grade students (no median age provided) and found that several students represented sound as crescent-shaped lines emanating to the object. While this study involved participants that were several years older than the participants in the current study, these findings point to misconceptions and representations that may also be relevant to younger students.

This unit was comprised of five sections, called learning sets, that were structured in an iterative fashion. The development of the unit was guided by the *NGSS* performance expectations in Table VI.1. Given the emphasis on energy as a common thread through all the 4th grade units, this unit focused on the ways in which sound and light can transfer energy from place to place (see 4-PS3-2). In Units 1 and 2, students explored the presence of kinetic energy and the effects of energy transfer from one moving object or entity (i.e., wind or water) to another object. This unit sought to support students to understand that energy is present in sound, light, and heat.

Table VI.1
Performance expectations guiding the development of Unit 3

4-PS3-2 Make observations to provide evidence that energy can be transferred from place to place by sound, light, heat, and electric currents.
4-LS1-1 Construct an argument that plants and animals have internal and external structures that function to support survival, growth, behavior, and reproduction.
4-LS1-2 Use a model to describe that animals receive different types of information through their senses, process the information in their brain, and respond to the information in different ways.

In the first two learning sets, students learned about the ways in which humans and non-human animals use energy from sound to communicate and survive. The lessons were designed to introduce students to the relationship between sound and volume, the idea that sound travels through the air, and that the transfer of sound involves a transfer of energy. These ideas were embedded in first-hand and modeling experiences designed to provide opportunities for students to engage with the phenomenon of sound and then grapple with ways to represent their observations and their thinking through the construction of models.

Even though the data informing the findings shared during this chapter are drawn entirely from Learning Sets 1 and 2, I will share the design of the remaining learning sets in order to provide a more comprehensive overview of the design of the unit. In Learning Sets 3 and 4, students learned about the ways in which humans and non-human animals use energy from light to communicate and survive. In the final learning set, students applied their knowledge to develop a proposal for a technology tool that could use energy from light or sound to improve either human or non-human communication (Table VI.2). The iterative design of the unit provided opportunities for students to engage in sense-making about energy from sound and light in the context of human communication and then extend their sense-making to communication that is unique to non-human animals (i.e., echolocation and bioluminescence).

Table VI.2
The driving questions that framed the inquiry for each learning set in Unit 3

Learning Set 1: How do we communicate with each other using sound in order to survive?
Learning Set 2: Why is sound important for animal survival?
Learning Set 3: How do we communicate with each other using light?
Learning Set 4: Why is light important for animal survival?
Learning Set 5: How can we use light or sound to help others communicate better?

Learning Sets 1 and 2 provided several opportunities for students to construct and use models to engage with the phenomena of sound. Students continued to construct drawn models with the purpose of explaining phenomena they had explored through investigations. However, unlike previous units, the use of data in informing these models was more heavily emphasized in the curriculum for this unit. Students constructed drawn models in *Flipbook* and on paper.

The class also constructed *class consensus models* for the first time during this unit. The construction of consensus models was included to provide opportunities for the class to share their thinking and come to consensus about the phenomenon they were modeling. Using models to reach consensus regarding the mechanism of a phenomenon is also an important aspect of sense-making with models (Schwarz et al., 2009). Baek and Schwarz (2015) shared the case of a 6th grade student whose epistemologies related to modeling (EIM), specifically related the use of empirical evidence in informing model construction, were influenced during the construction of consensus models. In addition, Schwarz and colleagues (2009) reported on the successful use of consensus models with 5th grade students. Therefore, the inclusion of consensus models in the curriculum for the current study was designed to support students' sense-making regarding concepts related to sound and epistemological aspects of constructing and using models.

Similar to the previous units, students engaged in modeling lesson after a lesson in which they engaged in a first-hand investigation or experience with the phenomenon that they would be modeling. However, unlike previous units, the modeling lessons in this unit explicitly identified the steps in the modeling cycle. Recall that the modeling cycle includes four steps: planning, constructing, testing, and revising (Louca & Zacharia, 2015). Each modeling lesson included these four components for the creation of students' individual models and the class consensus model (Figure VI.1). The use of these four steps in each modeling experience was designed to support students in developing an understanding of the modeling cycle. At the end of Unit 2, students engaged in all steps of the modeling cycle for the first time when they built physical windmill models; however, these steps were not formally identified or discussed. Based on these observations in Units 1 and 2, and the literature on engaging students in the practice of modeling, the addition of a formal planning step was included in the curriculum for this unit (Baek & Schwarz, 2015; Louca & Zacharia, 2015).

2 **Activity**	Creating Model Explaining Echolocation	1. Tell students that they will use what they have learned about echolocation to draw models that answer the **Question:** "How do animals communicate with echolocation?" 2. **Plan:** Project the class consensus model from Lesson 1.5 and have students *turn and talk* about what would need to be added or changed in this model in order to answer the new question. On a piece of chart paper, record students' ideas about what would need to be added or changed. This list will become the part(s) that need to be included in the new model. ○ Students should identify a source of sound, representation of the sound, representation of the sound bouncing off an object, a receptor of the sound. You may want to encourage students to think about how they will represent the sound bouncing off of an object, as this is very important in echolocation. **3. Build:** Ask students to draw a model in *Collabrify Flipbook* or on the student modeling sheet. **4. Test:** Have students share their models and get feedback using the feedback sheet and the 3Cs from another student. **5. Revise:** Have them revise the models based on the feedback.
3 **Activity**	Class Consensus Model	1. **Planning the Class Model**: Share a few student models to discuss component(s) needed to explain how animals communicate using echolocation as well as sharing different representations for sound and the behavior of sound waves bouncing off of objects. ***Note: At this point no common convention is needed to show how the sound is transferred as long as the model shows it being transferred.*** 2. Put your hand over each component and ask students if this item was removed from the model, would they still be able to use the model to explain what happened to the sound. Identify components that are unique in certain models and repeat the process to eliminate parts of the model that do not add to the explanation. 3. **Building the Class Model:** Ask the class to identify which parts must be in the model to explain how animals communicate using echolocation. Draw the model or have students come up and draw the model on the board as the class describes the components. 4. **Test the Model**: Ask students to describe how they could take the same parts and draw a model that explained how ships use sonar to detect if other ships are near them. Draw the model or have students come up and draw the model on the board as members of the class describe the components. 5. **Revise the Model:** Go through the feedback form briefly as a class and ask if any changes are needed in the model to explain what happened in both investigations.

Figure VI.1. Excerpt of modeling lesson from Unit 3. Each modeling lesson included the four steps of the modeling process and explicitly called out each step in the lesson plans to support the teacher in identifying students' progress through the modeling process for each model.

There were three modeling opportunities incorporated in Learning Sets 1 and 2. The first opportunity, called the *Sound and Distance model*, required students to construct a *Flipbook* model to explain how the volume of a sound changed as the distance from the source to the receiver changed. In the previous lesson, students were supposed to conduct an investigation to determine how the sound changed as they stepped farther away from a sound source. After the investigation, students graphed their data to determine the relationship between perceived volume of the sound and the distance from the source. After students completed this model, they engaged in several activities designed to facilitate class discussion and student thinking about the medium through which sound can travel and the role of energy in sound. Students investigated whether or not sound transfers energy by banging metal pans and spoons and observing how rice resting on plastic wrap stretched over a container was affected by the noise. After making observations of the rice, the curriculum called for the class to draw on their knowledge of energy to construct a consensus model explaining why the rice moved during the investigation. One of the important disciplinary core ideas associated with the *NGSS* performance expectation 4-PS3-2 is that energy is present in the phenomenon of sound (NGSS Lead States, 2013). The rationale for including this model was to support students in identifying that energy is present in sound and that the transfer of sound through a medium, such as air, also involves a transfer of energy. The third model that students created was a paper-and-pencil model explaining how animals use echolocation to communicate. Prior to constructing this model, students engaged with a text about the phenomenon of echolocation and used their own voices to simulate echolocation. The construction of the model explaining echolocation was intended to provide students the opportunity to apply and extend what they had learned about the nature of sound waves and the role of energy in Learning Set 1 to a different context in Learning Set 2. The modeling events that occurred during Unit 3 Learning Sets 1 and 2 are described in Table VI. 3.

Table VI.3
Unit 3 Modeling Events

Day #	Date	Lesson and Activities	Time
5	3.24.17	**Lesson 1.3 How can we explain to others why we hear sounds in some places and not others?** ***Activity 1:*** Students created graph of sound/distance activity from previous day. Teacher introduces lesson on modeling. ***Activity 2:*** Students discuss what should be included in their model, then use Chromebooks to begin modeling.	40 minutes
6	3.28.17	**Lesson 1.3 How can we explain to others why we hear sounds in some places and not others?** ***Activity 3:*** Students share model. Class creates class model then uses it to explain why sound couldn't be heard over longer distances. Class discusses how model could be revised to explain both cases.	45 minutes

12	4.18.17	**Lesson 1.5: How can we communicate using sounds when we are far away from each other?** ***Activity 2:*** Students bang drums and observe the movement of the rice ***Activity 4:*** Students model their investigation	20 minutes
13	4.19.17	**Lesson 1.5: How can we communicate using sounds when we are far away from each other?** ***Activity 4:*** Students explain the class model and discuss how he soundwaves travel from the pan to the rice. **Lesson 1.6: Why are some sounds different from others when we communicate?** ***Activity 1:*** Students listen to familiar sounds and discuss how they know what the sounds mean.	45 minutes
14	4.20.17	**Lesson 1.6: Why are some sounds different from others when we communicate?** ***Activity 2:*** Students complete investigation sheet for musical instrument investigation. ***Activity 3:*** Tuning fork in water demonstration. Teacher reviews concept of wavelength. ***Activity 4:*** Teacher demonstrates virtual oscillator.	40 minutes
24	5.8.17	**Lesson 2.3 How can human and nonhuman animals use their ears to "see"?** ***Activity 2:*** Students complete echolocation reading. ***Activity 3:*** Class watches echolocation videos. **Lesson 2.4 How can we explain to others how animals communicate using sound?** ***Activity 1:*** Teacher introduces modeling activity. ***Activity 2:*** Class constructed a "close" model as a group. Individual students begin work on their "far" models, using modeling sheet.	45 minutes
25	5.9.17	**Lesson 2.4 How can we explain to others how animals communicate using sound?** ***Activity 1:*** Reviewed prior learning and introduced echolocation modeling activity. ***Activity 2:*** Students draw model on modeling sheet to answer the question "how do animals communicate with echolocation?" ***Activity 3:*** Class develops class model. ***Activity 4:*** Students use flash sonar to identify distance and material.	50 minutes

Actual Learning Trajectory

In this section, I will share the sub-case of Ms. White's class as they engaged in the three modeling experiences described above. Figure VI.2 shows a map documenting the conceptual and epistemological sense-making that occurred during the sound portion of the unit. This figure shows the ways in which ideas related to the transfer of sound and epistemologies related to constructing models and communicating ideas through models were introduced and taken up by students throughout the unit.

As an overview, there were 14 sense-making ideas documented during the enactment of Learning Sets 1 and 2. This is slightly more than the 12 ideas documented during Unit 2, but less than the 28 ideas documents during Unit 1. All three units were enacted over approximately 18-19 hours of instruction. An analysis of the ideas in Figure VI.2 reveals that the conceptual ideas introduced and reiterated throughout the unit were related to the behavior of sound waves and the relationship between the size and spacing of sound waves. However, there is only one idea that relates sound to the concept of energy. In addition, ideas related to the choice and design of components necessary for models continued to be discussed.

As compared to the Unit 2 sense-making map, a similar proportion of the ideas came from students or co-constructions involving students (50% in Unit 2 and 57% in Unit 3, respectfully). Most co-constructed ideas in Unit 3 came from researcher-student co-constructions, which had not occurred before this unit. These co-constructions were comprised of ideas that were co-constructed between a student and myself during whole-class discussions. One explanation for this new type of co-construction and only one teacher-student co-constructions is that I continued to lead discussions that were designed to support the students regarding epistemological ideas of model and modeling as well as make connections to the conceptual ideas in the unit regarding energy.

The louder the sound, the farther the sound waves will travel: The sound and distance model. Learning Set 1 of the unit focused on the ways in which humans communicate using sound. The first modeling experience in which students engaged involved using data from their investigation to draw a model explaining how the volume of sound changed over different distances. Students began planning and constructing their sound and distance models in *Flipbook* on Day 5 of instruction. Ms. White began by asking students to look at the top of their data sheet from the investigation to find the question that they would be answering with their models, *How does the distance from the source of sound affect what we hear?* Then, she asked for ideas about the parts that needed to be included in the model. Nick stated that he would include sound waves; Serenity said "a sound source" and receiver. Nick's identification of sound waves was the first time that this term had been documented during science instruction. Ms. White directed students' attention to the key that the class had created when making their graph and told students that they also needed to include a key in their model, and "you have to show what each part means. Sender, receiver, source." However, she did not emphasize the presence of sound waves that Nick had identified to the class.

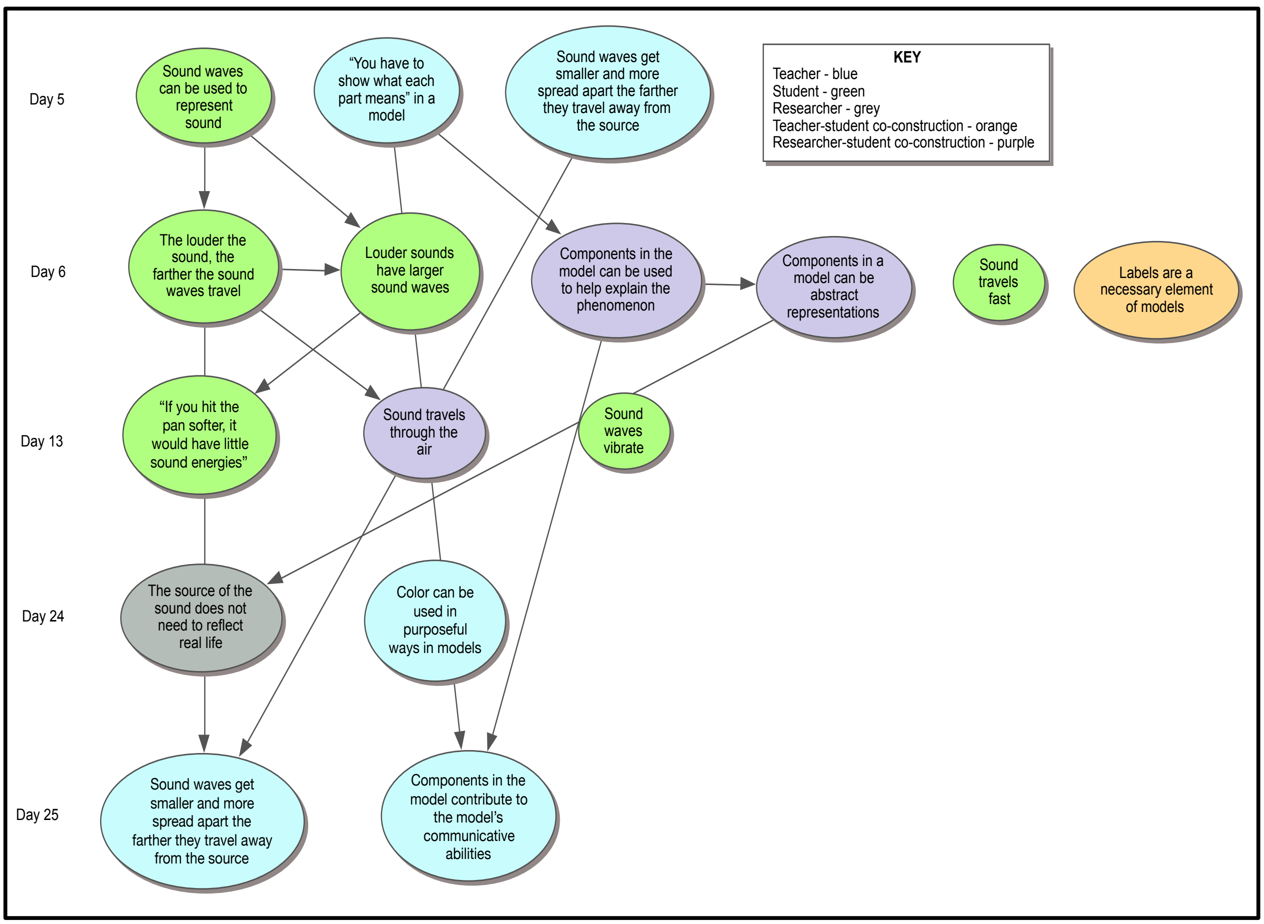


Figure VI.2. Unit 3 sense-making map illustrating the flow of ideas introduced and reiterated during whole-class discussions.

Due to equipment difficulties with the computers which prevented students from continuing to work on their models in *Flipbook*, the class moved to sharing their models and creating a class consensus model on Day 6. Ms. White asked for volunteers who had finished their models during the previous class to share and explain their models to the class. Three students shared their models (Figure VI.3). All three students included a representation of the source, receiver, and sound waves. Ms. White asked students to compare how sound was represented in each of the three models. This question provided an opportunity for the class to discuss different ways of representing the same phenomenon. The class began by discussing Kyle's model (Figure VI.3a).

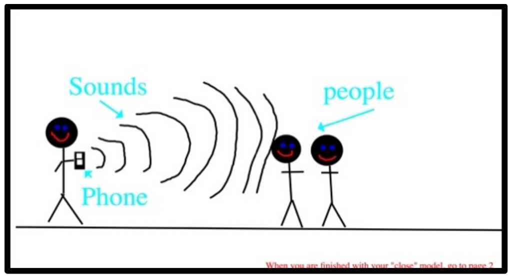
MU The sound is represented because when the phone is turned up, the sound waves gets to the people.

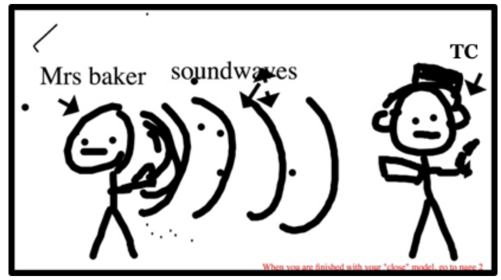
Ms. W Is there a reason, Kyle, why you chose to do it this way with the lines bigger here?

Kyle Because for me I heard it very loud and clear when I was farther away.

The discussion among MU, Kyle, and Ms. White highlighted a misconception that was introduced earlier in the class when students created the graph of their data. Several students claimed that they heard the sound from the speaker more clearly when they were farther away, as opposed to when they were close to the source of the sound. Kyle was one of the students who reported this. Despite showing the incorrect relationship, both MU and Kyle suggested important ideas about the nature of how sound travels. MU suggested that the louder the sound, the farther the sound waves would travel. When Ms. White asked Kyle if her statement matched with his thinking, Kyle provided a different reason for his representation of sound waves – that the sound was louder when he was farther away and this was why the size of his sound waves increased.

Kyle’s response suggested that there might be a relationship between the size of the sound waves and the volume of the sound.

(a) 

(b) 

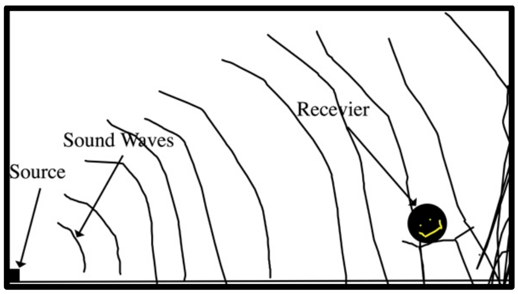
(c) 

Figure VI.3. The models shared by (a) TC, (b) Kyle, and (c) Nick during the whole class discussion of models explaining how the distance from the source of the sound affects the volume.

The discussion regarding how to represent sound waves over a distance and for different volumes continued as the class compared Kyle’s and TC’s models (Figures VI.3a and VI.3b). AR said that they were “kind of the same and kind of different…Because TC only has one person and Kyle didn’t label [MM].” Ms. White asked for additional ideas and GL shared, “the sound waves [in TC’s model] are the same size.” Ms. White revoiced this as, “so the sound waves are the same size in [TC’s] model and in Kyle’s they are gradually getting larger.” TH described physical differences between the two models (the drawings of the phones were different) and then described how the sound waves would change, as volume changed. He explained, “so it would be very big sound waves if the volume was big.” Ms. White revoiced TH’s explanation as, “so you’re saying the sound waves would be bigger the louder the sound and the sound waves could be smaller the more quiet the sound.” TH’s explanation of the relationship between the volume of sound and the size of sound waves was the clearest description shared so far in the class during science. I asked TH to share what kind of volume he thought that TC was showing in his model. TH stated, "they are showing a big sound because there are big waves." TC disagreed and said that the sound was softer. I asked TC what he could add to his model to help TH realize that the sound in the model was soft and Ms. White pressed him to be specific about the change he could make to his model.

TC Make it smaller.

Ms. W Make what smaller?

TC The sound waves

Ms. W Where would you make it smaller?

TC Farther away.

TC correctly identified that the sound waves got smaller the farther away the receiver was from the source. Until this discussion, the class had not formally discussed how to represent sounds waves. Despite this, students appeared comfortable in discussing the transfer of sound from the sender to the receiver by using the concept of sound waves and there was general consensus in the use of a curved line to represent a sound wave. Eshach and Schwartz (2006) found that 8th grade students also used this convention when drawing a diagram of how sound traveled, suggesting that students may have been exposed to this convention prior to engaging in formal study about sound. However, the students in Ms. White's class still held different ideas about the conventions of showing the changes in volume of the sound or how the size of sound waves changed over distance.

Another feature of models that was explicitly discussed was the abstractness of the components of the model. Recall that models are simplified representations that amplify certain aspects of a phenomena in order to provide an explanation the underlying mechanism or process of the phenomenon, develop hypotheses, or test predictions (Gilbert, 2004; Schwarz et al., 2009). In addition, because components of the model must work together to provide a causal explanation for the phenomenon, the components may not necessarily bear physical resemblance to the target phenomenon (Lehrer & Schauble, 2010; Manz, 2012). Lehrer and Schauble (2012) discussed the importance of moving children towards constructing and comprehending syntactic models, or models that bear similarities in function, as opposed to physical resemblance.

This idea of amplifying certain features and how to incorporate components that could be used to explain function instead of physical appearance arose when Nick shared his model with the class and his peers were invited to ask him questions (Figure VI.3c). Kyle asked, “How does the source work? Because I don’t see anyone there?” Ms. White rephrased this by asking Nick to identify the source in his model. Nick responded, “It is a speaker.” In his model, Nick did not include the phone that was used in the investigation. Instead, he included a more generic depiction of a sound source and labeled it, *source*. Kyle’s question prompted me to ask him whether or not he thought it was acceptable to label the speaker the source, as opposed to explicitly stating what the source was. According to the field notes taken during the class, “Some students indicate that they are not sure. Kyle says, maybe.” Based on the non-committal response, I rephrased the question as, “Could we use this model to talk about if Ms. White was holding a microphone instead of me holding a regular phone? Could the source count for Ms. Waller instead of me?” Again, there was no definite response from the students. The lack of responses from students suggest that they may have struggled with the wording of my questions, the idea that a model could look different from the phenomenon, or both.

I attempted to simplify the language of my question by asking, "So do models have to look exactly like real life?" Both Kyle and AR answered, "no." I reinforced the idea that models amplify certain components by saying, "This is a great example. Nick did a really good job showing that we have a source of a sound, but we don't have to know exactly what the source is." Kyle and AR's responses suggested that they may have understood the concept that models could look different from the target phenomenon, and that the wording of my questions may have been confusing or too complicated; however, it was not clear whether or not any other students in the class understood this idea.

The class continued to discuss Nick's model when he played the animation. MU asked Nick why the sound waves were moving in his model and he responded, "because the sound waves are slowly traveling to the receiver. However, TH asked if the sound waves move fast or slow and Nick responded, "sound travels fast." This was the first discussion during class about the speed of sound.

The sharing of student models and the resulting discussion demonstrated the role that models can play as a tool for mediating social interactions. Penner (2000) argued that models can serve as a way for students to externalize their thinking and a tool to support collaborative discussions. The presentations of the three models supported students to raise questions about aspects of the representations (e.g., The depiction of the source in Nick's model or TH's question to Nick regarding the speed of sound) or share their conceptual understandings related to sound (e.g., TH's explanation of the relationship between volume and the size of sound waves in response to TC's model). Even though the idea regarding the speed of sound did not get taken up or expanded on, the exchange between Nick and TH illustrated one way in which models serve as tools that can represent students' individual sense-making and mediate conceptual discussions among students.

After the sharing and discussion of students' models, the class moved to constructing a class consensus model. The previous discussions that the class engaged in regarding the ways they represented components in their models influenced the discussions related to the construction of their class model. The construction of this model began with a discussion of the source.

Ms. W	We will draw a class model. What do we need?
MU	Source. A person?
Ms. W	Do we need a person?
MU	No
Ms. W	You may like to have a person, but you just need what?
Ss	A label.

The discussion about how to represent the source reflected the ideas regarding what was necessary in the depiction of a component during the sharing of students' models. Ms. White reinforced the idea that the depiction of the source in the model did not need to mirror the physical appearance of that feature of the target phenomenon. In addition to reiterating an idea that the class previously discussed, the convention of labels was also reintroduced into the conversation about modeling. The use of labels in models was an idea that Ms. White had reiterated numerous times over the course of the year and many students included labels in their models. The use of labels was not discussed during the sharing of students' models, possibly because all students who shared models included labels. Students' use of labels in their own models and Ms. White's reminder to include labels in a class model suggests that the convention of labels may have become accepted in the class's practice of modeling.

Kyle suggested that the model also needed a receiver and added this component to the model on the board. GL added the component of sound waves, which prompted another discussion about the nature of the representation of the sound waves in the model (Figure VI.3a). After GL drew the sound waves, Ms. White shared, "TH thinks that the sound waves need to show the difference in the size. The closer they are [to the source], the larger they should be." According to the field notes from this class,

> the group has an exchange about whether the waves should be larger or smaller closer to the source. The class is divided on this. Ms. White asks, the farther it travels, should it get bigger? Teacher was unsure about whether or not she should let the students draw the sound waves getting bigger. She commented that perhaps students just needed a visual and allowed GL to draw the sound waves getting bigger. Teacher also brought up the idea of the distance between sound waves get farther apart (Field notes 3.28.17).

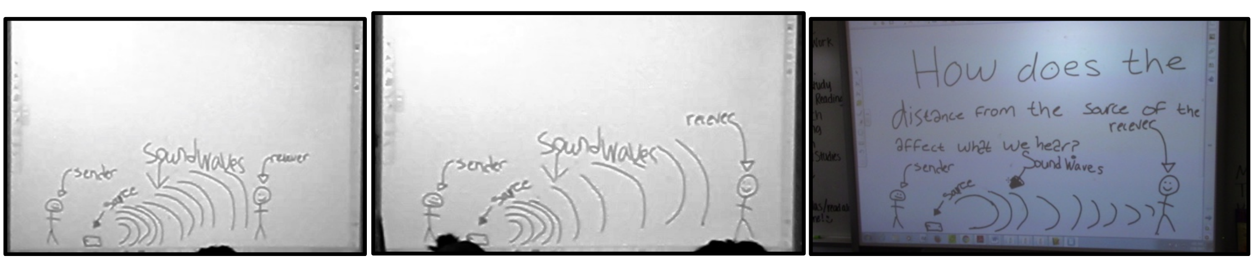


Figure VI.4. The (a) initial, (b) second, and (c) final consensus models that the class drew to explain how the distance from the source affects the volume of a sound.

After the construction of the initial model, Ms. White asked the class, "Does our model show how what we hear is different depending upon how far we are from the source?" She instructed students to show a thumbs-up if they answered yes. No students raised their thumbs up, but a few students put their thumps sideways or downward. When she asked the class what they could change, MU suggested that they move the person farther from the source. Ms. White then explained to students that the sound waves should have more space between them because the volume is decreasing as the sound gets farther from the source and asked Kyle to change the sound waves on the class's model to reflect her description (Figure VI.4b).

At this time, MU indicated to Ms. White that she disagreed with the representation of sound waves in the second iteration of the class consensus model (seen in Figure VI.4b). Ms. White invited her to the front of the classroom to explain how she thought the model should be changed. MU explained, "so the source you should draw the sound waves bigger to the source and they should get smaller." Ms. White asked MU why the sound waves were getting smaller and she replied, because the sound is getting softer." Ms. White polled the class again to see if they agreed with MU's explanation and 5 students raised their hands. At the point, the class had been engaged in whole-class discussion for about 35 minutes. Students' attentions were drifting and several students were not attending to Ms. White's question. However, given that five students raised their hands, this suggested that the class's discussion had influenced the thinking of a few students. MU changed the depiction of the sound waves on the model so that the sound waves were larger and closer together near the source and smaller and spread about farther away from the source (Figure VI.4c).

During the following class, students returned to their individual *Flipbook* models to finish them and received feedback from a partner regarding ways to improve their models. This class consensus model was the first time that the class had constructed a model together. Students' drew on their experiences during the sound and distance investigation to inform their decisions about their model. In this way, they did use their data to inform the construction of the class model, however students did not explicitly refer to their data when discussing what should be added to their model or in their conversations about how to represent the sound waves. Ms.

White did support students to test their model, by asking students if it was able to explain how the volume changed over distance. When students did not provide affirmative answers to her question, she encouraged the class to make changes to the model in order to address this question.

The class consensus model also served as a tool to mediate students' discussions about the representation of sound waves and provided an opportunity for different students to share their ideas in a public space. The use of the model led to a productive discussion about the nature of sound waves as they travel over distance. Figure VI.4 shows the progression of student thinking as it was documented through different iterations of the model. The class consensus model for the sound and distance investigation provide opportunities for students to externalize their thinking and collaboratively discuss different ideas.

Drawing from the social constructivist perspective in which learning must lead development (Palincsar, 1998; Vygotsky, 1978), this episode supports the claim that engagement in the class consensus model supported students' learning about specific concepts, which would lead to the development in students' understanding regarding the nature of sound waves and constructing representation that can be applied to more than one phenomenon (i.e., the volume of a sound over short and long distances).

"If you hit it softer it would make little sound energy:" The vibrating rice model. During the sound and distance modeling experience, the class discussed the presence of sound waves in the phenomenon of sound transfer and the movement of sound waves from the source to the receiver. However, they had not yet discussed the role that energy played in the transfer of sound or that the sound waves they had drawn on their models were representations of the transfer of energy. After finishing their sound and distance models, students engaged in activities related to exploring the role of energy in the transfer of sound. They constructed "cup" phones using two plastic cups, cotton string, twine, and wire. Students used these materials to connect the two cups together and investigated which material facilitated the clearest sound transfer.

After this investigation, on Day 12, the class also conducted the "vibrating rice" investigation using metal pans and spoons to investigate how the production of sound influenced the movement of rice that was located next to the pan. The students observed that banging the pans caused them to vibrate and made the rice to move or jump. In addition, the amount that the rice jumped depended on the intensity with which students hit the pan. Students used their observations to construct a class model explaining why the rice moved on Day 13. Before constructing the model, Ms. White led the class in a discussion sharing and analyzing their observations. She asked students if the rice had energy when it was moving and several students answered yes. Recall that in Units 1 and 2 students were working with the definition that objects in motion had energy. During the class discussion, IP shared her ideas about what would happen if she softly hit the pan with the spoon, which provided a connection between energy and sound waves. She explained, "the pan would like, if you hit it softer, it would not make as much sound energies, like so if you hit it softer it would make little sound energy." Ms. White revoiced this by asked, "it wouldn't have as much energy?" IP agreed. I asked IP about her phrase "making different sound energies" and she responded by saying that she meant "little sound waves." IP's original explanation made a connection between the sound produced by hitting the pan and the presence of energy. When she changed her answer to "little sound waves" this could have suggested that she was correcting herself to discuss sound waves instead of energy. An alternative interpretation is that she recognized a relationship between the size of the sound waves and the amount of energy transferred to the pan by hitting it with different intensities.

However, IP’s explanation was limited to the action of hitting the pan, as opposed to suggesting that the sound energy traveled through the air.

The class drew a model to explain what caused the rice to move (Figure VI.5). Using this model, I led a class discussion in which students discussed what caused the rice to move. My goal during this conversation was to support students to recognize that the energy transfer that occurred when hitting the pan also transferred energy through the air to the rice. First, I asked students, “Did the pan itself make the rice move?” Several students said no, and I posed the question, “What made the rice move?” Kyle responded, “the vibration of the sound waves.” This response included two important ideas: (1) that sound waves were involved in making the rice move, and (2) the sound waves vibrated. However, Kyle did not include an important aspect of the explanation that the energy from the sound waves traveled through the air.

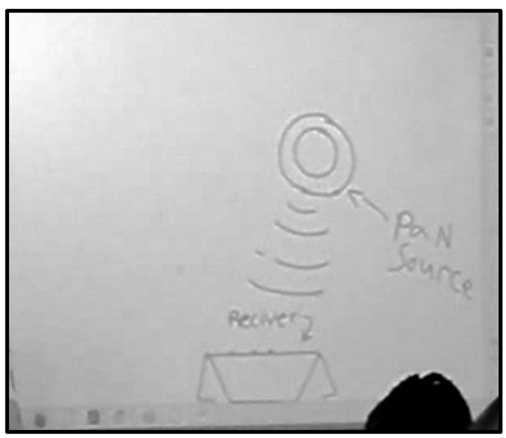


Figure VI.5. The consensus model the class constructed explaining the vibrating rice investigation.

I continued to ask questions to help support students to observe that the energy from the sound waves was traveling through the air in a similar fashion to the way in which the energy from the sound of their voices traveled through the material connecting the cups in their cup phone investigation.

MM On our model, what is the sound energy doing? Where is it going? Based on our model, where does it start?

Serenity The pan.

MM And it goes to the?

Serenity Rice

MM So what are the sound waves traveling through? Think back to the cup investigation. What did that sound have to travel through so you could hear what your partner was saying?

Serenity The string.

MM The material, right? And some of it didn't travel very well. So, in this case, what is the sound traveling through? Is it traveling through wire?

HK Air.

MM Right so in this case the sound waves aren't pushing the rice. What is pushing the rice?

LM The vibrations.

MM The vibrations in what?

LM The air.

At the end of this discussion, a few students (specifically HK and LM) demonstrated the understanding that the sound from the pan was transferred through the air. However, the class's discussion suggests that this concept was difficult for students to grasp. The abstractness of sound waves (an invisible entity) traveling through air (another invisible entity) causing an object to move may have been difficult for students to understand due to the fact that only the resulting movement of the rice was observable. Both the time of day and the difficulty of the concept being discussed during the conversation may have caused many of the students to disengage.

The class consensus model served as a starting point for the discussion but did not serve as a tool to mediate the classes discussion about the transfer of energy through air to the object. This could have due to the complexity of the concept and the simplicity of the class's model. The class included a representation of sound waves but did not include a representation of energy transfer from the spoon to the pan or from the vibrating air to the rice. This limited the class's ability to use the model to support their discussion. However, during this discussion, I encouraged students to refer back to the model and explain what the model was showing. This was a purposeful move to attempt to support students in explaining the model the class had constructed. However, given the limitations of the model they constructed, this move may have challenged the students' sense-making instead of supporting it.

"The sound is coming back:" The echolocation model. The class's study of sound culminated in Learning Set 2 with the study of echolocation. The process of echolocation begins with the production of sound that is sent into the environment from the sender who is also the source of the sound. The sound waves collide with objects in the environment and are either absorbed or reflected by the object. The reflected sound waves bounce off the object back into the environment and to the source of the sound. The volume of the sound waves that return to the source is much lower than the volume of the sound originally produced. The source analyzes the volume of the returning sound waves to build a picture of the environment (Stromberg, 2013). Students engaged with a text and videos explaining how bats and humans used echolocation to communicate and navigate in their environments. The phenomenon of echolocation was chosen due to the important ways in which organisms interpret and respond to the sounds they produce and receive in echolocation and the ways in which this phenomenon was responsive to the *NGSS* performance expectations that were included in this unit, specifically 4-LS1-2 (see Table VI.1).

On Day 24, the class constructed a model to explain how echolocation worked. The process of constructing the class consensus model highlighted several difficulties students were experiencing in understanding the relationship between sound waves and distance that was introduced during the sound and distance model. Ms. White told the class that they were going to draw a model "about what echolocation is" (Figure VI.6). She called on different students up to draw different components of the model. MU volunteered to draw an animal. She and Ms. White briefly debated about whether or not it needed to be an animal, because they had also learned about how humans use echolocation. Ms. White reminded her that she could just draw the source, without specifying whether it was an animal or a human. MU drew a human and labeled it as the source. The class would continue to discuss about what could represent the source in a model explaining echolocation at several points over the next two class periods.

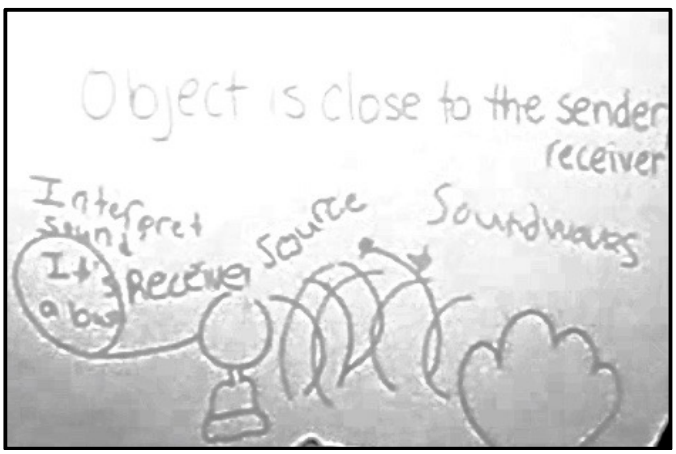


Figure VI.6. The consensus model constructed by the class to explain echolocation when the object is close to the source/ receiver.

NK drew sound waves and added an object for the sound to bounce off of when Ms. White asked, "where is the sound going?" Another student added sound waves reflecting back from the object to the source/ receiver. Ms. White suggested that he add them in a different color, so that they would be easier to see. Ms. White's suggestion about the use of different colors modeled the ways in which students could use color in a purposeful way in their models. The class did not discuss the use of color in this model; however, Ms. White was modeling the decision-making process regarding the representation of sound waves by narrating her thinking regarding the use of color.

After students drew the model on the board, Ms. White appeared ready to move on to the next step in the lesson. However, students had not discussed the representation of sound waves that they had drawn in this model or what the model communicated about the distance from the source/ receiver and the object, an important aspect of echolocation. I posed some questions to the class regarding what their model communicated about echolocation, which revealed that students did not have a clear understanding of how sound waves traveled in echolocation and were not applying to this model what they had learned in Learning Set 1 regarding the relationship between volume and distance.

MM How could we tell if something was close or far away?

TC It was how long the sound came back.

MM Was it it's speed?

Kyle How loud or soft something is.

MM Is there a way on our model, or even make another model, to show that something that's far away?

Ms. W How the sound waves would look?

MM What could we change about this model?

Kyle You could change how far the object is.

Serenity You could show the distance between the source and the object. You could write the distance.

MM What makes the sound loud or soft? Think back to that model that we made a couple of weeks ago. When something is loud or soft, what does that mean?

Student Because it is soft?

MM How did you show the sound on your models before?

CH The farther from it, the more quieter it gets because you're getting farther from it.

MU The sound waves! When it gets farther from you, they get smaller.

MM Can we take that same idea and apply it to this model?

MU Yes

MM To show how our source and our receiver can tell things that are close together and far apart? So, what would this model be an example of? The object is close to you or far away from you?

MU and other students: Close

MM Thumbs up if you agree that this is something that is close to you? [About 7 thumbs go up]

Samuel Close… because the source has sound waves and it's not coming back so far away so it can hear it?

MM Anyone want to add to that?

Serenity Because the sound waves are larger.

This excerpt illustrates the struggle that students experienced in understanding the relationship between the size of sound waves and the distance between the source and the object. The context of echolocation was different from the context of the sound and distance investigation that they had previously modeled because, instead of the sound waves traveling in one direction, they were now traveling in both directions.

This excerpt also demonstrates how the model served as a tool to mediate class discussion with the support of the questions that I posed to the students. In addition, students were still grappling with the idea of using the representation of components in the model to show distance. Serenity suggested that the class write the distance on the model, which would have effectively communicated the idea. However, when Ms. White and I pushed the class to consider the sound waves and the sound and distance models they constructed, MU, Samuel, and Serenity drew on their sense-making from the sound and distance model to identify ways the representation of sound waves could also communicate the relative distance between the sources and the object. Recall that students drew two models after the sound and distance investigation to explain how the volume changes over distance. MU, Samuel, and Serenity drew on the conventions that the class used to show changes in volume over distance in the discussion regarding how to communicate relative distance in the echolocation model.

In order to check whether the students understood the behavior of the sound waves in echolocation, I suggested to Ms. White that students draw a model in their notebooks to explain how the sound waves would look if the object was far away from the source/ receiver. This activity proved to be very effective in identifying those students who had grasped the concept of the shrinking size of sound waves as they traveled away from the source and those who were still struggling with the concept. Many students were still struggling to understand that the size of the sound waves continued to shrink as they bounced off the object and returned to the source/ receiver. Ms. White chose to debrief with three randomly selected students regarding their models. Each model supported class discussion about a different important aspect of the echolocation model.

Figure VI.7. CH's echolocation model explaining the process of echolocation when the object (bird) is close to the source.

CH was first to share his model (Figure VI.7). He correctly explained that the "sound waves are getting smaller going to the object because it is getting softer and they are getting shorter and smaller on the way back to the receiver because they are getting softer" (Field notes 5.8.17). Ms. White checked for students' understanding of the idea that CH explained by asking, "What is happening the sound waves as they are coming back? Are they getting bigger or smaller?" Several students say that the sound waves get larger. Ms. White replied, "No they are getting smaller, because the sound is quieter, so our sound waves are not as big. Check on your model, it that what is showing? A difference in the size of sound waves? Are they all the same size? They need to be getting smaller."

MU shared her model next (Figure VI.8). When she projected her model, Ms. White asked her what she was missing. MU identified that she was missing "The sound coming back." Ms. White reminded the class, "We have to show the sound coming back to the person. They are the one sending out that sound and getting it back." MU also had the sender and receiver labeled as two different people. Ms. White reminded her that the class was talking about echolocation and that the sender and the receiver was the same person. MU's model provides an illustrative example of the ways in which student-constructed models can capture students' thinking and be used as a tool to discuss and confront inaccuracies in their understanding. MU was a highly-engaged student during this lesson and the preceding conversations regarding echolocation. It appeared that she understood the behavior of the sound waves during echolocation; however, her model suggested otherwise.

Figure VI.8. MU's model explaining echolocation when the object is close to the sender/ receiver. MU added the sound waves traveling from the object to the sender/ receiver after sharing her model with the class and receiving feedback from Ms. White.

The third student to share his model was TC. He had labeled the person in his model as both the source and receiver, included a car as the object, and had labeled his sound waves (Figure VI.9). Ms. White narrated her interpretation of his model by saying, "I notice that your sound waves are traveling in the same direction both ways." TC disagreed with this statement and explained, "No. The sound waves bounce off the car and then come back to the receiver." Ms. White reminded him that this model was supposed to show the object farther away and asked, "What can we do to show that the car is further from our source?" TC replied, "Make them longer." Ms. White repeated how the sound waves needed to change over distance, explaining, "and as its getting farther away the sound waves need to be smaller because they are quieter and traveling farther away." This discussion reiterated the idea that models could be used to communicate ideas and the interpretation of the viewer may not match that of the creator.

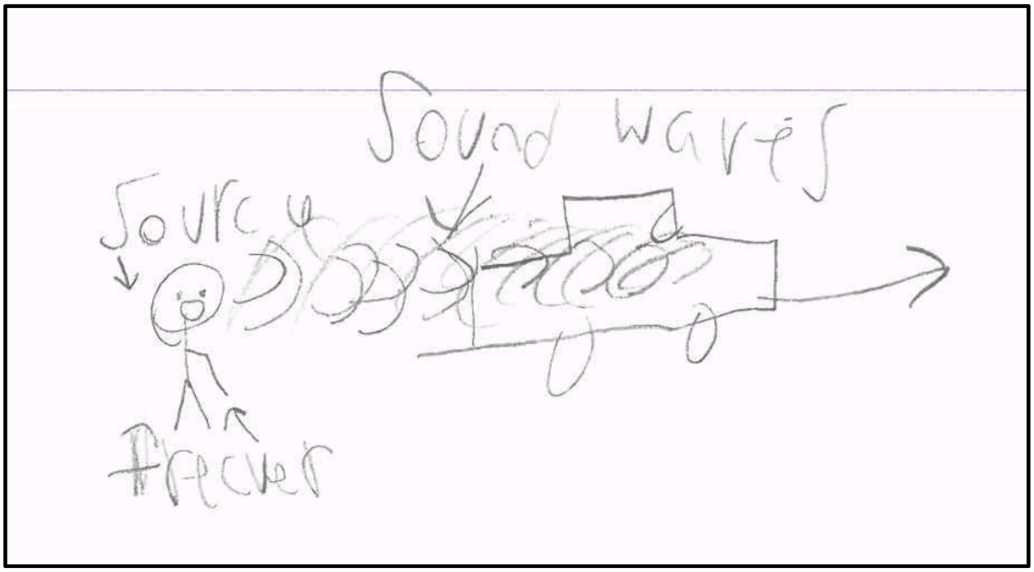


Figure VI.9. TC's model explaining echolocation when the object (a car) is close to the source/ receiver.

Ms. White told students that they would continue to work on this in the next class. She shared with me at the end of class that she did not feel that students had a firm understanding of the concept of echolocation and decided that the class would construct a consensus model explaining how echolocation worked when the object was far away during the next science class.

The uses of models to externalize student thinking and serve as tools for collaboration and discussion were readily apparent in this lesson, especially as students shared and explained their models with the class. For example, when TC projected his model and Ms. White commented that the sound waves were only traveling in one direction, TC used his model to explain why he felt she was incorrect. In addition, the process of asking students to construct individual models after they constructed the class consensus model provided the opportunity for

Ms. White to assess which students had developed an understanding of echolocation and which students were still struggling with the ideas associated with echolocation.

On Day 25, the class continued their discussion regarding echolocation. Ms. White and I discussed ways of supporting students to develop a better understanding of the relationship between the size of sound waves and distance. We decided it might be helpful to show students the class consensus model that they constructed for the sound and distance investigation. Ms. White called on Caleb to read the question written at the top and HK to explain the model. He said, "The model shows the source makes the sound going to the receiver." Ms. White asked about the sound waves and what happened to them the farther they traveled. HK responded, "they're getting smaller." Ms. White reinforced this idea and provided an additional example meant to support students' sense-making regarding the changes to sound waves over a greater distance.

> They get smaller and they should be getting farther apart. I want you to think, have you ever seen a pebble in a pond? I know when my boys throw a rock into the water, the ripples start out really tight at the source around that pebble and what happens to those rings? But what happens to the ring sizes? They get further apart. That's the same thing with our sound waves. They are getting smaller because the sound is getting smaller, but they are also getting farther apart. That's something we need to remember (05.09.17 Video).

Before class, Ms. White shared with me that she chose this example because the movement of the concentric rings in the pond are visible and she felt that students might be familiar with this phenomenon. After reviewing the sound and distance model, Ms. White realized that she did not have a copy of the echolocation model from the previous class saved on her computer and invited students to redraw this model on the board. The class was able to reconstruct the model from the previous day very easily and this exercise served as additional reinforcement of the concept of echolocation.

After reconstructing the model explaining how animals and humans use echolocation when the object is *close*, they moved on to constructing a model to explain how animals and humans use echolocation when the object is *far away* (Figure VI.10). Ms. White instructed the students to construct the model on their papers, while members of the class contributed to the consensus model on the board. She indicated to me that she felt this would be a good way to reinforce the concept of the relationship between the size and spacing of the sound waves and distance.

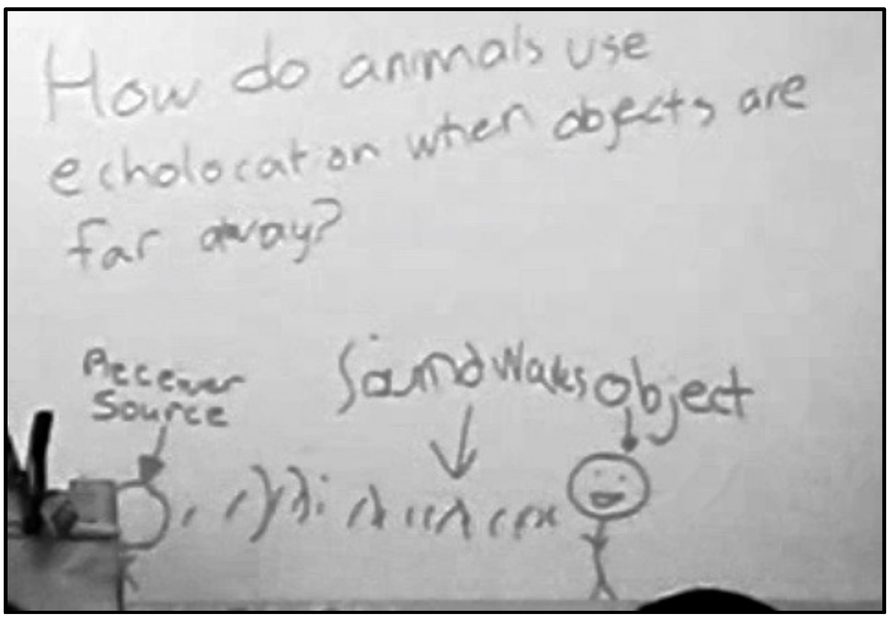


Figure VI.10. The class's consensus model explaining how animals use echolocation when the object is far away.

As Ms. White selected students to contribute to the class model, she asked clarifying questions to reinforce the relationship between the size and distance between sound waves and the distance from the source. MU drew a person and labeled it both source and receiver. Ms. White asked the class, "why is this person that she drew both the source and the receiver?"

Serenity answered, "because they make the noise and when it bounces off the object, they hear it." Then, Ms. White selected HK to draw another component of the model. He chose to draw a second person. Many students in the class had chosen to draw people as both the source/ receiver and the object in their individual and class echolocation models. In order to prompt students to think about the other things that could serve as sources and objects, I asked the class, "we've drawn two models now with people as the object. Does the object have to be a person?" Students provided additional ideas regarding what could serve as an object.

TC It can be metal.

MM Are you thinking of the video? What was in the video?

TC It bounces right back off of it and goes back to the source. A bat.

TH To figure out what path to take to go outside.

AR They can find food.

MM It can be anything…

Ms. W A bat and a bug…

MM *Can* it be a person? Can the bat sense a person? [original emphasis]

RM Yeah.

At the end of this conversation, HK left the person that he drew on the model and labeled it "object." This was the second conversation in the context of the echolocation model that students engaged in regarding how to represent the source. Interestingly, none of the students suggested inventing a more generic representation of the source. One of the benefits of engaging students in the process of modeling is that they have the opportunity to invent their own representations (diSessa, 2004; Lehrer & Schauble, 2012; Manz, 2012). diSessa (2004) identifies the ability to invent new representations as a dimension of meta-representational competence. He suggests that reasonable expectations for students could include modifying or combining existing representations as a way to invent new ones. The students in Ms. White's class were grappling with the idea of how to represent the source, as they had been given both human and non-human examples of echolocation. A generic representation would have addressed this issue; however, the use of abstract representations may have been too difficult for students to consider, given the struggles they were encountering in understanding the concept of echolocation. One way to support students in inventing their own representation of echolocation may be to provide them with multiple examples of pre-constructed representation that they could evaluate and modify.

TC added sound waves to the class consensus model. Before Ms. White allowed TC to draw the sound waves, she asked the class, "what happens to these sound waves the further they get from the source?" HK answered, "They get smaller and they spread out." Ms. White repeated and elaborated on HK's answer. She said, "they get spread apart more and get shorter. They start out close and as you go farther away, spread them out farther." TC began to draw sound waves on the class's model, however Ms. White stopped him and modeled how to draw the sound waves getting shorter and more spread apart from the source to the object. Then, she allowed TC to draw sound waves traveling back toward the receiver. As TC was drawing the sound waves, Ms. White instructed him to space them farther apart.

After TC finished, Ms. White circulated around the room to check students' progress on their models. She requested the class's attention and drew sound waves on the board that got bigger as they traveled. She told the class that she was seeing students draw sound waves that resembled the ones she had just drawn on the board and asked, "what's wrong with these?" AR replied, "they are getting bigger and they aren't getting spread out." Ms. White also told the class, "I'm also noticing some of you keeping your sound waves the same size. They should be getting small and spaced farther apart." Despite the construction of two class consensus models and Ms. White's repeated reminders, students still struggled with the representation of sound waves as they moved farther from the source.

As a conclusion to this activity, I asked the class, "why is it important that we show the sound waves getting smaller?" In the discussion that followed, several students shared ideas that represented the students' development of ideas regarding the nature of sound waves.

CH They are getting quieter.

MM What are we trying explain in this model?

Serenity We are trying to show because it is further away.

MM Can you please repeat that so everyone can hear?

Serenity When sound waves are travelling farther, they are getting softer.

MM Why do we need to show them getting smaller and further apart?

TC Because the farther they move, the softer they get.

MM Would someone be able to make sense of this model? Could they look at it and figure out what is going on? What would you know about the sound?

TC That it is getting softer.

MM What happens on the way back?

HK They get shorter because they stay softer.

MM For some of you, your sound waves are getting smaller, then big again on the way back. How does a bat know if something is close to them or far away?

RM That it bounced off the object.

MM What did they hear?

HK They heard it louder.

MM It was louder when it was closer. What do they hear when it is farther?

HK It gets softer.

My contributions to this discussion also reinforced the idea that the components of models contributed to the model's ability to communicate ideas. For example, using the class model to identify whether the object was close or far away from the source. This idea was repeated several times over the two days of instruction related to the echolocation model.

Conclusions from the class case. The class's engagement in modeling experiences related to sound provided an opportunity for individual student and class models to serve as tools that mediated students' discussions, externalized their thinking, and provided opportunities for Ms. White to assess students' sense-making of different concepts related to sound. The creation of consensus models provided opportunities for students to engage in collaborative sense-making while engaging in the practice of modeling and emphasized the role that models play in communicating ideas. In addition, the construction of consensus models supported conversations regarding the choice and representation of components in the models, which was a conversation that began during Unit 2.

Students' sharing of their individual models also positioned them to defend their design choices in their individual models in response to alternative interpretations by other members of the class. This process may have reinforced the idea that models are used to communicate ideas. In the previous two units, the class engaged in minimal sharing of models and instead received feedback from a single peer. They also did not engage in creation of class consensus models. The incorporation of the class-wide sharing of models and the creation of class consensus models may have facilitated discussions regarding the epistemological ideas related to the practice of modeling.

Students were repeatedly faced with the challenge of representation during the consensus model activities, especially when constructing models of echolocation. There were several conversations regarding the representation of a source, because they had learned about several different examples of human and non-human use of echolocation. Students frequently decided to include a human as the source, possibly because it was easiest for them to relate to a human's use of echolocation. The class did not progress to using a generic representation of the source, an idea that was briefly discussed during the sharing of Nick's model of the sound and distance investigation. The class's struggle supports findings in the literature regarding young children's difficulty with considering models as representations with similarities in function, as opposed to physical attributes (Lehrer & Schauble, 2012; Louca & Zacharia, 2015; Manz, 2012).

The *Framework for K-12 Education* (2012) states that energy can be understood at a macroscopic scale through the phenomena of light, sound, and heat, but that the concept of energy is best understood at a microscopic scale. The design of the Unit 3 curriculum did not involve any exploration or discussions related to the role of air molecules in the transfer of energy or that the production of sound was the result of a transfer of energy into the surrounding air (NRC, 2012a). Students could have been supported to engage in discussions regarding these two ideas during the creation of the *vibrating rice* model.

The investigation and modeling opportunity in which students engaged was constrained to one aspect of the phenomenon of sound – volume. Volume was chosen because changes in volume are familiar to students and easy to qualitatively measure. However, the class did not have conversations about why they thought volume decreased over time. Ms. White's enactment of these lessons followed the curriculum, specifically in that the emphasis was placed on the macroscopic aspects of sound and students' observations, instead of prompting students to think about why changes in volume occur. A discussion regarding the underlying causal explanation of why volume changes would require students to understand the role of energy in the transfer of sound.

In addition, students' focus on volume ignores other important aspects of the phenomenon of sound, such as the dispersal of sound waves from the source. This proved problematic during the construction of the echolocation models. Ms. White's continued emphasis of the relationship between the size of the sound waves and the volume of the sound in the process of echolocation reflected students' previous experiences and the instructions she received in the curriculum. While she was correct the volume of the sound that returns to the source is much quieter, the sound does disperse in all directions both when it is produced by the source and when it reflects off of objects.

The ideas of energy transfer that the class began to discuss in a limited way during the construction of vibrating rice model were also not carried through to the construction of the echolocation models. The role of energy transfer in the production and transfer of sound is central to an understanding of why volume decreases. Students could have been engaged in generating explanations regarding why volume decreases over distance because energy is transferred to the surrounding environment. This explanation is stated as one of the disciplinary core ideas (PS3.B) in the *Framework for K-12 Science Education* (NRC, 2012). The sole emphasis on volume and the lack of discussion related to energy transfer may have contributed to the confusion that students experienced regarding an explanation of echolocation.

Constructing models that communicate abstract ideas and serve as analogs, as opposed to serving as literal representation, of the target phenomenon is more cognitively demanding for students (Lehrer & Schauble, 2012). The complex nature of the relationship between the size and spacing of sound wave and distance, especially in the context of echolocation, coupled with the creation of a model that required the use of more abstract components (e.g., a generic source of sound) may have created a modeling situation that was too cognitively demanding for 4th grade students. Students demonstrated more success in constructing the sound and distance models in comparison to the echolocation models. More research should be conducted regarding elementary students' prior knowledge of sound and developmental trajectories regarding the development of their understandings related to sound in elementary school. The case of Ms. White's class suggests that students' sense-making developed to a point of understanding the relationship between volume and distance. That is, many students were able to understand the behavior of sound waves in the context of the sound and distance model and developed an understanding of the general behavior of sound waves in echolocation (e.g., they bounce off an object and travel back to the source); however, many students struggled to develop a more detailed understanding of the size and spacing of sound waves in echolocation.

Focal Students' Sense-Making

In this section, I will report data gathered from focal students' Unit 3 pre- and post-assessments, their sound and distance models, and the associated interviews. The Unit 3 pre- and post-assessment included questions regarding concepts related to both sound and light; however, I will only report students' responses to two questions related to sound on the assessment, due to the focus on this chapter on students' sense-making related to energy from sound. The excerpt from the assessment with the two questions related to sound in shown in Figure VI.11.

Unlike the post-assessment interviews in Units 1 and 2, the Unit 3 post-assessment interview did not include a novel task in which students were asked to apply concepts from the unit. Instead, the Unit 3 pre- and post-assessment interviews included the prompt, "Your class has spent a lot of time learning about energy this year. How is energy involved in communication?” This prompt was designed to elicit students’ thinking about the role of energy in communication and the ideas regarding energy that students had engaged with over the year. The choice to use this prompt, as opposed to a novel task, was due to the fact that this was the final science unit of the school year and I was interested in the extent to which students drew on experiences or concepts from previous units when answering this question.

Some lighthouses also have large foghorns as well. The foghorns send out low, moaning sounds to tell the boat captain about danger.

4. Using as much detail as you can, draw a model to explain how the boat captain hears, interprets, and responds to the sound.

   In your model, make sure to include how the boat captain:
   - hears the sound
   - interprets the sound (how does he know what the sound means?)
   - responds to the sound

5. Explain what you drew in your model. In your explanation, describe how the transfer of sound involves the transfer of energy.

Figure VI.11. Excerpt of Unit 3 pre- and post-assessment showing questions related to sound that were discussed during the pre- and post-assessment interviews.

The sub-cases of the four focal students reported in the chapter were chosen because all four focal students had also participated as focal students in at least one other unit. In each sub-case, I will share findings related to students’ prior knowledge related to sound, sense-making regarding energy transfer from sound and epistemological aspects of models, and endpoints related to sound at the end of the unit.

Sophie. Sophie demonstrated typical prior knowledge regarding the production and reception of sound and sound energy, as compared to her peers. In her Unit 3 pre-assessment interview, she described the model she drew in response to Question 4 on the unit pre-assessment as, “The other captain was honking his horn at the other boat because they were almost going to hit each other.” Sophie’s model included lights emanating from both boats (Figure VI.12). The lines from the boat on the left were “the lights,” and the lines from the boat on the right were “the sound.” Her incorporation of these lines suggests that she was considering ways to represent the projection of light and sound away from their sources in her model. However, Sophie’s model is missing components to explain how the boat captain hears, interprets, and responds to the sound.

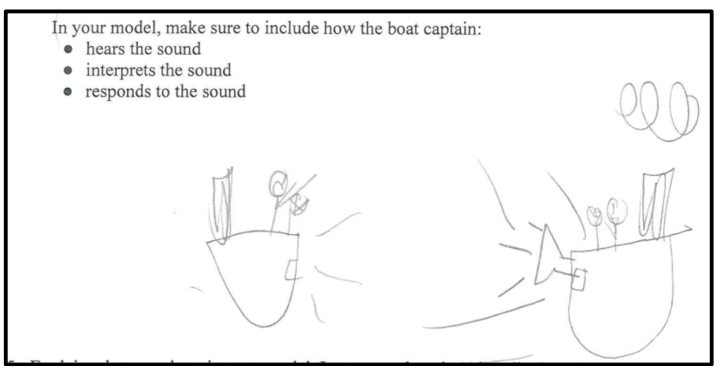


Figure VI.12. Sophie’s Unit 3 pre-assessment model explaining how a boat captain hears, interprets, and responds to the sound from a foghorn.

When I asked how the transfer of sound involves a transfer of energy, Sophie shared her current understanding about energy and how she was applying it to her understanding of sound.

MM How do you think the transfer of sound involves a transfer of energy?

S(ophie) It moves, the sound, it travels.

MM Do you think that uses energy?

S Yah.

MM What do you know about energy that makes you say that?

S That it can move.

MM That energy can move?

S Well it can make things move.

MM Okay, so in this case what would the energy be moving?

S The boats.

MM What about sound? How might energy be involved with the transfer of sound?

S The sound makes noise like energy does sometimes.

MM Does sound move?

S Yah.

Sophie's explanation regarding how the transfer of sound involved the transfer of energy revealed that she had an understanding that sound travels and that energy could cause things to move. It is unclear if she developed her understanding regarding energy during science or if she arrived to fourth grade with this understanding; however, the idea that energy causes objects to move was one that was emphasized during Units 1 and 2. Sophie appeared to have difficulty identifying what the energy from sound could move. She stated that sound could move and that sound used energy, but she was not able to apply her explanation that energy moved objects to the concept of sound. She identified the boats as being moved by energy, as opposed to identifying an object being moved by the energy from sound.

When asked to explain how energy is involved in communication, Sophie identified that a microphone was an example of how energy was involved in communication, because "you have to have energy to make it work." Sophie's application of energy in the example of the microphone draws on the idea of electrical energy, a major concept in Unit 2. It is possible that Sophie was drawing on her recent experiences in Unit 2 to inform her thinking about this question. In her Unit 3 pre-assessment interview, Sophie demonstrated that she held ideas about the nature of sound and transfers of energy that could eventually be refined and integrated into an explanation about the role of energy in hearing.

Sound and distance model. During Sophie's interview regarding her sound and distance model, she shared her thinking about how sound waves travel and ways to represent them. Sophie was not able to finish her model explaining how she could hear sounds that were close to her (Figure VI.13a); therefore, the interview focused more on what she drew in Figure VI.13b to explain how she could hear sounds that were far from her. Sophie's model depicted the sound waves increasing in size as they traveled away from the source. This representation reflected a misconception that was debated during the class's discussion regarding how to show the movement of sound waves in the class consensus sound and distance model. Recall that the class originally showed the sound waves increasing in size, but then after discussion and MU's explanation of her thinking, they changed the sound waves to be decreasing in size and increasing in distance from each other. When I asked her about how she planned to draw the sound waves in Figure VI.13a, she stated, "They'd be smaller…. They are going to be closer together probably." This description suggests that Sophie was drawing on ideas that her introduced during the class discussion and accurately described how the sound waves would look different when the source and receiver were close together.

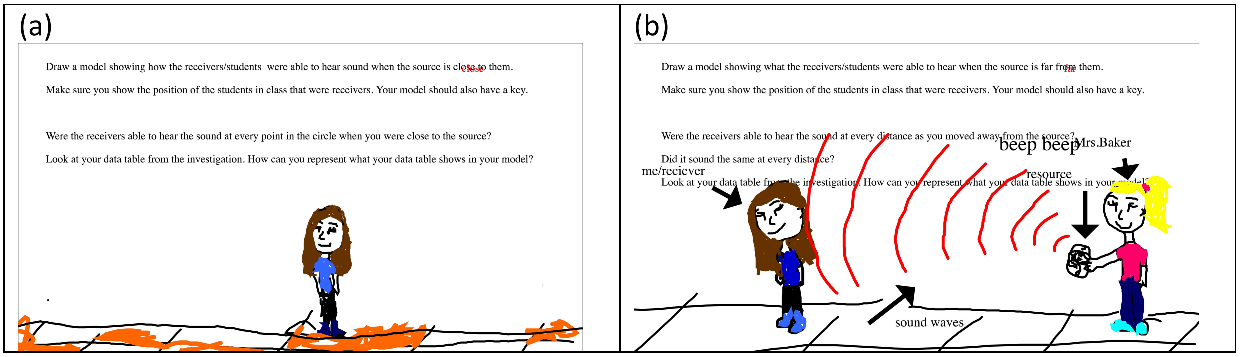


Figure VI.13. Sophie's model explaining how she hears sounds that are (a) near her and (b) far away.

When I asked Sophie to compare her model to the class's consensus model, she identified the difference in the representation of the sound waves and explained, "I did my sound waves small at the beginning and bigger at the end. Because the sound is traveling" (Sophie Unit 3 Interview #2). Sophie was consistent in her explanation regarding how she thought sound waves changed, suggesting that the experience of constructing the class consensus model did not prompt her to re-examine her own understanding when she returned to her individual model in the following class. Clark and Linn (2013) explained that students develop understandings through their everyday experiences that may remain stable until a sufficiently powerful experience prompts them to reexamine their existing understandings. Sophie may have already held the idea that sound waves increase in size and the construction of the class consensus model was not sufficiently powerful for her to realize that her thinking did not align with the representation of sound waves in the consensus model.

Sophie's model included detailed drawings that reflected many of the details of the investigation. The details in her model suggested that she had not considered the features that were displayed as a part of the models that three students shared on Day 5 before the class constructed the consensus model (Figure VI.4). Sophie's model reflected the finding in the literature that children tend to think of models as literal representations of phenomena instead of communicating the mechanism of a phenomenon (Lehrer & Schauble, 2010).

At the end of the interview, I asked Sophie, "Do you think that making and constructing models is helpful for learning about different things?" This question was designed to elicit students' thinking about the role that models play in communicating or developing ideas. Sophie stated, "yah, because it's kind of like what could happen, or it's like a mini-version of what actually would happen." When I probed further about Sophie's thinking regard how this could help her learn, Sophie responded, "You can learn what the parts of something are, because of the labels. You could see how something works." These responses revealed several epistemological ideas that Sophie held regarding the use of models. First, she described models as showing "what could happen" and "a mini-version of what actually would happen." These characterizations suggest that Sophie considered models to be a representation of a real phenomenon and processes on a smaller scale. This description of models was also reflected in the physical resemblances with the phenomenon that Sophie included in her sound and distance model. Sophie's response also suggests that she understood that models could show a process on a smaller scale.

In addition, Sophie's response referenced Ms. White's repeated characterization of the stream table model as a way to "see erosion firsthand" and the class's discussion of using models to study something you cannot see during Unit 1 (see Chapter 4). She also discussed the role of labels in models as a way to "learn what the parts of something are." Her identification of labels suggests that she considered labels as an important aspect of models and that she understood their purpose in communicating information about the model. Sophie's response to this question illustrates that she was developing an understanding about one of the role of models in science – that they can be used to explain processes and phenomena; however, her Unit 3 Sound and Distance model suggests that she incorporated physical features of the phenomenon as important aspects of the model.

Her explanation about the use of models during this interview also reflected ideas that she shared during her Unit 1 post-assessment interview. During the Unit 1 post-assessment interview, Sophie indicated that she could learn a lot from using the stream table because it "is kind of like actual erosion" (Sophie Unit 1 Interview #3). In addition, Sophie referenced the idea that models were similar to, but not the same as, the target phenomenon when she explained her answer further, stating, "Well because it's kind of like an actual like, well, land, area of land but it's not really but it's still helpful." Sophie's explanation from Unit 1 was a less developed version of the same explanation that she gave during the Sound and Distance Interview (i.e., that models are smaller scale representations of a target phenomenon). This suggests that Sophie's understanding about how models could be used to communicate a process and represent a target phenomenon had broadened over the year to now include an understanding about the scale of models.

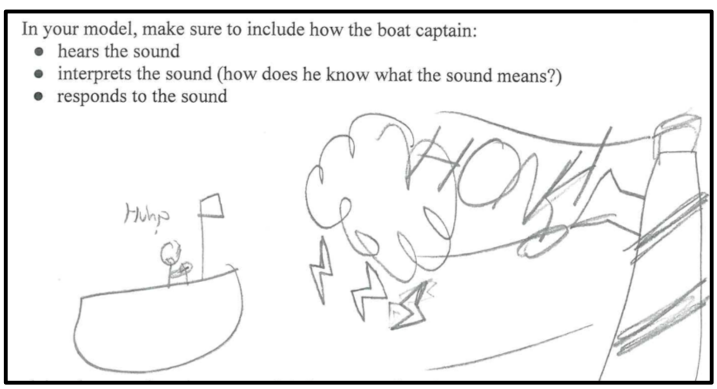


Figure VI.14. Sophie's Unit 3 post-assessment model explaining how a boat captain hears, interprets, and responds to the sound from a foghorn.

Post-assessment interview. Sophie's model on her post-assessment included features that were not included in the model on her pre-assessment (Figure VI.14). She included a representation of the boat captain interpreting the sound (see "thought bubble"), a representation of the sound generated by the fog horn, and lines emanating from the foghorn. Similar to her pre-assessment model, Sophie did not include sound waves in her model. In her post-assessment interview, Sophie described her model as, "The lighthouse is honking its horn because they are going to run into a storm, and so they can drive away from it." Her model and her explanation focused solely on the observable aspects of her model, as opposed to explaining the process by which the captain was able to hear, interpret, and respond to the sound. When I asked Sophie to elaborate on the process by which the sound gets to the boat, she identified that the sound travels via sound waves and the sound waves were lines that traveled from the fog horn to the captain (Sophie Unit 3 Interview #3). Despite not including sound waves in her model, Sophie readily identified sound waves as the mechanism by which sound travels. However, she did not give enough detail regarding her thinking about the appearance of the sound waves to know whether or not she still thought that sound waves increased in size as they moved farther away from the source.

Sophie's elaboration of the assessment question regarding how the transfer of sound involves a transfer of energy suggests that Sophie was still applying her thinking regarding the role of energy in moving objects.

MM How does a transfer of sound involve a transfer of energy? How does sound traveling involve energy?

S It moves.

MM What moves?

S The sound waves.

MM So, does that have to do with energy, the sound waves moving?

S Kind of.

MM Can you tell me more about that?

S Hmm, well because when something moves, it creates energy.

MM So do sound waves have energy?

S Yes.

MM Why?

MM Because they are traveling.

Sophie applied the same definition of energy to this question in the post-assessment interview that she did in the pre-assessment interview, but she was able to apply this thinking to sound waves in the post-assessment interview. Sophie explained that sound waves travel and, because of this, she knew that sound waves had energy. However, she incorrectly stated that energy is created when something moves. However, this is a well-documented misconception that children have regarding energy and a distinction that students struggled with during Unit 2 (see Chapter 5) (Hammer et al., 2012). This suggests that Sophie's understanding regarding energy is still developing due to the fact that she moved back and forth between discussing objects having energy and objects creating energy during the unit. Sophie's answer to this question during the post-assessment interview demonstrates a slightly more nuanced understanding of the concept of energy in relation to sound waves, because she was able to apply her understanding about energy as evidence that sound waves have energy because they travel (or move).

Sophie continued to apply her understanding of the presence of energy in moving objects when she responded to the prompt, "How is energy involved in communication?" She responded, "certain movements…like the way the boat goes." Sophie's example drew on the idea of kinetic energy, as opposed to energy from sound. However, this response was more related to the concepts that she had been learning about during Unit 3, as compared with her response to this question in the pre-assessment interview, suggesting that Sophie was drawing on her experiences from Unit 3 to answer this question.

Summary. Sophie demonstrated development in her understanding regarding the role of energy in the transfer of sound from the source to the receiver. Her sound and distance model interview revealed that she held a misconception about the way in which distance affects the size of sound waves; however, she was able to apply her understanding of energy in a slightly more nuanced way in the post-assessment interview, as compared to the pre-assessment interview. Sophie also demonstrated development in her understanding regarding the concept of energy during the unit. She entered this unit with some understanding that moving objects have energy and was able to apply this definition to sound waves at the end of the unit. She also demonstrated development in her sense-making regarding the role of models in science from Unit 1 to Unit 3. Her ideas related to the role of models in Unit 3 suggest that she had developed an understanding that the scale of models is smaller than the target phenomenon and models can communicate ideas about a process; however, she was still developing an understanding of models as a representation instead of copies of the phenomenon.

Samuel. Samuel demonstrated low prior knowledge regarding the production and reception of sound and sound energy, as compared to his peers. Figure VI.15 shows the model that Samuel drew to explain how the boat captain hears, interprets, and responds to the sound from the foghorn on his Unit 3 pre-assessment. When I asked him to explain his model, he explained,

> S(amuel) Yeah, the horn is making it honk, so they know where--if somebody is--so then, the captain can see--can hear--can hear the honk and so if he hears it, he will honk too, I guess.

MM Okay. So, he honks back? So, how does--so, so this horn makes the sound, right? How does that sound get all the way to the captain?

S It's really loud.

MM Okay. So, if it were quiet, would it get to the captain?

S No.

MM No? Okay.

S But it's really loud, so I would get--so I made it big.

MM I see. Okay. So, this--you wrote it big so that--to show that it was loud.

S Mm-hmm.

Samuel's explanation suggests that he held a foundational understanding that the volume of the sound would influence the captain's ability to hear it. In addition, he explained that he wrote the word, *honk*, in a large size to indicate it was loud. This suggests that Samuel was considering ways to represent important information, such as the volume of the sound, in his model. When asked how the transfer of sound involved a transfer of energy, Samuel answered, "I don't know," suggesting that Samuel was not applying knowledge about energy to the context of sound or that the wording of the question was too difficult or not accessible.

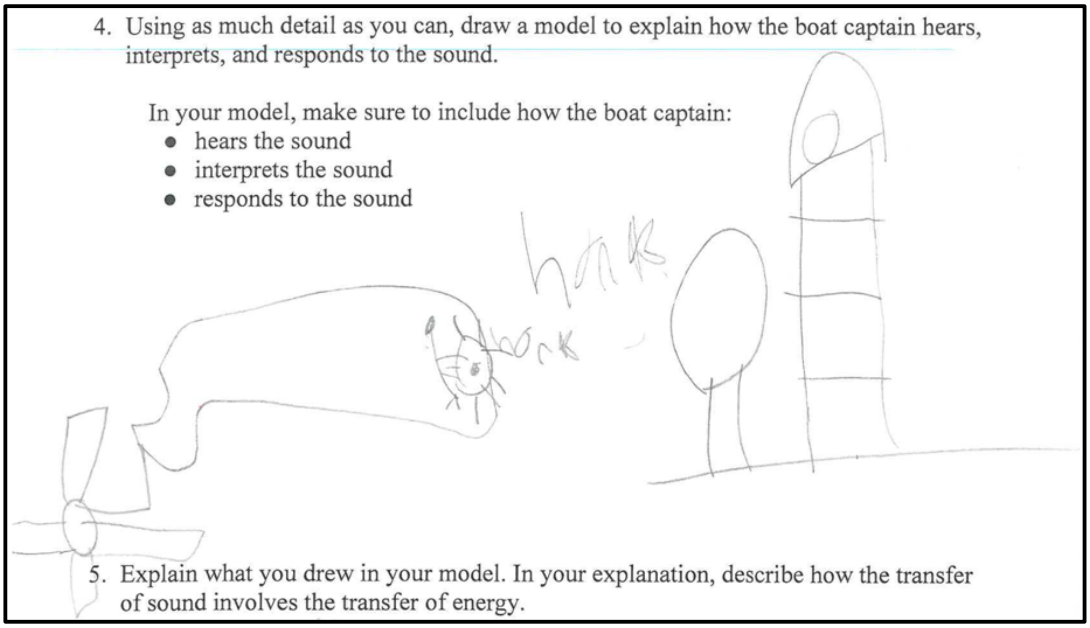


Figure VI.15. Samuel's Unit 3 pre-assessment model explaining how the boat captain hears, interprets, and responds to the sound from the foghorn.

Samuel shared similar thinking to Sophie regarding how energy is involved in communication by drawing on his knowledge of electricity and technology. He described megaphones, microphones, and phones as ways that energy might be involved in communication (Samuel Unit 3 Interview #1). For both the megaphone and microphone, Samuel also indicated that they could be used to speak louder, suggesting that he was also considering the importance of volume in communication or may have been prompted by my questions regarding Question 4 on the pre-assessment to think about volume.

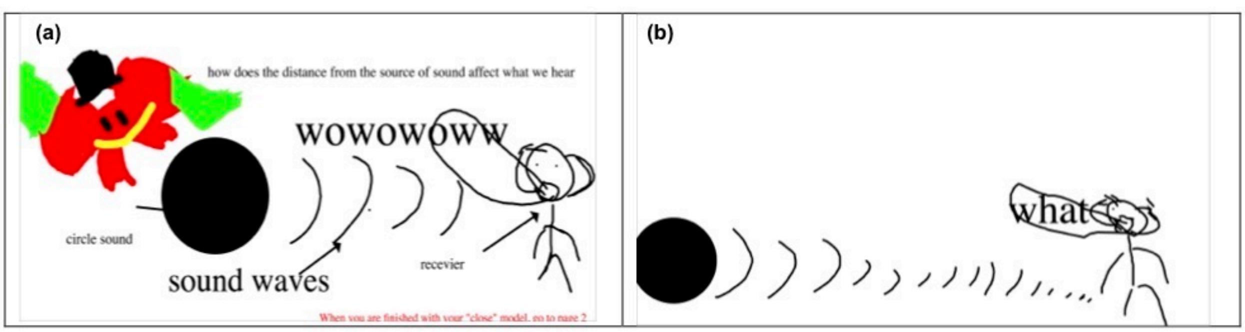


Figure VI.16. Samuel's model explaining the relationship between volume and distance when the source is (a) close to the receiver and (b) far away from the receiver.

Sound and distance model. Samuel's sound and distance model reflected the ideas that the class had discussed when constructing the class consensus model. Recall that the class constructed the consensus model before students were able to finish their individual models due to technical difficulties with the computers. Samuel's model included sound waves that decreased in size as they travelled away from the source (Figure VI.16). His source was also an abstract representation, instead of reflecting the phone or speaker that was used in the investigation. Samuel's model also included representations meant to communicate the volume of the sounds through the receiver's expressions. Samuel explained,

> Okay. So, the circle is making noise. And it's going to the person telling him something. And he's saying wow [….] So, their circle is really far away. And it's going--it's loud, and then it's going--it's going shorter and shorter and too short [….] And the person says what because he can't hear it very well (Samuel Unit 3 Interview 2).

Samuel's explanation suggests that he was considering ways to communicate the volume of the sound in his model, the differences in the volume between short and long distances from the source, and the size of the sound waves. Samuel described the size of the sound waves as getting shorter when the receiver is far from the source of the sound. He also demonstrated how he was inventing representations in order to communicate different volumes through his use of different reactions from the receivers in his models. His consideration of the communicative power of his model was also reflected in his Unit 2 water wheel model. In the water wheel model, Samuel chose the color yellow, "because yellow kind of looks like energy" (Samuel Unit 2 Interview #2). In Samuel's Unit 3 sound and distance model, he provided representations of responses that might occur when a sound is close (WOW) and a sound that is far away

(WHAT?). This suggests that Samuel's was continuing to think about representative ways to communicate important ideas in his model.

Samuel also included superfluous elements in his model, specifically the drawing of a crab (Figure VI.16a). When I asked him about the presence of the crab, he did not have a reason for including it besides explaining that the source of the sound was the "crab's sound." While this element technically does not belong in the model and models are only supposed to include components that contribute to a causal explanation of a phenomenon (Gilbert, 2004; Schwarz et al., 2009), engaging younger students in the practice of modeling may require allowing them to include their own elements that facilitate their interest and engagement in constructing models. Lehrer and Schauble (2012) and Manz (2012) suggest that young children can be introduced to the practice of modeling by using and constructing models that share physical resemblances to the target phenomenon. However, this could be extended to also allowing students to include their own components that they may have included in their mental models of the phenomenon, even if these components are not present in the target phenomenon and do not contribute to a causal explanation of the phenomenon. Samuel's model clearly showed the relationship between the distance between the source and receiver and the size of sound waves. In addition, he was able to explain this relationship and the resulting impact on the volume of the sound. His inclusion of the crab made the model more interesting for him and did not interfere with his ability to construct the model or communicate his understanding.

Samuel also shared during his interview that he thought, "it's good to make models so, like, you can think what is happening." This response to the prompt regarding whether or not models were helpful to learning about things suggests that Samuel was thinking about models' roles in communicating processes or mechanisms. This response was similar to Sophie's response, further suggesting that the students' interactions with models had supported the development of their understandings about the role of models in explaining processes or mechanisms in phenomena.

Samuel's response to this prompt reflected a more articulate view of the use of models than he shared during his Unit 1 modeling pre- and post-assessment interviews. During these Unit 1 interviews, Samuel revealed a *model is synonymous with the phenomenon* perspective to his discussions about the stream table. For example, his observations about the stream table used the language of the target phenomenon, suggesting that he did not differentiate between the stream table model and an actual stream. Samuel's sound and distance model, as well as his response to the prompt about the helpfulness of models, suggests that he was developing an understanding regarding the use of models to explain a phenomenon but that the model and the phenomenon were not the same. For example, he drew on his experience from the investigation to construct the sound and distance model; however, his model did not resemble the participants or procedure that were used during this investigation. This suggests that he may have differentiated the model from the actual phenomenon.

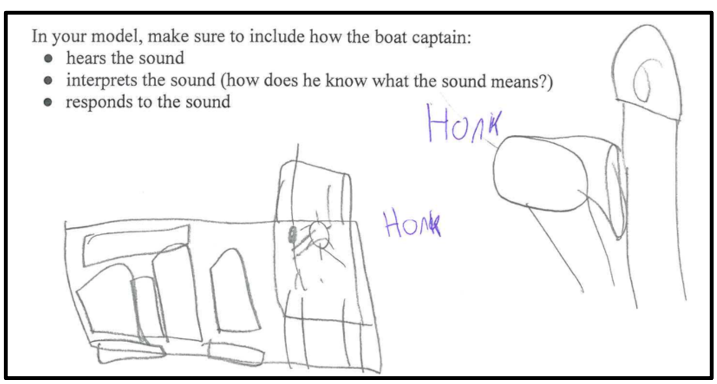


Figure VI.17. Samuel's Unit 3 post-assessment model explaining how the boat captain hears, interprets, and responds to the sound from the foghorn.

Post-assessment model. Samuel's Unit 3 post-assessment interview revealed the ways in which his understanding regarding the transfer of sound was still developing and context specific

(Figure VI.17). When he explained his model, he said, “It makes a really loud noise, so, so, so he knows that--so, like, he knows that he’s close to the lighthouse, which is meaning that he’s close to land.” However, neither his model nor his explanation of his model in his interview included any mention of sound waves. When I asked him to explain more about the noise, he decided to add a component showing the noise that was made by adding the word, *Honk*, in purple ink. Samuel used phrases in a similar way in his pre-assessment model and the sound and distance investigation. That is, he used phrases to communicate ideas that were important to the model. In his post-assessment model, Samuel used the word, *honk*, to show the noise that is made by the foghorn and the response by the boat captain.

When I asked Samuel to explain how the honk got from the foghorn to the captain, he drew on his understanding of volume and explained, “because the foghorn is super--the foghorn is super big, and so the bigger it is, the louder it is [….] So, so the captain can hear it, and so, so the captain honks his horn” (Samuel Unit 3 Interview #3). Samuel’s use of the concept of volume and the size of the foghorn is similar to the explanation that he gave in the pre-assessment interview regarding how the captain could hear the foghorn. I asked him if there was a way to show how the sound gets from the foghorn to the captain, and he responded, “draw the lines.” Samuel chose not to add these to his model during the interview but indicated that the class had talked about the lines previously and referred to them as, “the path.” He did not apply his understanding of the relationship between the size of sound waves and the distance from the source of the sound that he shared during the sound and distance model interview to the context of the Unit 3 post-assessment. It is also possible that Samuel had been thinking about the class’s more recent study of light and the importance of the path of light when discussing how humans and other animals see. The Knowledge Integration Framework (Clark & Linn, 2013) suggests that knowledge is constructed in concepts or fragments within specific contexts or experiences. Additional experiences of a similar nature or context can prompt individuals to apply these knowledge fragments to new contexts. As students encounter more contexts in which knowledge fragments can be applied, they can apply their knowledge fragments to a greater number of contexts and integrate these fragments into existing understandings of the phenomenon, resulting in more coherent and refined understandings that can be generalized to many different contexts. Samuel's explanation of his Unit 3 post-assessment model suggests that he did not identify similarities the contexts of the sound and distance model and the post-assessment model in order to apply his understanding of sound waves and the way they change over distance to the post-assessment model.

Samuel introduced new ideas regarding his thinking about the transfer of sound in his response to the prompt, How does the transfer of sound involve a transfer of energy? He explained, "Because it--the wind is blowing [….] It's blowing it, and it's, like, super hard. So, the harder the wind is, the louder it is. And so, like, if it's super, and if it's a little wind, it won't honk that loud." This response suggests that he could be thinking that the wind could carry the sound (e.g., "the harder the wind is, the louder it is") or that the volume of the horn is purposefully made louder because of hard wind (e.g., "if it's a little wind, it won't honk that loud"). This response did not involve ideas related to energy, but Samuel did share additional thinking about the ways in which the volume of the sound could be influenced. Samuel also did not share ideas related to energy when I asked him how energy was involved in communication. He shared, "with, like, anything, like a flashlight." This response reflected similar thinking to his response during the pre-assessment interview when he listed several electronics.

Summary. Samuel's lack of response regarding the role of energy or energy transfer in the transfer of sound and, more generally, communication suggests that he had not developed an understanding of energy transfer over the year. His interviews and models in Units 1 and 2, suggested that he had not developed an understanding of energy transfer in the context of erosion from water or from moving water or wind to other objects. Instead, he mostly focused on the observable features of these phenomena in his model. The same pattern occurred during Unit 3, in which Samuel focused mainly on the observable components of the phenomenon of the transfer of sound in his pre- and post-assessment models. Despite struggling to develop an understanding regarding energy transfer, Samuel did reveal a developing understanding about the nature of sound waves and the relationship between sound waves and distance in his sound and distance model and associated interview.

Samuel's Unit 3 models provide evidence that he continued to think about the ways in which representations could be used to communicate information in his models. Specifically, he used phrases to communicate the volume of a sound in all three of his Unit 3 models. The use of phrases still represents observable components of the phenomena, as opposed to using sound waves to communicate the same information, which he only used in one model. However, the use of words may serve as an intermediate step between omitting all references to sound in the model and including sound waves. Samuel's thinking regarding the purpose of the phrases in his models could serve as a resource that Samuel could draw on as his understanding of the practice of modeling and the concept of the transfer of energy increases.

Caleb. Caleb demonstrated high prior knowledge regarding the production and reception of sound and sound energy, as compared to his peers. When explaining the model on his pre-assessment that he constructed in response to Question 4, Caleb identified sound waves as a part of his model and explained, “The sound waves go to his boat so that he can hear” (Figure VI.18). Caleb was familiar with sound waves and their role in role in hearing a sound prior to the beginning of this unit. He did not have ideas related to the prompt, *how does the transfer of sound involve a transfer of energy?* This suggests that he was not able to apply the knowledge that he had constructed regarding energy during the previous unit to the context of sound. Caleb also drew on his knowledge of communication and electricity when he answered the prompt regarding the role of energy in communication. He explained, “like in restaurants they have the open sign and when that thing is off it means that they are closed and when it’s lit up that means they’re open.” Caleb’s responses during his pre-assessment interview suggest that he was aware of sound waves and the common representation of using curved lines to represent them. He was also able to explain that sound waves were necessary for hearing a sound.

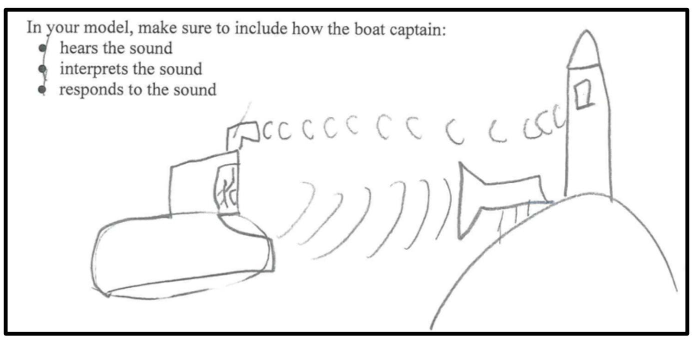


Figure VI.18. Caleb’s Unit 3 pre-assessment model explaining how the boat captain hears, interprets, and responds to the sound from the foghorn.

Sound and distance model. Caleb shared his thinking regarding the relationship between the size of sound waves and distance, as well as the ways in which data informed the construction of his model, in his sound and distance model and interview (Figure VI.19). Caleb’s model included specific features of the investigation that the class conducted, suggesting that he may still be considering his models to be depictions of target phenomena. In addition, Caleb included a label denoting “10 feet” in his model, “because the question was how far can you hear it.” Caleb’s rationale for including the distance suggests that he was considering his model as an answer to a question and that the data from his investigation informed the construction of his model. While this question was not precisely the question that students were tasked with answering in their model, Caleb was still able to show how the sound waves changed over distance.

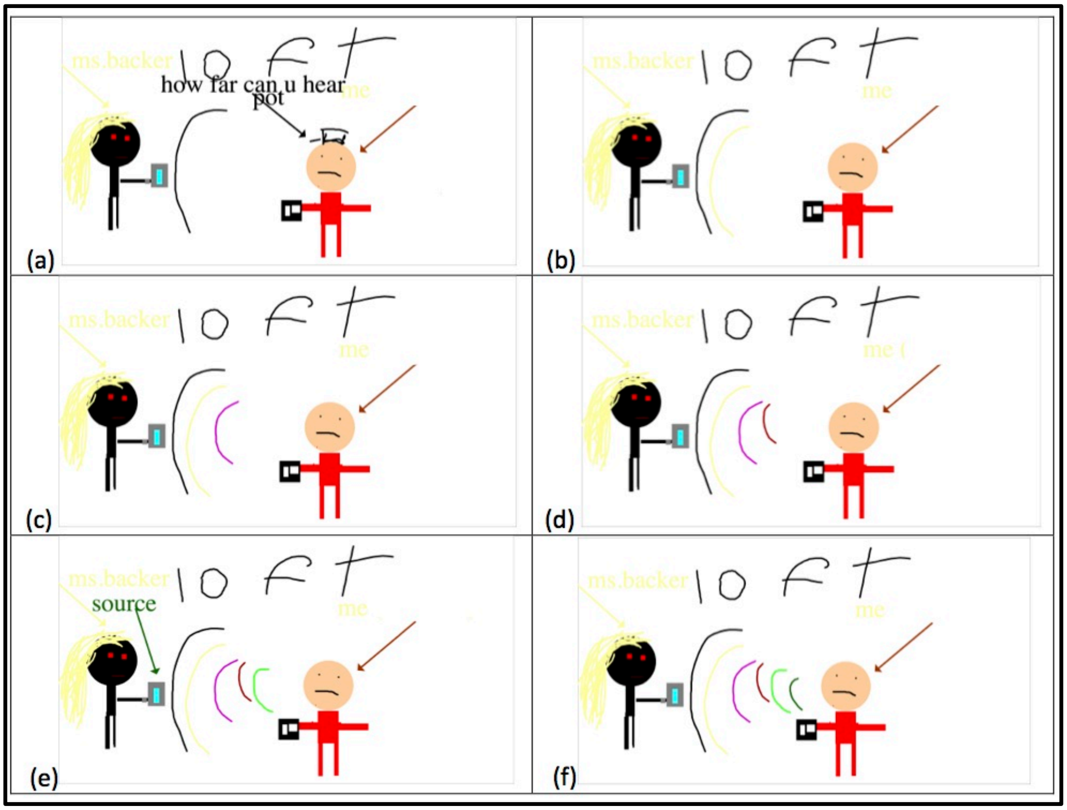


Figure VI.19. Caleb's *Flipbook* sound a distance model explaining how sound changes over distance. The images a-f are the different slides in his model that are animated to show the soundwaves traveling from the source to "me" (Caleb).

Caleb also demonstrated an understanding of the relationship between the size of sound waves and distance during his interview. He stated that, "it is easier to hear when you are really close and the farther away it gets quieter." His model reflected the understanding that had been discussed at length during the process of constructing the sound and distance class consensus model. Caleb demonstrated an understanding of the presence of sound waves on his Unit 3 pre-assessment, but the sound waves in his pre-assessment model were all the same size. The change in his representation of sound waves in his sound and distance model suggests that he had developed greater understanding of ways to represent sound waves in order to show the ways in which they change over distance and how this affected the volume of the sound.

When I asked why his sound waves were different colors, he responded, "I don't know, I just felt like making my model colorful." Similar to Samuel, this is another example of how providing younger students with freedom to make creative decisions that may not align with the practice of modeling could be beneficial in order to engage students in the practice. Caleb's sound waves showed the correct relationship; however, they are all different colors and the different colors do not denote meaningful differences among the individual sound waves.

Caleb also used animation in his model to illustrate the movement of the sound wave. Similar to the model Nick shared during the class's discussion before constructing the consensus model (see page 227), Caleb also used the animation feature to depict how sound waves move from the source of the sound to the receiver. Both Caleb and Nick's uses of animation demonstrate how this feature in *Collabrify Flipbook* can support students to show the process by which sound waves travel.

Despite Caleb's increased understanding of sound waves, his use of the features in *Flipbook,* and the data from the investigation to construct his model, he did not demonstrate understanding of the role of models in science. When I asked if he felt that models were helpful for learning about things, Caleb initially responded, "yah," but when I asked why he answered that way, he was not able to articulate his thinking. I rephrased the prompt to ask what he liked about constructing models and he explained, "that you can like draw it and make the characters look like however they want. And you have almost every color. With pencils, you only have gray." In Unit 2, Caleb used colors in meaningful ways to illustrate the presence of electricity and provided rationale for his choice of the color yellow in his model. Caleb did not demonstrate the same approach to the use of color in his sound and distance model. Caleb's explanation suggests that an interest in drawing motivated him to construct models that included creative elements but also included important insights into his sense-making regarding phenomena. The same insights may not have been gathered if Caleb had only constructed models using paper and pencil, as this activity may have been less engaging to Caleb.

Unlike Sophie and Samuel, Caleb did not draw on the class's discussions throughout the year, especially in Unit 1, regarding the role of models in seeing phenomena. Caleb was not a focal student during Unit 1, therefore it is not possible know if his thinking had developed at all from the beginning of the year. However, Caleb's reference to the features of the *Flipbook* that he liked using suggests that this modeling tool supported his engagement in the practice of modeling.

Post-assessment model. Caleb's post-assessment model and interview revealed that he applied the understanding he developed during the sound and distance investigation to the context of the post-assessment question (Figure VI.20). In his model, Caleb drew sound waves that were decreasing in size as they moved from the source to the receiver, "because the farther something is, the harder it is to hear." This explanation mirrors the one that Caleb gave during his sound and distance interview.

It is not known how Caleb considered the transfer of sound to involve a transfer of energy, as this question was accidentally skipped during the interview. However, Caleb's response to the question, how is energy involved in communication, revealed limitations in his understanding of energy. He explained, "Sometimes when you lose your voice, it's because you lost your energy and you have to wait for it to come back," and "How people use lights, use electricity energy." Caleb's response draws on the colloquial application of energy to people and the way in which energy was discussed in Unit 1. A common use of the term, *energy*, is to refer to people as having energy (Hammer et al., 2012). Caleb's response regarding losing your voice due to a loss of energy is an interesting combination of communication and energy. Students discussed the role of vocal chords in producing sound during class; however, they did not discuss what it meant to lose your voice. Caleb was likely drawing on his prior knowledge or experiences in answering this question.

He also provided the example of using electrical energy to communicate through using lights. Students spent several class periods learning about the ways in which humans used light to communicate (e.g., through the use of Morse code on ships). Caleb may have been drawing on this example in his response. Caleb's response suggests that his understanding of the concept of energy transfer had not developed during Units 2 or 3, as he also struggled to incorporate ideas related to energy when he answered the novel task question about the pool balls at the end of Unit 2.

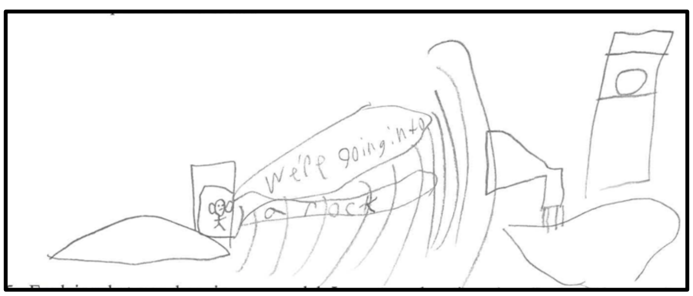


Figure VI.20. Caleb's Unit 3 post-assessment model explaining how the boat captain hears, interprets, and responds to the sound from the foghorn.

Summary. Caleb's Unit 3 models and interviews reveal that his sense-making regarding the relationship between distance and sound waves developed during the unit, and that he was able to apply his understanding of how the size of sound waves changed in the context of the sound and distance investigation to the context of the question on the unit post-assessment. However, Caleb's sense-making regarding the role of energy in the transfer of sound did not appear to have developed during Unit 3; however, this is not clear, due to the omission of this question from the post-assessment interview.

Caleb did not demonstrate an understanding of the role of models in communicating ideas about a phenomenon but did use features of the *Flipbook* program to support his explanation of how sound waves travel and change over distance. His use of this tool was consistent with how he used these features in the water wheel model in Unit 2. One possibility is that Caleb was drawing on the ideas of using data to inform his model and considering the ways that animation could be used to show a process but was not able to articulate these ideas. Baek and Schwarz (2015) characterize students' epistemologies in modeling (EIMs) as reflections of students' specific practice in modeling, as opposed to broader epistemologies of the practice of modeling. Similar to Sandoval's (2015) argument for the use of practical epistemologies that are specifically related to students' use of scientific practices, students' EIMs are developed through their formal instruction and everyday experiences, as well as their engagement in constructing and using models. In addition, Baek and Schwarz (2015) emphasize that these EIMs can be contextual and unstable. Caleb's consistent use of animation in his models could be an example of an epistemology in modeling that he held regarding its use in communicating the underlying process or mechanism in a phenomenon. His inability to articulate the ways in which models were helpful for learning may be the result of a mismatch between the context-specific nature of these EIMs and the broad nature of the question.

Kiara. Kiara demonstrated low prior knowledge regarding the production and reception of sound and sound energy, as compared to her peers. In her pre-assessment interview, she explained that she drew the fog horn as her model (Figure VI.21), and shared her understanding that volume affected the captain's ability to hear by explaining, "because they probably turn it up real loud so they can hear it and stuff." Kiara also shared how that she thought "when they turn it on, it echoes probably" in response to how the prompt regarding the boat captain interprets the sound. Eshach and Schwartz (2006) also found that some students discussed echoing when sharing their understanding of sound. While the phenomenon of echoing is not involved in the interpretation of the sound, Kiara's comment suggests that she considered echoing to be related to the idea of sound and the transfer of sound.

She also drew on her knowledge and experiences from Unit 2 when sharing how energy is involved in communication. She explained, "probably they have to plug in something to turn on the light, or a switch. Because when the captain sees the light, they know they were trying to help them not go into any rocks or anything." Kiara's response referenced the idea of electricity that was prominent in Unit 2.

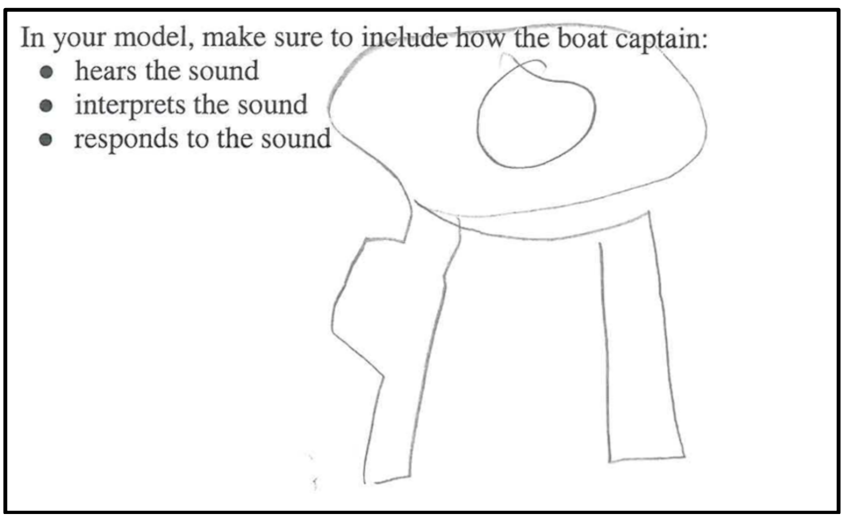


Figure VI.21. Kiara's Unit 3 pre-assessment model explaining how the boat captain hears, interprets, and responds to the sound from the foghorn.

Sound and distance model. Kiara's sound and distance model and interview revealed how her thinking regarding the nature of sound waves and the transfer of sound waves had developed. Recall that Kiara struggled in Unit 2 with her understanding of energy transfer in both the water wheel and wind turbine contexts. Her Unit 3 sound and distance model and her associated explanation suggest that she had developed an understanding of the role of sound waves in hearing a sound. Kiara included sound waves in her model and addressed the idea that sound waves are invisible when she described the third slide of her model shown in Figure VI.20c, stating, “This is, usually you can’t see them, but these are the sound waves by her ear.” This observation by Kiara demonstrates a shift in her thinking from Unit 2, when she only included and discussed observable features of the phenomenon that the class was studying.

Kiara further demonstrated that she was considering ways to improve her model’s ability to explain the phenomenon of hearing sounds by including two unique components that other focal students did not include: a Bluetooth speaker “because it is making it more louder for her to hear” (Figure VI.20a), and the receiver’s ear “so that she can hear” (Figure VI.22b). These two components were not explicitly discussed in the sound and distance investigation or during the creation of the class consensus model. Students did engage in an activity in which they constructed “ears” to improve their own ability to hear sounds of different frequencies. This activity may have influenced Kiara’s thinking regarding the inclusion of the ear in her model.

The purpose of this model was for students to show how distance affected the volume of the sound because of the changing size of sound waves. Kiara’s model does not address the relationship between volume and distance, but she included components that were important for the phenomenon of hearing sounds, which appeared to be the phenomenon on which she focused in her explanation of her sound and distance model. An important aspect of modeling is the inclusion of components that contribute to a causal explanation of the phenomenon and exclusion of unrelated component (Manz, 2012). Kiara’s emphasis on the receiver’s ear in Figure VI.20b suggests that she felt this was an important component to include in the model in order to explain how sound is heard. In addition, while the Bluetooth speaker may not be necessary to explaining the phenomenon of hearing a sound, it is loosely related to the idea of volume and it is an example of a sound source.

Throughout her discussion about her sound and distance model, Kiara explained how the receiver in the model is dancing. This is another example of how providing younger students some creative freedom in constructing models may engage them in the practice of scientific modeling. Kiara included several important components in her model; in addition, she could articulate her understanding about the role of sound waves in hearing sound as well as the invisible nature of sound waves. The story embedded within her model, that the Bluetooth speaker was playing a sound loudly so the girl could dance, provided Kiara an entry point into the practice of modeling.

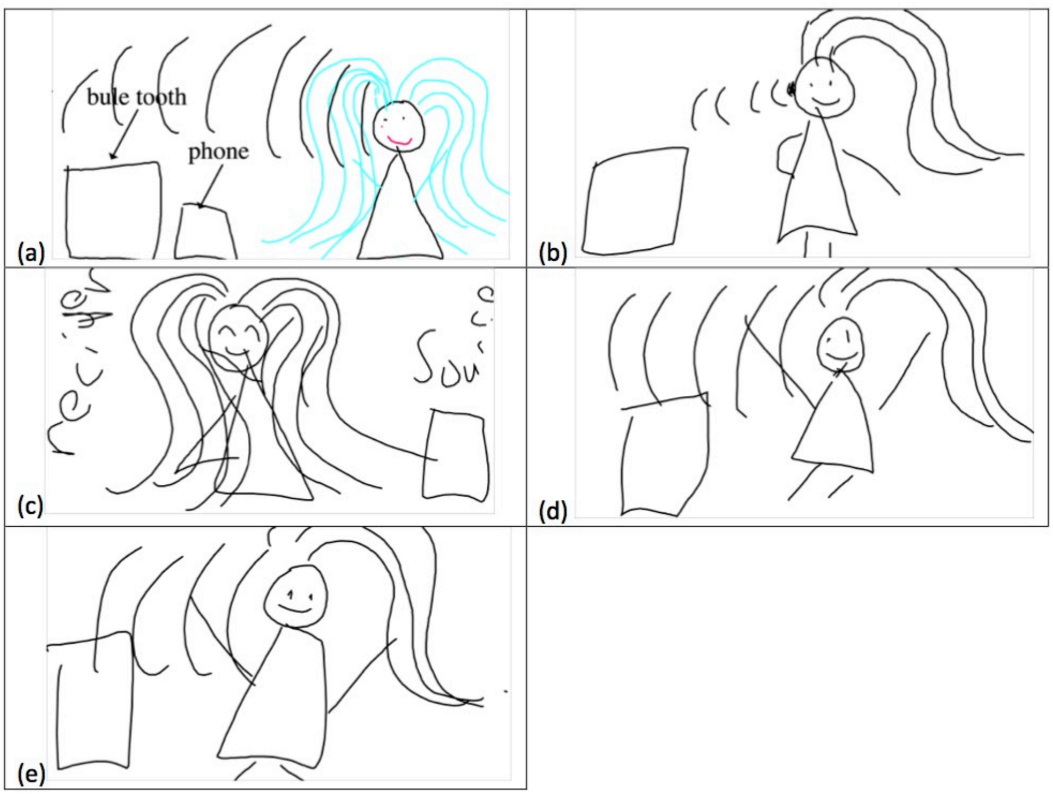


Figure VI.22. Kiara's *Flipbook* sound a distance model explaining how sound changes over distance.

Kiara was also able to articulate the role that models play in communicating ideas when she responded to the question regarding the helpfulness of models for learning. She explained, “yes, because maybe some people don’t understand maybe like if you draw a picture and see how what can actually happen, maybe you can understand it.” Kiara’s response reflects the idea of a model representing a phenomenon. Lehrer and Schauble (2012) identify this idea as foundational to understanding the role of models in science. Kiara also specified drawing a picture suggesting she associated drawn models, such as those constructed using paper and pencil or *Collabrify Flipbook*, with the practice of modeling.

Post-assessment model. Kiara drew on her knowledge of sound waves when explaining her model on the Unit 3 post-assessment (Figure VI.23). Initially she described her model by identifying the components, “That’s the horn that’s right there and that’s the boat and that’s the light house.” Her post-assessment model included a greater number of components, as compared to her pre-assessment model, suggesting that Kiara’s identified additional components that were important for her model on the post-assessment. This could have occurred due to familiarity with the assessment question, as this was the second time she had seen this question, or because she was becoming more familiar with the practice of modeling and identifying important components necessary to answer the question guiding the model’s construction.

Kiara had written “sound waves” in response to Question 5, *How does the transfer of sound involve a transfer of energy?* When I asked how the captain hears the sound and about her answer regarding sound waves, she referenced the idea of echoing that she discussed in the pre-assessment interview but was not able to incorporate ideas about energy into her answer.

MM How does the captain hear the sound?

K(iara) Because it blows very, very loud and they hear it. It echoes out of the big thing right there. [pointing to the fog horn on her model]

MM You mentioned sound waves down here.

K When it echoes the sound waves they get bigger and bigger so the captain can hear it more.

Kiara's response revealed that she held the misconception regarding the relationship between the size of the sound waves and the distance that the class had discussed while constructing the class consensus model. Unlike during her interview regarding the sound and distance interview, Kiara was able to identify a relationship between sound waves and distance. Despite being an incorrect description of the relationship, this explanation suggests a development in her sense-making regarding the relationship between sound waves and distance, as she was able to articulate the presence of a relationship. Building on the Knowledge Integration Framework perspective (Clark & Linn, 2013), the next step to support Kiara's sense-making would be to provide additional experiences that prompt her to confront her current (inaccurate) understanding of this relationship and support her refinement and replacement of this understanding with the accurate relationship.

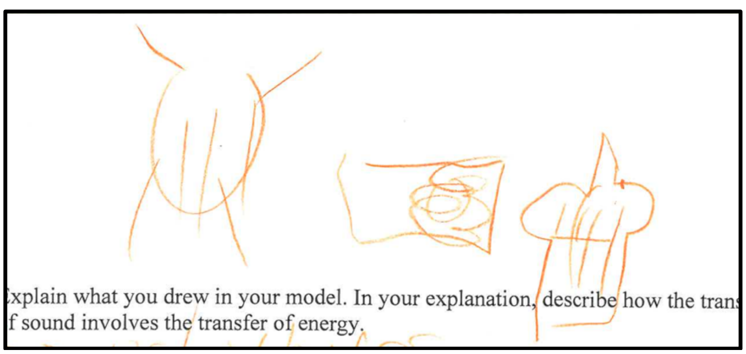


Figure VI.23. Kiara's Unit 3 post-assessment model explaining how the boat captain hears, interprets, and responds to the sound from the foghorn. Her model shows the foghorn (left), boat (center), and lighthouse (right).

Kiara's reference to echoing further suggests that she associated the idea of echoing with the phenomenon of hearing and it was activated by this question. When I asked Kiara how the transfer of sound involved a transfer of energy, she could not answer and said, "I forgot." Unfortunately, this limited the remainder of the interview, because when I asked how energy was involved in communication, Kiara could not answer and again said, "I forgot." Kiara's post-assessment interview revealed that her sense-making regarding the phenomenon of sound and the relationship between sound waves and distance was developing. She still held an incorrect understanding regarding this relationship but had established that a relationship existed, which was an important first step to developing an accurate understanding of the relationship.

Summary. Kiara demonstrated development in her sense-making regarding the phenomenon of sound from the beginning to the end of Unit 3. In addition, her sense-making regarding epistemological aspects related to the role of models and the inclusion of components that contribute to the explanation of the phenomenon in the model appeared to develop between Units 2 and 3.

Kiara struggled greatly during Unit 2 regarding her sense-making of the idea of energy transfer. Her interviews in Unit 3 suggest that she still does not hold an understanding of energy transfer. However, her sound and distance model and her post-assessment model and associated explanations revealed that she had developed an understanding of the presence of sound waves in the phenomenon of hearing sound and that there was a relationship between the size of sound waves and distance. Her understanding of this relationship was backwards, as well as her understanding of how volume is affected by distance, but she had developed ideas that could serve as resources for future experiences related to the phenomenon of sound.

Kiara's models and her decisions about the components to include in them reflected greater understanding of the ways in which components could contribute to the model's causal explanation of the phenomenon. Her understanding was still very foundational; however, she was able to articulate why she included the components in her sound and distance model (e.g., the ear was important for hearing the sound). During Unit 2, Kiara's models included nonsensical features and she was not able to explain how they contributed to the model. One explanation for Kiara's development in her understanding of modeling is that she demonstrated increased understanding of the phenomenon of hearing, as compared to the phenomenon of energy transfer in Unit 2. Her increased understanding of sound waves and sound supported her development of the practice of modeling and suggests that she held enough prior knowledge to engage in modeling aspects of the phenomenon of sound. Passmore and colleagues (2013) suggest that engaging students in the practice of modeling provides opportunities for sense-making with and about models. Kiara's increased sense-making in Unit 3, as compared to Unit 2, provides an example of the concurrent development of conceptual and epistemological understandings that engaging in modeling can provide.

Conclusions from Unit 3

Focal students' models and interviews during Unit 3 provide insight into the ways in which models can serve as tools for supporting and assessing sense-making. The models that students constructed on the pre- and post-assessments served as ways to assess their understandings of the transfer of sound. However, students' explanations of their models were critical in capturing a holistic picture of students' sense-making, as students provided additional insights into their thinking during the interviews that were not evident in their models. The sound and distance models also provided opportunities for students to share their sense-making regarding the relationship between sound waves and distance. These models reflected a range of understandings and the extent to which constructing the class consensus model prior to students finishing their individual models influenced their sense-making. For example, Kiara did not discuss a relationship between sound waves and distance during her sound and distance interview, Sophie described an incorrect relationship, and both Samuel and Caleb included the correct relationship. These findings suggest that the class consensus model influenced some students' sense-making but not others.

Despite including sound waves in their sound and distance models, focal students demonstrated varied application of the ides of sound waves in their unit post-assessment model. Caleb was the only focal student to include sound waves in his unit post-assessment model. Kiara wrote that sound waves as her response to the question regarding how the transfer of energy was involved in the transfer of sound, but her explanation of her answer revealed that she held an incorrect understanding of the relationship between the size of sound waves and distance. Samuel suggested that he should add lines to his model but did not refer to them as sound waves, and Sophie did not include sound waves but described how sound waves traveled from the source to the receiver in her model. A comparison of students' unit pre- and post-assessment models revealed that there were some changes from pre- to post-assessments but also many similarities. One explanation is that the question prompted students to think about the observable elements of the situation described in the question, as opposed to, the causal explanation of how sound travels. This also suggests that students were still focused on the observable components in models, as opposed to the invisible components used to provide a causal explanation. Another explanation is that students' understanding of sound waves was contextualized to the investigation they conducted and they did not recognize similarities between that context and the context of the assessment question.

In addition, students' prior knowledge did not have the same effect on the development of students' sense-making regarding ideas related to the transfer of sound, as had been observed in Unit 2. Both Kiara and Samuel demonstrated low prior knowledge at the beginning of the unit, but their understandings of the transfer of developed during the unit. Samuel developed an understanding of the relationship between the size of sound waves and distance and Kiara developed an understanding of the role of sound waves in hearing sounds. It may be that the ideas related to sound that Samuel and Kiara developed were more concrete than the idea of energy transfer discussed in Unit 2. Another explanation is that both Samuel and Kiara held pieces of prior knowledge that were enough to facilitate their engagement with the phenomenon of sound, suggesting that there may still be a minimal threshold of prior knowledge of a phenomenon is required in order to engage productively in the practice of modeling about a phenomenon.

All four focal students struggled with the idea of energy as it related to sound transfer. Sophie demonstrated the most developed understanding, as compared to the other three focal students, and was able to extend the idea that moving objects have energy, including sound waves. We need to acknowledge that she entered Unit 3 with the idea that moving objects had energy. The other three students did not demonstrate understandings regarding the role of energy in sound and also had struggled in Unit 2 to apply ideas of energy transfer to their explanations of their water wheel and windmill models. This suggests that the use of models in the unit may not have adequately supported students' sense-making related to the idea of energy transfer in sound. The vibrating rice model was designed to support students' sense-making regarding that the transfer of sound involved a transfer of energy. Sophie was the only focal student who demonstrated development in her sense-making regarding this idea. Prior research on the development of children's understanding regarding energy suggests that the first aspect of the development is an understanding the energy can be present in many forms (Lui & McKeough, 2005). The students in this study may have also struggled with the application of ideas of energy transfer to the context of sound because they had not yet developed the understanding that sound transfers energy from place to place.

The selection of components that were necessary for the model was an emphasis of the class consensus modeling activities. This idea was also prevalent in focal students' individual models. For example, Caleb demonstrated the use of data to inform his model and answer the question that he had identified for his model. Focal students also included inventive representations in order to communicate ideas in their models. Some of these representations were not central to the causal explanation of the model but may have supported students' engagement in the construction of the model. For example, Caleb discussed how he included sound waves of different colors because he wanted his model to be colorful; Kiara's model showed a girl dancing; Samuel's model included a crab. These aspects of focal students' models were not relevant to the purpose of the model for explaining how sound traveled from the source to the receiver but allowed students to personalize their models and generated interest in constructing them. Given that these students were new to the practice of modeling and relatively young, they may have benefitted from creative leeway in order to productively engage in the practice of modeling.

However, this creative allowance must be monitored, as it can inhibit students' productive engagement. Sophie included very detailed drawings in her sound and distance model, which required a lot of time to create. Her focus on these drawings, as opposed to completing the model, limited her ability to share what she knew about the relationship between sound waves and distance. In addition, it may have reinforced her thinking that models looked the same as the target phenomenon. This tension also occurred in Unit 2 when students discovered how to import images from the internet to their water wheel models. For a majority of the class, these images were not related to the topic of their models and did not support their abilities to communicate ideas. Instead, they served as distractions and time sinks during the construction phase of modeling. Ms. White led the class in a discussion about the use of pictures and if they contributed to the explanation in the model. This is one example of how the teacher was vital in mediating and supporting students' engagement in the practice of modeling.

Focal students also demonstrated development in their epistemological understandings related to modeling. The prompt in the sound and distance model interview was effective for eliciting students current thinking regarding the role of models. Three of the four focal students discussed the role of models in explaining how something works. The emphasis suggests that Sophie, Samuel, and Kiara were developing an understanding related to the use of models a representation of the target phenomenon; however, it is possible that they still considered models to reflect features of the target phenomenon in order to explain the underlying mechanism. This idea also reflects Ms. White's explanation of models over the year of science. Sophie was the only student to discuss the role of scale in models, specifically that models are a smaller scale than the target phenomenon. Caleb stated that models were helpful to learning but did not offer ideas related to the role of models in science; however, his use of animation in multiple models suggests that he found this feature salient to his modeling practice. Students' ideas related to the helpfulness of models for learning suggests that they considered the use and construction of models helpful for learning and had developed understandings related to their own practice of modeling, an example of Sandoval's practical epistemologies (2015).

CHAPTER VII

Conclusion

This study investigated how the features of models, and the contexts in which they were taught and used, influenced 4th graders' sense-making and engagement in the practice of using, interpreting, and constructing models across a year of instruction. I used case study methods to document the sense-making of one 4th grade class as they engaged in the use and interpretation of models and the practice of modeling within the context of a project-based learning science curriculum. The case of Ms. White's class was divided into multiple sub-cases, each detailing the class's collective sense-making and students' individual sense-making regarding both concepts used to explain phenomena and epistemological ideas related to the practice of modeling.

This chapter is separated into four sections. In the first section I discuss my findings related to the trajectories of: students' sense-making regarding the concepts they engaged with through the practice of modeling, sense-making regarding the epistemological ideas related to the practice of modeling, and the influences of prior knowledge and technology on sense-making. The second section identifies implications for curriculum, instruction, teacher learning, and policy. The third section discusses limitations of the study; and the final section provides future directions for this research.

Development of Students' Conceptual Sense-Making with Models

Overall, students demonstrated development in their sense-making of the individual phenomena covered in each of the three units (i.e., erosion, renewable energy, and sound). The sense-making maps across the three units illustrate that engagement in the use and construction of models supported students to generate and take up important ideas related to the concepts in each unit and epistemological aspects of practice of modeling, as well as provided opportunities for Ms. White to seed important ideas regarding the use and construction of models. Interviews also revealed that focal students developed increased understandings regarding the phenomena in the units. In Unit 1, all focal students demonstrated development in their understanding related to the factors that influenced the process of erosion from water; in Unit 2, five out of six focal students demonstrated development in their understanding that energy was present in renewable forms of energy; and in Unit 3, all focal students demonstrated development in their understanding of the behavior of sound waves.

The construction of models also supported students' sense-making regarding the conceptual ideas central in each unit. In Unit 1, the use of the stream table, rain, and wave table models supported students to identify factors that caused erosion from water (i.e., the slope of a hillside, the intensity of rain, or the frequency and size of waves). In Unit 2, constructing models of wind turbines and testing them to determine if students' designs could make a generator spin appeared to support the development of all focal students' understanding of the process of using energy from wind to generate electricity to different degrees. In Unit 3, many students incorporated sound waves into their models to explain why the volume of a sound decreases over distance, despite not being told directly to include this component, which allowed the class to have discussions regarding the representation of the sound waves to communicate differences in volume.

In addition to the specific phenomena that drove students' inquiry during the units, the 4th grade curriculum integrated the concepts of energy and energy transfer throughout the units of study. The curriculum was designed to build on ideas related to energy and energy transfer as students progressed through the units. Unit 1 was designed to introduce students to the concept of kinetic energy and that moving objects have energy and this energy is transferred when two objects collide. In Unit 2, the curriculum was designed to expose students to two examples of energy transfer through the process of generating electricity and support them to draw on their understanding of energy transfer to explain how water and wind can be harnessed to generate electricity. In Unit 3, students were expected to apply the idea of energy transfer to an explanation of how sound travels.

The development of students' understandings related to the concepts of energy and energy transfer were varied. These concepts remained difficult for students to engage with and articulate across all three units. One possible explanation is that students' discussions regarding energy and energy transfer were contextualized within the central phenomenon of each unit; students may not have recognized similarities across the different contexts in which the same idea of energy transfer could be applied. For example, during Unit 1, students did incorporate ideas related to energy in the whole-class discussions during their engagement with different models, such as the difference in energy between heavy rain and light rain and the speed of the steel ball hitting the container. However, students' discussions in Unit 2 suggest that they did not apply the idea that objects transfer energy to other objects when they collide when they used water wheel and windmill models and investigated how spinning objects could transfer energy to another object to make it spin in Unit 2.

There were two instances during class discussions and interviews in which students recalled previous experiences with models. IP recalled the rain model when discussing how the class could change the force of the water hitting the water wheel and Caleb referenced the steel ball investigation during his discussion of the billiard ball task in the Unit 2 post-assessment interview (see Chapter 5). However, these were the two only examples of instances when students drew connections to previous experiences with models and neither IP nor Caleb made connections to the concept of energy transfer in either instance.

Students struggled in both Units 2 and 3 to apply the idea of energy transfer to a causal explanation of the phenomena they were studying. In Unit 2, students observed multiple instances of the transfer of energy in the water wheel and the windmill models. However, focal students' drawn models did not include representations of energy transfer. In addition, interviews with focal students revealed that, while students progressed in their understanding of the path of energy transfer as the unit progressed, their understandings at the end of the unit were still incomplete. Students also struggled to relate the presence of sound waves in the transfer of sound to the concepts of energy and energy transfer. Most of the class discussions were related to the idea of sound waves as the mechanism for the transfer of sound from the source to the receiver. In addition, only one focal student during this unit, Sophie, recalled the idea that moving objects had energy in her explanation of how energy was involved in communication. Despite this, Sophie was not able to relate this idea to the concept of communication. Students engaged in an investigation that was designed to prompt them to think about the transfer of energy through air between the source of the sound and the receiver during the vibrating rice investigation. However, when the class constructed a model to explain why the rice moved, the class discussed the presence of energy transfer but did not represent it in the model.

In addition, the creation of models in which students focused on the representation of sound waves may have limited students' abilities to consider the ways in which their knowledge of energy transfer could be applied. The focus of the conversations regarding the construction of the model were related to the representation of sound waves, as opposed to the vibrations of the air and the transfer of energy represented by the sound waves. One approach to address this would be to introduce students to the concept that air is composed of microscopic entities that are moving and collide, causing a transfer of energy that leads to the vibrations that produce sound. The *Framework for K-12 Education* states that sound is more easily discussed at a microscopic level than at a macroscopic level (NRC, 2012a). The experience of Ms. White's class and the difficulties they faced in considering the idea of energy transfer as it relates to sound illustrates this point.

Another possible explanation for the difficulty that students faced in representing energy transfer in their model is that this representation required students to grapple with complex conceptual and epistemological ideas simultaneously. Students had to understand that energy was transferred from one object to another object and had to understand that showing invisible processes was an important aspect of modeling. Given that students had not been introduced to the particulate nature of matter, they could have invented representations to communicate the idea of energy transfer. However, given the complexity of the concept of energy transfer, they may not have been able to conceptualize what a representation of this could look like. Forbes and colleagues (2015) found a similar pattern when analyzing 3rd grade students' model-based explanations of the hydrologic cycle. Students struggled to conceptualize the ways in which water returned to the atmosphere and omitted these representations in their models. Taken together, constructing these models may have required more cognitive overhead than was developmentally appropriate for 4th grade students and demonstrates one way in which the conceptual and epistemological components need to be balanced to allow students to productively engage in both dimensions of the practice of modeling.

Despite these difficulties, focal students did demonstrate greater understanding of the concept of energy transfer in the context of the novel task at the end of Unit 2, as compared to the contexts of renewable energy or sound. Recall that during the Unit 2 novel task, students were asked to explain how billiard balls moved after watching a video of a person using a pool cue to hit one ball, which then hit a second ball. Focal students demonstrated a range of understandings related to energy transfer from a very foundational observation that motion was involved to tracing the path of motion from the arm of the person holding the pool cue through the last ball falling into the pocket. The examples of energy transfer among the billiard balls are more concrete than the examples of energy transfer within the water wheel or windmill systems. This suggests that students may have held greater understanding of the concept of energy transfer than they were able to demonstrate through modeling the ways in which renewable energy sources could be harnessed to generate electricity.

Development of Students' Epistemological Sense-Making with Models

The study of students' engagement in the practice of modeling over the year of instruction revealed a set of epistemological ideas that students engaged with that could inform a trajectory of epistemological thinking related to the practice of modeling. The analyses of the collective sense-making discussions in Ms. White's class and individual sense-making of focal students illustrated different epistemological ideas that were introduced and taken up throughout the year as students engaged in the practice of modeling. I will provide a discussion of the trajectory of collective sense-making observed in Ms. White's class and insights gained regarding individual sense-making of focal students in order to provide a possible progression of epistemological ideas with which 4th grade students could engage.

During Unit 1, class discussions focused on the purpose of models. This was supported through the discussion prompts embedded in the curriculum, as well as Ms. White's reminders that models could be used to "see things." The data suggest that students took up this idea during their class discussions at the end of Unit 1 and built on ideas regarding the use of models to include ideas of the trustworthiness of the model and using models to explain phenomena that cannot be seen in real life (i.e., the process of erosion). The use of the stream table may have supported students in thinking about the purposes of models due to the fact that students were modeling a phenomenon with a process that occurs over a long period of time. In addition, the class constructed a scientific explanation drawing from their experiences with the rain model, which may have supported students to consider this model of a trustworthy source from which they could gather data to write an explanation of how rain caused erosion.

The focal students demonstrated a range of epistemological perspectives related to modeling that ranged from *the stream table model is synonymous to the phenomenon* to *the stream table model only shows some ways in which water can shape the land.* In addition, three of four focal students demonstrated development in their thinking regarding limitations of the stream table models from the beginning to the end of the unit. diSessa (2004) argued that students must understand the purpose of different forms of representations before they are able to evaluate them. These findings suggest that students were capable of considering the limitations of the stream table model and that engagement in Unit 1 supported the development of their thinking regarding the stream table model's limitations.

In Unit 2, students focused on the ways in which they could communicate ideas through models, such as the use of conventions and the inclusion of invisible components, and the role of the model as a functional analog to the target phenomenon. The purpose of the models that students constructed during this unit was to explain a process that they had not directly observed in their own investigations. Therefore, students had to apply what they observed in either the water wheel or windmill investigations to the phenomenon of lighting a bulb. These models involved a degree of abstract thinking that had not been required in students' modeling experience in Unit 1.

Students worked with multiple invisible entities in their models, including the idea of energy transfer between objects and the presence of electricity. Interviews with focal students suggested that several of them were mindful of the way in which they represented electricity in their water wheel models, and to a lesser extent in their windmill models. In addition, analyses of focal students' models suggest that they included invisible entities that had visible results (e.g., wind that moved the turbine and electricity that lit the bulb). This suggests that students may have been prompted to consider certain invisible entities as a way to explain visible effects. The lack of invisible representations of the process of energy transfer within students' models is not entirely unsurprising given that existing literature has documented students' struggles to consider hidden mechanisms (Baek & Schwarz, 2015; Forbes et al., 2015) and natural tendency to attend to the visible aspects of a phenomenon over the invisible aspects (Lehrer & Schauble, 2012). Given that the effects of energy transfer could be explained using macroscopic elements (i.e., wind causing the turbine to turn or water causing the water wheel to spin), students may not have been prompted to consider the hidden mechanism at work in the system. This suggests that more support needs to be given to students to think about the role of models in explaining hidden mechanisms and the centrality of hidden mechanisms in the practice of modeling.

In Unit 3, class discussions continued to center around the representation of components in students' models. This unit offered the first experience that students had with consensus models and the class completed these at three different times during their exploration of sound. During the construction of the class consensus models, students engaged in conversations regarding the representation of the source of the sound. Several students who contributed to the consensus models and shared their own models, drew representations of the investigation set-up. However, there were conversations regarding what components needed to look like and one student, Nick, shared his model that included a generalized source of sound in his model, which led to a discussion about whether or not components needed to reflect the real-life situation being modeled. Similar to Unit 2, students used data from their investigations to inform the design of their models. These data were mostly comprised of observations, but students used numerical data from their sound and distance investigation to inform the construction of their sound and distance model. Only one focal student discussed how he used these data in his model, suggesting that this epistemological aspect of the practice of modeling required additional support.

The models constructed by focal students during Unit 3 also provided examples of students bringing their own creativity to the practice of modeling. Three of four focal students created models with stories that were unrelated to the phenomenon of sound but also included important components necessary to explaining the relationship between volume and distance. This creativity was not observed in the models constructed by focal students in Units 1 or 2. One possible explanation is that the phenomenon of sound was more abstract than the phenomena that students modeled in earlier units, and therefore students engaged with this more abstract phenomenon by placing it in a concrete context. For example, Kiara's model included a girl that was dancing to music from a Bluetooth speaker and included components to explain how the girl heard the sound. Samuel included a crab in his model, which did not serve a role in the explanation of the model. These examples illustrate how students' creative decisions may have provided opportunities for them to engage in the practice of modeling in ways that they found interesting and motivating. Allowing students to incorporate their creativity into their models, while engaging in normative modeling practices that reflect the epistemological aspects of scientific modeling, may provide an additional entry point into the practice of modeling.

In summary, students' engagement with different types of models across different phenomena over the year of instruction informed a trajectory of epistemological ideas related to the practice of modeling within which 4th grade students were able to engage. Engagement with physical models provided opportunities for students to first learn about the purpose of models to study a phenomenon that occurs on a large scale. Then, students drew their own models of this same phenomenon as a way to engage students in an initial experience in the practice of modeling. Students engaged in additional experiences in constructing physical models followed by drawn models of phenomena, which provided opportunities for them to consider and discuss ways to improve the communicative power of their drawn models and different ways of identifying and representing components necessary for each model. Students also began considering the ways in which their models could be informed by data from investigations. As the phenomena with which students engaged and asked to explain through models became more abstract, students began grappling with ways to represent components in generic terms, so that their models could explain multiple situations, as well as considering the ways in which their investigations and experiences could inform the construction of models of phenomena that they did not directly experience.

Students' Engagement in Scientific Sense-Making in the Practice of Modeling

The construction of models also provided opportunities for students to engage in scientific sense-making by sharing their models, receiving and responding to critiques, and coming to consensus through the construction of class consensus models. Ford (2012) argued that students must "attain a 'grasp' of scientific practice—that is the ability to participate in key forms of discourse and activity that form the epistemic basis of scientific claims" (p. 208). Students engaged in different opportunities for sharing and critique throughout the year. At a whole-class level, the process of constructing consensus models during Unit 3 supported students to engage in the dialogic process of introducing and debating ideas, as well as building on each other's ideas. In addition, the sharing of models during Unit 3 also provided opportunities for students to ask questions of each other and consider different ways of representing the same phenomenon. Interviews with focal students suggested that they considered feedback thoughtfully and provided reasons for whether or not they incorporated feedback they received from peers. These opportunities suggest that students began to engage in scientific sense-making in modeling, especially towards the end of the year.

Engagement in the practice of modeling also provided opportunities for students to make their ideas visible and serve as tools for discussion and collaboration. The use of consensus modeling documented the process of constructing and critiquing representations. Both Manz (2012) and Penner (2000) documented the use of students' models as tools that could be used to represent ideas and develop shared understandings of what engagement in the practice of modeling looks like. This study documented the development of students' engagement in the practice of modeling and scientific sense-making from more peripheral participation at the beginning of the year to more central participation at the end of the year.

Role of Prior Knowledge in Sense-Making

Focal students were chosen to represent a range of prior knowledge as compared to their peers due to the hypothesis drawn from the Knowledge Integration Perspective that students' prior knowledge serves as building blocks for their learning and plays a key role in their repertoire of ideas (Clark & Linn, 2013). As hypothesized, prior knowledge was dependent on the phenomenon of study and individual student's amounts of prior knowledge varied among units. The influence of prior knowledge was complicated and did not lead to predictable paths of sense-making; all focal students demonstrated productive conceptual and epistemological sense-making, with the exception of one student in Unit 2. Kiara was considered to have low prior knowledge regarding the use of renewable energy sources to generate electricity. Her models and interviews throughout the unit did not reflect a change in her sense-making regarding the conceptual ideas in Unit 2. In addition, she struggled to construct models related to the phenomena of the windmill and water wheel. In contrast, Nick was also considered to have low prior knowledge regarding the use of renewable energy sources to generate electricity but demonstrated a large increase in his sense-making with respect to the phenomena in the unit and was able to engage with the ideas of the unit in meaningful ways through the practice of modeling. Upon closer inspection of Kiara and Nick's responses on the Unit 2 pre-assessment, which served as the prior knowledge measure, there were also qualitative differences that suggest that a minimum threshold of understanding may need to exist in order to students to productively engage in sense-making about phenomena through the practice of modeling.

Analyses of focal students' prior knowledge in Units 1 and 3 also support this hypothesis of a phenomenon-specific threshold for prior knowledge. All focal students in Unit 1 and Unit 3 demonstrated increases in conceptual sense-making. Kiara also served as a focal student for Unit

3 and demonstrated engagement in both conceptual sense-making and epistemological sense-making related to modeling. The sophistication of her epistemological understandings related to modeling were lower in comparison to the other focal students, but this may have been because her struggles during Unit 2 limited the sense-making in which she could engage in Unit 3. In addition, one focal student, Samuel, who was considered to have low prior knowledge at the beginning of Unit 1, demonstrated increases in conceptual sense-making but not epistemological sense-making in Unit 1. However, Samuel's epistemological understandings related to modeling did develop over the rest of the year. This supports the hypothesis that a threshold of prior knowledge might need to be achieved to enable students to engage in productive sense-making.

A prior knowledge threshold also aligns with findings from the literature that conceptual knowledge and epistemological understanding related to the practice of modeling are co-constructed (Lehrer et al., 2008; Manz, 2012). Focal students' development of conceptual knowledge and epistemological ideas related to modeling co-developed in this study, unless students did not have a minimum understanding of the target phenomenon. Manz (2012) found that the development of 3rd graders' knowledge regarding plant reproduction supported their engagement in different forms of modeling. The findings from this study support this hypothesis and further illustrate the ways in which knowledge and the practice of modeling co-develop. These findings also support the claim made above that the conceptual and epistemological components of modeling with which 4th grade students are expected to engage must be balanced.

Role of Technology in Supporting Students' Engagement in Modeling

The use of *Collabrify Flipbook* supported students to engage in the practice of modeling by allowing them to show processes through the animation tool. Not all students took advantage of this feature, but those who did demonstrated their thinking regarding the processes that could be used to explain the target phenomenon. Several focal students used animation to show the process of electricity traveling from the water wheel or windmill to a bulb in Unit 2 and sound waves traveling from the source to the receiver in Unit 3. In addition, the use of *Flipbook* provided students with tools to invent their own representations that may not have been possible using pencil and paper, particularly, animation. This was most apparent when students were drawing representations of electricity. One focal student, Caleb spoke about the affordances of *Flipbook* and the greater use of color that the program provided him when constructing models. The use of *Flipbook* may have also encouraged students to think more creatively about their models, as was witnessed in Unit 3.

The use of *Flipbook* also limited students in their engagement in the practice of modeling. The number of features in the program occasionally hindered students' abilities to engage meaningfully in the practice of modeling. This was evident during Unit 2 when many students in Ms. White's class discovered that they could import images from the internet. In addition, some students demonstrated a greater focus on the design of their models instead of thinking about the components or the purpose that their models served. This focus on design over function may have also occurred if students had constructed paper and pencil models; however, students only constructed one paper-and-pencil model at the beginning of the year, and more research would be needed to determine if one medium promoted more productive engagement in the practice of modeling over another medium.

Implications

Curriculum and instruction. The findings from this study provide insight into the ways in which the curriculum and Ms. White's instruction supported students' engagement in the practice of modeling and suggested ways in which curriculum and instruction might better support students to engage in this practice.

Engaging in epistemological sense-making related to modeling. Throughout the year, the curriculum provided opportunities for students to discuss their thinking related to the practice of modeling. These conversations were most present in Unit 1, when students reflected throughout the unit about the different types of models they used and the purposes for using models. More opportunities for these conversations should be integrated into the curriculum throughout the year to provide additional opportunities for students. In order to support teachers in facilitating these discussions, supports, such as discussion prompts and slides, should be provided in the curriculum. These tools can support teachers to engage in discussions with their students, especially if they feel unsure about how to facilitate such discussions.

The use of consensus models can also provide an entry point into conceptual and epistemological discussions related to modeling. The construction of consensus models was only included in the curriculum in Unit 3. The discussions that were observed during their construction suggest that this activity could be beneficial in supporting students' engagement in modeling across the entire year. Students' productive engagement in the construction of consensus models in Unit 3 may have been due to their previous modeling in Units 1 and 2; however, previous literature has documented the use of consensus modeling with elementary school children (Acher et al., 2007; Baek & Schwarz, 2015; Schwarz et al., 2009) and suggests that productive engagement in consensus modeling should be possible at earlier times in the year as well. The use of consensus modeling across the entire year could support an ongoing conversation regarding the construction of models and the epistemological considerations of modeling.

The documented trajectory of collective sense-making that occurred in Ms. White's class with respect to epistemological ideas related to modeling suggests that class discussions should be focused on the epistemological aspects of models, including: (a) the purpose of different types of models; (b) what conceptual information different models communicate; and (c) evaluation of models, including the affordances and limitations of different models. The findings from this study demonstrate that 4th grade students are capable of engaging in conversations of this nature and contributes to the growing body of literature that suggests elementary school students are capable of engaging in complex conversations regarding the epistemological aspects of models (Forbes et al., 2015; Lehrer et al., 2008; Lehrer & Schauble, 2012; Manz, 2012; Zangori et al., 2017).

Engaging in sense-making about the concept of energy transfer. Throughout the year, students struggled to engage with the concept of energy transfer as it applied to the central phenomena of the different units. One hypothesis is that students' sense-making regarding the concept of energy transfer remained too contextualized to the different phenomena of the units. Supporting students to apply the knowledge they developed to new contexts requires supporting them to draw connections among multiple contexts (Clark & Linn, 2013). Adding opportunities in the curriculum for students to record the ideas they developed related to energy transfer across time and to consider the ways in which they can be applied to new phenomena could support students to think about the role of energy transfer more centrally in their explanation of phenomena. The use of a chart to record students' developing ideas about energy is currently being considered in the revisions for the next iteration of Unit 3, as a way to support students to draw connections across the contexts of the units.

In addition, re-examining the progression of phenomena across units may be necessary. The phenomena of study across the three units moved from concrete to abstract; however, it may have moved too quickly to adequately support students in the development of their understanding related to energy transfer. This was evident in the differences in students' understandings as related to the concept of energy transfer in renewable energy and energy transfer in the problem of the billiard balls. Focal students were more able to articulate their understandings about energy transfer in the more concrete context of the billiard ball problem. This suggests that adding additional sub-phenomena within Units 2 and 3 that are more concrete could help move students towards an application of energy transfer in the more abstract phenomena of renewable energy and sound.

Students' sense-making regarding the different forms and transfers of energy across the year supports the findings from Herrmann-Abell and DeBoer (2018). Specifically, they found that ideas related to kinetic energy were easier than transferring energy by forces (i.e., push or pull and magnetism), and both of these were easier than transferring energy by sound. Within the idea of the transfer of energy by forces, the authors found that contact forces (i.e., push or pull) were more accessible than non-contact forces (i.e., magnetism). These three ideas represent major ideas related to energy covered in each of the three units.

Herrmann-Abell and DeBoer (2018) also suggested that elementary-aged students were able to engage with concrete, observable examples of the concept of energy but not the application of energy ideas to real-world examples. Focal students in this study were most able to engage with the example of erosion caused by water in Unit 1 and the billiard balls task in Unit 2, both of which are observable and concrete examples of energy transfer and involve the idea of kinetic energy and the transfer of energy by contact forces. Focal students struggled with the transfer of energy from sound as well as explaining energy transfer in the context of the windmill and water wheel models, both of which require the applications of ideas about energy transfer to a real-world context. In addition, Herrmann-Abell and DeBoer found that elementary students performed as expected on questions written for elementary students; however, middle and high school-aged students performed worse than expected on questions written for middle and highs school. This suggests that, while elementary students are being supported to develop grade-appropriate understandings related to energy, older students are not developing more complex understandings related to energy as expected.

The findings from Herrmann-Abell and DeBoer (2018) demonstrate the study of learning progressions can be used to inform the design of curriculum; however, studies of instruction are equally important to understand the contexts in which these understandings develop and the ways in which students can be supported to develop these understandings. In addition, additional research is needed to understand the ways in which instruction can better prepare elementary school-aged students to engage with more complex concepts related to energy at the middle and high-school grades.

Students' ability to engage in discussions about energy transfer may have also been limited by their inability to talk about energy transfer on a microscopic level. Previous work by Acher et al. (2007) and Samarapungavan et al. (2015) demonstrate that young children (1st and 2nd graders) are capable of developing simple particle models and discuss microscopic entities that exist in matter. Therefore, introducing 4th grade students to the idea that the media through which energy is transferred (e.g., water or air) is made up of tiny, invisible entities that collide with each other in the same ways as larger objects, could provide a more concrete example in which students could ground their thinking about energy transfer. This analogy could provide students with experiences to draw on when describing the invisible process of energy transfer that is required to explain all of the phenomena included in the *Multiple Literacies* curriculum.

The influence of prior knowledge on sense-making. The role that prior knowledge may play in conceptual and epistemological sense-making suggests that some students may require more support to demonstrate a minimum threshold of prior knowledge in order to productively engage in sense-making through the practice of modeling. The use of prior knowledge assessments can provide information to teachers as a way to identify students that may need more support. Curricula should provide teachers with ways in which to engage students in experiences that could bolster their prior knowledge, so that they can engage in sense-making with the important ideas in the curriculum. One way to do this is to leverage the collective experiences of the students in the classroom and purposefully group students, so that members of the classroom with less prior knowledge work with students will more prior knowledge. This could have been beneficial to Kiara during Unit 2, when she struggled to construct models of the water wheel and windmill. Collaborating in a pair or small group may have provided her with the added benefit of another's students' prior knowledge and allowed her to productively engage in the practice of modeling. In addition, designing additional experiences for students with lower prior knowledge may provide them with additional cognitive resources that they can draw on when engaging with the phenomenon of interest in the unit.

The use of assessments to assess conceptual and epistemological sense-making. The use of different types of assessments in this study illustrated affordances and limitations to administering separate or integrated conceptual and epistemological assessments and has implications for the ways in which students' engagement in the practice of modeling should be measured. Interviews with focal students in Unit 1 regarding the answers on their separate content and epistemological assessments yielding finer-grained insights into their thinking at the beginning and end of the unit, as compared to interviews regarding the integrated pre- and post-assessments in Units 2 and 3. Providing separate content and epistemological assessments regarding the phenomenon of interest and one or more models that students will engage with during each unit may provide more insight into students' conceptual understandings, as well as their epistemological understandings related to modeling in the context of every unit. For example, in Unit 2, a content assessment could be comprised of questions related to different sources of renewable energy and how they are used to generate electricity. An epistemological assessment could be comprised of similar questions to the Unit 1 modeling assessment regarding the stream table, except the focus of the assessment would be the use of the water wheel or windmill model. Despite the limitations observed in using an integrated assessment, assessment questions that ask students to construct models are useful for documenting students current understanding of the practice of modeling and their current application of conceptual ideas to the modeling context. Constructing assessments that incorporate all three types of questions – content-specific, epistemological ideas related to specific models, and performance tasks in which students construct models – may provide insights into multiple dimensions of students' prior knowledge, sense-making, and engagement in the practice of modeling.

The role of technology. The use of *Collabrify Flipbook* provided students with the opportunity to construct animated models, which is not possible with pencil and paper. Similar to previous studies (Chang, Quintana, & Krajcik, 2014; Wilkerson-Jerde et al., 2015), the data from this study suggest that the use of animation in the practice of modeling can provide opportunities for students to think about the underlying processes at work in a phenomenon, when they may not do so otherwise. However, this study demonstrates that animation programs can be used effectively with younger students. In addition, *Collabrify Flipbook* is an online application that is accessed through a website, meaning that students can use this application on any device as long as there is access to the Internet. Technology has become a mainstay of American classrooms; however, the amount and quality of this technology varies widely and is influenced by socioeconomic status (Purcell, Heaps, Buchanan, & Friedrich, 2013). Finding ways to provide all students with access to technological tools that can support their engagement in scientific practices, such as the practice of modeling, can may increase student interest and motivation, as well as provide them with better approximations of scientific practice.

There are also practical considerations for the use of technology in classroom setting that were observed during this study and are important to note. The use of technology provides convenient ways to save and store student work, which can be more reliable than relying on students to store their own work. However, inevitable technical difficulties and the time required to set-up and put away computers can complicate their use in classrooms. The use of technological tools is a core component of the design of PBL for science (Marx et al., 1997). These realities of using technology need to be weighed against the instructional benefits and limitations when considering how to best integrate technology into instruction.

Teacher learning and professional development. The findings from this study highlight the important role that teachers play in supporting students' sense-making and engagement in the practice of modeling. However, adopting a model-based approach to instruction and incorporating the practice of modeling into science instruction would require a shift from typical approaches to elementary school science instruction (Zangori et al., 2017; Windschitl, Thompson, & Braaten, 2008). This work suggests that teachers need opportunities to develop their own understandings related to the practice of modeling and the concept of energy transfer in order to support students' engagement and sense-making in the practice of modeling.

The observations of Ms. White's instruction suggest that she felt more comfortable discussing certain epistemological features of models, specifically the role of models "to see things"; therefore, this was the aspect of modeling on which she focused. In addition, many of the moments during the enactment of the curriculum in which I stepped in to provide support to Ms. White were related to supporting students to identify or discuss epistemological aspects related to the practice of modeling. Providing teachers with a greater number of experiences in the practice of modeling, as well as time to reflect on their experiences would provide opportunities for them to see the utility of engaging students in the practice of modeling and develop greater depth of knowledge regarding the epistemological aspects related to modeling from which they could draw when supporting students to engage in this practice. Zangori et al. (2017) suggest providing teachers with rationales for implementing model-based explanations as a way to increase their use in classroom instruction. Engaging teachers in the same practices that we ask them to engage students in could be one way to provide these rationales in inviting ways.

Policy. The study of students' engagement in the practice of modeling during the enactment of the *Multiple Literacies* curriculum demonstrates the ways in which the use of PBL can support this engagement. PBL curricula incorporate authentic problems that students must investigate as a way to engage students in meaningful inquiry (Krajcik et al., 2007; Condliffe et al., 2017). The driving questions and phenomena that drove student inquiry during this curriculum provided logical reasons for students to engage in modeling in order to test hypotheses and communicate ideas. Recent literature has argued that elementary science curriculum should include more opportunities for students to engage in the practice of modeling

(Forbes et al., 2015; Windschitl et al., 2008; Zangori et al., 2017). PBL may provide the necessary contextual features to support students' increased engagement in the practice of modeling, while addressing the required standards. However, this would require significant changes to the curriculum and professional development that teachers receive. If the *Next Generation Science Standards* are to be implemented with fidelity, finding curriculum and pedagogical approaches that conserve the multi-dimensionality of the standards is critical.

The findings of this study demonstrate that significant time is required to support students to engage in the practice of modeling. Providing sufficient time to engage in the construction of artifacts is one characteristic feature of PBL (Condliffe et al., 2017). The time spent engaging students in the practice of modeling in this curriculum was composed of a number of elements: (a) whole-class discussions, which require multiple turns of talk on the part of the teacher and the students; (b) the construction of models; (c) providing and receiving feedback on models; (d) revising models; and (e) opportunities to share models and reflect on the experience. The time required to complete these units is a stark contrast to the national trend in the amount of time spent on science in elementary school classrooms. The 2012 National Survey of Science and Mathematics Education found that 4th-6th grades teachers reported teaching science for an average of 24 minutes per day (Banilower, Smith, Weiss, Malzahn, Campbell, & Weis, 2013). This would not be sufficient time to engage students in either PBL curricula or practice of modeling. The findings from this study provide evidence for the use of modeling as a way to support the co-development of conceptual and epistemological understandings related to modeling; however, teachers must be able to teach science for sustained periods of time in order this type of co-development and meaningful engagement to occur.

Findings from this study regarding trajectories of conceptual and epistemological development can also contribute to the body of research on learning progressions. Learning progressions are empirically-informed and theoretically-grounded trajectories of students' development as it relates to engaging in the practices of science (Duschl, 2008; Schwarz et al., 2009). Schwarz and colleagues have developed multiple learning progressions that detail trajectories of engagement in different epistemological aspects of the practice of modeling for upper elementary and middle school students (Baek & Schwarz, 2015; Baek et al., 2011; Forbes et al., 2015; Schwarz et al., 2009; Zangori et al., 2017). The findings from this study can contribute to the ongoing development of learning progressions for upper elementary school students. In addition, the findings regarding the interplay between conceptual and epistemological sense-making could inform additional learning progressions that focus on the co-development of conceptual and epistemological ideas. Often, the development of these ideas is treated separately; however, more recent work has begun to suggest performance-based learning progressions (Forbes et al., 2015). In addition, as discussed above, this study contributes to the body of literature describing the instructional context in which learning progressions occur. Studies of this kind complement the research on learning progressions, as they provide insight into the instruction contexts that can support students' learning and development.

Critique on the Curriculum and Instruction

The purpose of this study was to document students' sense-making through their engagement in the practice of modeling across a year of instruction. As such, students' ideas, in whatever form they were offered, were recorded and considered equally regardless of the correctness of their content. Readers could be understandably concerned at the number of non-normative science ideas that students still appeared to hold at the end of the year, in spite of my argument that the use of modeling and the curriculum and instruction supported students' sense-making. For example, in Chapter 5, Nick describes the electricity in his model as moving slowly through a wire. This is not a scientifically accurate statement; however, it provides insight into his sense-making regarding the process of generating electricity. The goal of this study was not to evaluate students' conceptual knowledge regarding the many phenomena they studied. There are numerous studies that focus on the development of students' conceptual knowledge, especially regarding students' understanding of energy. The findings in this study suggest that modeling could be a promising way to engage students in considering the complex phenomena, but more needs to done to support their conceptual development.

Limitations

A limitation of this research is that it was a single case study. A case has its own set of particularities, which define its context (Dyson & Genishi, 2005). This limits the ability of the findings in this study to generalize beyond the boundaries of Ms. White's classroom (Merriam & Tisdell, 2016). There were aspects of the context that could be considered typical, such as Ms. White's lack of experience with PBL and students' varied levels of prior knowledge with respect to the phenomena; however, there were also aspects of this enactment that were unique and would inhibit replication of these findings. Ms. White received a great deal of in-class support from myself and other researchers that influenced her enactment of the curriculum. In addition, I stepped into teach science on the days that Ms. White was absent, which also influenced students' experiences of the enactment of the curriculum.

Focal students may have also experienced the curriculum differently due to the number of interviews conducted with them within a unit. These interviews were not designed to influence sense-making; however, they provided additional opportunities for students to interact with the models they used and constructed and I did correct students' explanations if they were interfering with their abilities to engage with the questions I was asking. In this way, the interviews were, in fact, a form of intervention that may have influenced their trajectories of sense-making in ways that would not have occurred if they had not participated as focal students.

In addition, I worked to mitigate interview fatigue on the part of the focal students by attempting to limit the number and length of my interviews to what was absolutely necessary; however, some focal students obviously grew tired of interviews by the end of each unit and by the end of the year, in the cases of focal students that participated in multiple units. Their weariness may have limited the amount they wished to engage and share their sense-making with me during interviews.

There were also methodological limitations in this study that limited the types and quality of data I was able to collect at different times. Technological challenges with the video camera and audio recording devices on specific days of enactment forced me to rely on field notes when analyzing specific moments of instruction. The loss of video or audio data in these instances decreased my ability to triangulate specific findings and provide consistently thick descriptions that drew on multiple data sources. In addition, the realities of working in the classroom setting meant that student absences led to the removal of focal students during specific units or the delay of interviews with focal students, as well as lost artifacts. This reality resulted in the loss of data that could have been beneficial to the study.

My role as a researcher and a participant-observer during this study also contributed to the biases I hold, which influenced my interpretation of my findings. I worked to identify these bias through reflecting on my positionality and subjectivity as it related to my role in this study. I believe the most influential bias that I hold is that I believe science should be engaging and meaningful for elementary school students and engaging them in the practice of modeling is central to this goal. I have worked to provide examples of instances which both support and refute this claim. In addition, I hold great respect for Ms. White, who was navigating a new curriculum and a large class size, while allowing me in her classroom every day. I recognize that children's development may limit the ways in which they are able to engage in this practice in 4^{th} grade and there are alternative instructional choices that could have been made at times during the enactment of the curriculum. I worked to provide detail regarding the classroom context, including the instructional choices that Ms. White did or did not make, and the ways in which this influenced students' sense-making.

Future Directions

This study has illuminated several different directions for future research regarding development of students' sense-making and the ways in which curriculum and instruction can support this development. Given that this was a single case study, conducting additional case studies in 4^{th} grade classrooms would allow me to conduct comparative analyses of students' collective and individual sense-making across different classroom contexts and test the hypotheses generated as a result of this study. In addition, this study contributes on a small-scale to our understanding of the longitudinal development of sense-making through the engagement in scientific modeling; however, more data are needed regarding trajectories of individual students' conceptual and epistemological sense-making related to the practice of modeling. The findings regarding the role of prior knowledge on students' sense-making require additional research to determine the ways in which students with low levels of prior knowledge can be supported to engage in sense-making while engaging in the practice of modeling. These comparative analyses could also contribute to the development of instructional and learning theories through propositional generalizability (Stake, 1995).

This study also demonstrated the utility of studying students' sense-making across multiple phenomena. Previous work in this area has mostly been constrained to studying sense-making related to a single phenomenon, but more studies should be conducted studying students' sense-making across time and across multiple phenomena to continue to understand the influences of different conceptual terrains on the co-development of conceptual and epistemological understanding related to modeling. These types of studies would also contribute to the field's understanding of how sense-making develops across time and trajectories of this development.

This study drew solely on qualitative methods to study and assess students' sense-making through the practice of modeling. The use of quantitative methods and measures, such as the development of rubrics and learning progressions, could provide additional insights into changes in students' modeling practices across the year and contribute to the ongoing conversation in the field regarding assessing and tracking students' sense-making.

Studying differences in enactment among teachers with different amounts of experience with PBL and, specifically, this curriculum could inform additional revisions to educative supports in the curriculum and the design of professional development that would help teachers enact the curriculum with fidelity. Students require heavy support when initially engaging in the practice of modeling (Windschitl et al., 2008). The professional development delivered during the enactment of this curriculum was not a part of the current study. However, the ways in which Ms. White supported her students to engage in the practice of modeling and the struggles she encountered during the enactment of the curriculum can be used to inform the design of future professional development.

Conclusion

This study contributes to the ongoing conversation in the field of science education regarding ways to engage students in meaningful approximations of practice and demonstrates the ways in which the study of students' sense-making can inform the design of curricula that supports these kinds of meaningful engagement. The *Next Generation Science Standards* calls on educators deliver multi-dimensional science instruction that provides students with opportunities as opposed to a list of facts. This is a challenging task. Studies, such as this one, provide examples of the benefits and challenges experienced by teachers and students as they work to engage in this type of opportunity- and sense-making-rich curriculum.

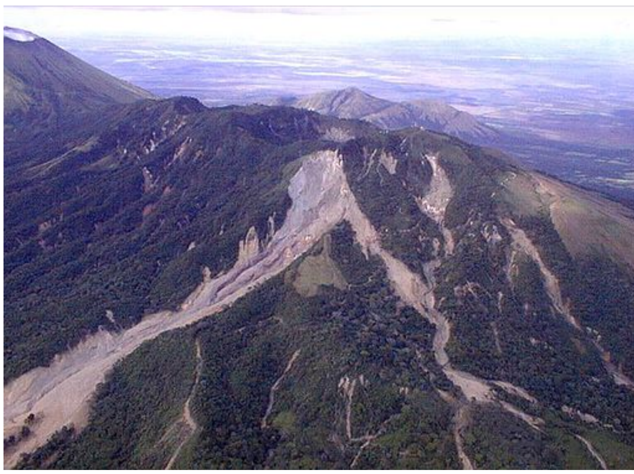
APPENDICES

APPENDIX A

Unit 1 Content Assessment

1. **How did the land get shaped this way?**

2. How did the land get shaped this way?

3. How did the land get shaped this way?

APPENDIX B

Unit 1 Modeling Assessment

1. How much can you learn about the ways water changes the land by using the stream table? Circle your answer.

    A lot **Not much** **Nothing at all**

2. Does a steam table need to look exactly like a real stream or river in order to answer questions about how water changes the land? Circle your answer.

    Yes **No** **Not sure**

Explain your choice.

3. Using a stream table, what kinds of observations can you make about how water changes the land? List as many observations as you can.

4. **Blake** says that using stream tables can be a very helpful way for scientists to study how water changes the shape of land.
    Lesley disagrees and says that stream tables are not that helpful to studying how water changes of the shape of land.

    Circle the name of the person you most agree with. **Blake** **Lesley**

    Explain your choice.

5. Can you use the stream table to predict how water will change the land?

    Yes **No** **Not sure**

Explain your answer.

APPENDIX C

Unit 2 Assessment

Name: ____

Unit 2

Renewable energy sources are ones that can be used again and again.

1. List as many sources of renewable energy that you can think of.

2. Choose one source of renewable energy that you listed above. Draw a model to explain how this renewable energy source can be used to provide electric power for your home.

Renewable Energy Source ________________________________

3. Explain what is happening in your model.

APPENDIX D

Unit 3 Assessment

Lighthouses are used to warn boats when they are getting close to the shore or are near dangerous rocks in the water. Normally, lighthouses communicate with boats using flashing lights at the top of the lighthouse. These lights tell the boat captain to be cautious. This is very important at night when the captain may have trouble seeing.

1. Using as much detail as you can, draw a model to explain how the boat captain sees the light from the lighthouse.

2. Using as much detail as you can, explain what you drew in your model. Make sure explain how the parts of your model work together!

Boats also have their own lights, kind of like headlights on cars, so that captains can see dangers at night. A boat captain sees that the boat is headed towards very large rocks. Using as much detail as you can, draw a model to explain how the boat captain sees the rocks at night.

3. Using as much detail as you can, explain what you drew in your model. Make sure explain how the parts of your model work together!

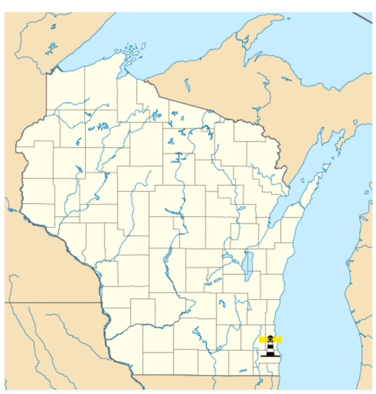
Some lighthouses also have large foghorns as well. The foghorns send out low, moaning sounds to tell the boat captain about danger.

4. Using as much detail as you can, draw a model to explain how the boat captain hears, interprets, and responds to the sound.

   In your model, make sure to include how the boat captain:
   - hears the sound
   - interprets the sound (how does he know what the sound means?)
   - responds to the sound

5. Explain what you drew in your model. In your explanation, describe how the transfer of sound involves the transfer of energy.

There are many lighthouses located along the coast of Lake Michigan. One lighthouse is located in Wind Point, Wisconsin (lighthouse on the map).



Below is a data table showing from how far away boat captains can see the light from the Wind Point lighthouse in different fog conditions – a clear night (no fog), light fog, and dense fog.

Distance from the lighthouse	Clear Night (no fog)	Light Fog	Dense Fog

5 miles	Yes	Yes	Yes
10 miles	Yes	Yes	No
15 miles	Yes	No	No
20 miles	Yes	No	No

6. Using the data table, write a scientific explanation to answer the question,

How does the amount of fog affect the distance from which the boat captain can see the lighthouse?

Claim (*What is the answer to the question?*):

Evidence (*What data supports your answer? Make sure to describe the pattern in the data that provides the evidence.)*

Reasoning (*What science ideas explain why your data supports your claim?*):

APPENDIX E

Unit 1 Interview Protocols

Unit 1 Pre-Assessment Interview

Interviewer will show student their content assessment.

1. In Question 1, you answered __________. Can you tell me more about your thinking?
2. In Question 2, you answered __________. Can you tell me more about your thinking?
3. In Question 3, you answered __________. Can you tell me more about your thinking?

Interviewer will show student their modeling assessment.

4. Can you tell me more about why you answered that you only learn _________ from the stream table?
5. Is there something you would change about the stream table so that you can learn more from it?
    a. (If student answered yes to #5) What kinds of predictions do you think you can make using the stream table? What could you explain using the stream table?
    b. (If student answered no or not sure to #5) Can you tell me more about why you answered no/ not sure to this question?
6. Is there something you would change about the stream table so that you could use it to make predictions or explain things?

Unit 1 Post-Assessment Interview

Interviewer will show student their content assessment.

1. In Question 1, you answered __________. Can you tell me more about your thinking? In Question 1, you answered __________. Can you tell me more about your thinking?
2. In Question 2, you answered __________. Can you tell me more about your thinking?
3. In Question 3, you answered __________. Can you tell me more about your thinking?

Interviewer will show student their modeling assessment. Focus on questions 1 and 5.

4. Can you tell me more about why you answered that you only learn _________ from the stream table?
5. Is there something you would change about the stream table so that you can learn more from it?
6. (If student answered yes to #5) What kinds of predictions do you think you can make using the stream table? What could you explain using the stream table?

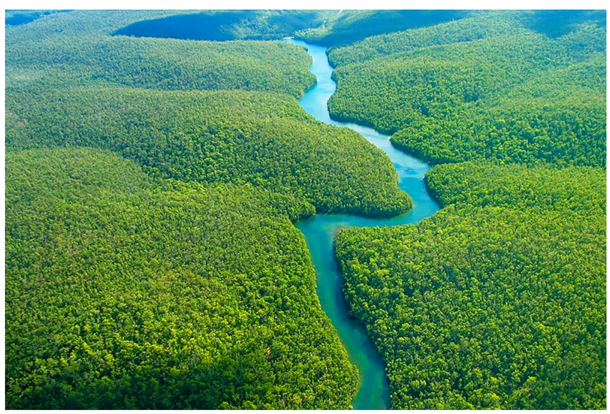
7. (If student answered no or not sure to #5) Can you tell me more about why you answered no/ not sure to this question?
8. Is there something you would change about the stream table so that you could use it to make predictions or explain things?
9. I noticed that you are spending a lot of time investigating with stream tables. Why do you think you are doing that? What is investigating with the stream table helping you figure out?

Model created at the end of Unit 1:

10. Can you tell me about your model? What does your model explain (or predict)?

Transfer Task:

11. How did the land get shaped this way?



12. This is a photograph of a river and the land surrounding it. What do think this land will look like in 1,000 years?

APPENDIX F

Unit 2 Interview Protocols

Unit 2 Pre-Assessment Interview

1. (In response to Question 1) Can you tell me more about why the sources you listed are examples of renewable energy?
2. (In response to Questions 2 & 3) Can you tell me about your model? What does your model explain?

Unit 2 Water Wheel Model Interview

1. Can you tell me about your model?
2. Can you tell me how you revised your model?
    a. Refer to responses on the back of the feedback sheet.
3. What is your model explaining?
    a. If necessary, what is the question your model is answering? Can you tell me how your model answers this question?
4. How well do you think your model explains how a turning water wheel can create electricity?
5. Is there anything you would change so that your model better explains how a turning water wheel can create electricity?
6. How is energy represented in your model?
    a. If no representation, how do you think you could represent energy?
7. Do you remember doing the crank generator investigation?
    a. What did you figure out in that investigation?

b. Did you include that information in your model? How could you include that information in your model?

8. Would you recommend that students use Flipbook to make models? Why or why not?
    a. Is there a way we could help students learn how to use Flipbook better?

Unit 2 Windmill Model Interview

1. Can you tell me about your model?
2. What question were you trying to answer when you made your model?
3. Your class has talked a lot about energy during this unit. Can you explain how energy is involved in the process of lighting the house that you have shown in your model?
    a. Adjust based on the process that students show in their model.

Show student the model of the windmill farm.

4. Can you tell me what you think this model is explaining?
    a. Tell student (if they did not already say it) that this model explains how wind energy can be used to produce electricity.
5. Is there anything that you would want to add or change about this model so that it could better explain how wind energy can be used to produce electricity?

6. Is there anything you want to add or change about the model you drew after looking at this model?

Unit 2 Post-Assessment Interview

3. (In response to Question 1) Can you tell me more about why the sources you listed are examples of renewable energy?
4. (In response to Questions 2 & 3) Can you tell me about your model? What does your model explain?
5. The driving question for this unit was, Where does the energy to light my house come from?
    a. Can you tell me what you have learned that would help you answer this question?

Transfer task – Show video clip

6. Can you tell me what you see in the video?
7. Think about what you know about energy. Can you describe why the balls roll?
8. This is a model that a student drew to answer the question, Why do the pool balls roll?
    a. Can you tell me what you see in this model?
    b. Is there anything that you would suggest to this student to add or change? Remember the checklist that you have been using to give feedback to your classmates.
9. What else would you have liked to learn about how we get energy to light our homes?

APPENDIX G

Unit 3 Interview Protocols

Unit 3 Pre-Assessment Interview Protocol

1. Can you tell me about your model?
    a. If student included something to indicate the light is traveling, ask specifically about this feature of their model and what it means.
2. Can you tell me more about your explanation of your model?
    a. If student included something in the explanation that was not discussed above, ask student to show where that idea is in their model.
3. Can you tell me more about your model in question 3?
    a. If student included something to indicate the light is traveling, ask specifically about this feature of their model and what it means.
4. Can you tell me more about your explanation of your model?
    a. If student included something in the explanation that was not discussed above, ask student to show where that idea is in their model.
5. Can you tell me more about your model in question 4?
    a. If student included something to indicate the sound is traveling, ask specifically about this feature of their model and what it means.
6. Can you tell me more about your explanation of your model?
    a. If student included something in the explanation that was not discussed above, ask student to show where that idea is in their model.
    b. If student does not discuss transfer of energy, ask student, *how do you think the transfer of sounds involves a transfer of energy?*
7. Can you tell me more about the claim you made?
    a. If students did not write an answer or are unsure about the claim ask, *what do you notice about the data that is shared in the data table?*
    b. Remember a claim is the answer to the question. How could you answer this question?
8. Can you tell me more about the evidence you included in your explanation?
    a. Remember that evidence should support the answer you gave in your claim. Is there any data that supports your claim?
9. Can you tell me more about the reasoning you included in your explanation?
    a. What science ideas help you explain the data and your claim?
10. You have been learning a lot about energy this year. How do you think energy might be involved in communication?

Sound and Distance Model Interview

1. Can you please explain your model?
    a. If student does not include sound waves, ask how does the person hear the sound?

    b. If student does not include a source, ask where is the sound coming from?
2. You got some feedback from a partner about your model.
    a. What was the feedback your partner gave you? What suggestions did your partner give you?
    b. Did you make changes to your model based on your partner's suggestions? Why or why not?
    c. Was it helpful to get feedback from your partner?
3. How is your model similar to the model your class made?
4. How is your model different to the model your class made?
5. You have made many models about many different things this year. Have you found constructing models helpful for learning about different things, like how water wheels power houses or how water changes the land, helpful to your learning?

<u>Unit 3 Post-Assessment Interview Protocol</u>

1. Can you tell me about your model?
    a. If student included something to indicate the light is traveling, ask specifically about this feature of their model and what it means.
    b. If student's explanation is illegible or has something not mentioned in the student's verbal explanation, ask "Can you tell me more about your explanation of your model?"
        i. If student included something in the explanation that was not discussed above, ask student to show where that idea is in their model.
2. Can you tell me more about your model in question 3?
    a. If student included something to indicate the light is traveling, ask specifically about this feature of their model and what it means.
    b. If student's explanation is illegible or has something not mentioned in the student's verbal explanation, ask "Can you tell me more about your explanation of your model?"
        i. If student included something in the explanation that was not discussed above, ask student to show where that idea is in their model.
3. Can you tell me more about your model in question 4?
    a. If student included something to indicate the sound is traveling, ask specifically about this feature of their model and what it means.
    b. If student's explanation is illegible or has something not mentioned in the student's verbal explanation, ask "Can you tell me more about your explanation of your model?"
        i. If student included something in the explanation that was not discussed above, ask student to show where that idea is in their model.
        ii. If student does not discuss transfer of energy, ask student, *how do you think the transfer of sounds involves a transfer of energy?*
4. Can you tell me more about the claim you made?
    a. If students did not write an answer or are unsure about the claim ask, *what do you notice about the data that is shared in the data table?*
    b. Remember a claim is the answer to the question. How could you answer this question?
5. Can you tell me more about the evidence you included in your explanation?

    a. Remember that evidence should support the answer you gave in your claim. Is there any data that supports your claim?
6. Can you tell me more about the reasoning you included in your explanation?
    a. What science ideas help you explain the data and your claim?
7. Your class spent a lot of time learning about communication.
    a. How do you think energy might be involved in communication?
    b. What did you find most interesting about learning about communication?

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