A Study of the Design and Enactment of Scientific Modeling Tasks to Support Fourth-Grade Students' Sense-Making

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Abstract: A major goal in education is to provide students with opportunities to engage in "deep learning," in which knowledge and skills transfer to novel contexts. This study took place in one 4th grade classroom and drew on design-based research methods to investigate how the design and enactment of scientific modeling tasks in a project-based science unit influenced 4th grade students' sense-making regarding the concept of energy transfer and their epistemological understandings about models and the practice of scientific modeling. Data sources for this study included field notes, video, student artifacts, assessments, and student interviews. Students developed emergent understandings of the concept of energy transfer and the role of models to test, refine, and communicate ideas. This study has implications for the design and incorporation of scientific modeling tasks in curricula, as well as the field's understanding of the development of upper elementary students' sense-making regarding the concept of energy transfer.

Keywords: Sense-making, Scientific Modeling, Project-based learning

Research question and theoretical framework

A major goal of education is to support students to transfer the knowledge they construct from the classroom context to future civic, workplace, and family contexts, referred to as "deep learning" (NRC, 2012). The *Next Generation Science Standards* (NGSS) responded to this call by proposing standards for science education that included not just content knowledge, but also interpersonal practices such as collaboration, as well as other practices identified as characteristic of science that would support students to experience scientific phenomena in authentic and meaningful ways (NGSS Lead States, 2013).

One practice identified by NGSS is scientific modeling. The research question guiding this study was, *How do features of the design and enactment of scientific modeling tasks influence 4th grade students' sense-making of the concept of energy transfer?* Sense-making is a cognitive process that could support students in deep learning. 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). Engaging in scientific sense-making allows students to participate in talking and reasoning characteristic of scientific practice (Ford, 2012).

Models are critically important in the construction, development, and communication of scientific knowledge (Gilbert, 2004); they serve as simplified representations that allow us to describe, predict, and explain natural phenomena by highlighting specific elements of the phenomenon and relationships among the elements that the modeler considers important in order to explain the behavior of the phenomenon and the associated underlying processes (Gilbert, 2004; 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). Instead, they serve as analogs to the phenomenon representing the underlying mechanisms (Lehrer, Schauble, & Lucas, 2008). Models allow children to represent, test, and revise their thinking in a concrete way, and then interact with that representation to develop their conceptual and epistemological understandings (Penner, 2000). In addition, engaging in the practice of modeling provides opportunities for both individual and collective sense-making about scientific phenomena (Ford, 2012; Manz, 2012).

Historically, the practice of scientific modeling has been considered too complex for young children (Manz, 2012); however, empirical studies have demonstrated that elementary-aged children can be supported to engage in the interpretation of models and the practice of modeling in productive ways (Ero-Tolliver et al., 2013; Lehrer & Schauble, 2012; Lehrer et al., 2008; Louca & Zacharia, 2015; Manz, 2102; Wilkerson-Jerde, Gravel, & Macrander, 2015; Zangori, Vo, Forbes, & Schwarz, 2017). Students' construction of models can take many forms, including paper-and-pencil, physical objects, computer animations, or computerized simulations. Exposing elementary-aged children to multiple types of models when investigating a phenomenon could support them to develop their "representational repertoire" (Ero-Tolliver et al., 2013, p. 2151), an epistemological understanding that different types of models provide different kinds of information (Schwarz et al., 2009), and make sense of the phenomenon being modeled (Manz, 2012). Building physical objects can 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. In addition, computer animation supports children to consider the processes at play in phenomena (Wilkerson-Jerde et al., 2015). The use of different forms of scientific models can serve as tools to support students' sense-making about phenomena and the epistemological aspects of using and constructing scientific models.

As stated previously, sense-making is a social process that requires engagement in the practices of science (Ford, 2012; Manz, 2012). Due to the emphasis on engagement in the practice to support sense-making, I drew on the social constructivist theory of learning to study how engagement in the practice of modeling and the use of models influences students' sense-making about energy transfer. According to Vygotsky (1978), learning is a social process that is context-specific, mediated by psychological tools, and results in changes in an individual's psychological development (Palincsar, 1998). Models can serve as a tool that mediates interactions between students and the teacher and externalizes 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 by interacting with one of the tools that this community uses.

The use of physical and computer-animated models to support students in making sense of phenomena can also provide opportunities for them to develop epistemological understandings about models and modeling. Given the benefits of engaging students in the practice of modeling to promote deep learning, it is useful to investigate the different features of the instructional context that support productive engagement in the practice of modeling and the use of models to support students' sense-making.

Significance

This study contributes to the field's understanding regarding how engaging students in the practice of scientific modeling through the use and construction of physical and computer-animated models may support elementary school students' sense-making about the concept of energy transfer. In addition, this study builds on previous empirical work by studying the development of students' sense-making regarding the concept of energy transfer across multiple phenomena. This study also demonstrates how theories of learning and development can be applied in an educational context to better understand how digital tools and instructional strategies can support the development of students' sense-making.

Research methods

Participants and context

This study took place in a K-5 elementary school, in which 63% of students are White, 24% are African American, and 6% are Hispanic/ Latino; 66% of students qualify for free or reduced lunch; and only 10% of 4th grade students demonstrated proficiency or advanced proficiency on state English Language Arts achievement measures. The participants were Ms. White (a pseudonym) and her 35 fourth-grade students. The racial and socioeconomic makeup of this class mirrored that of the school.

Ms. White enacted a year-long project-based learning (PBL) science curriculum as a part of the *Multiple Literacies in Project-Based Learning* Project. This project has designed 3rd and 4th grade project-based learning 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. PBL engages students in meaningful, authentic inquiry and provides opportunities for participation in the practices of science, including modeling, 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). Two prominent features of PBL are the use of a driving question to frame the unit of inquiry and the creation of student artifacts throughout the unit.

The data for this paper were drawn from one of three fourth-grade units. This unit was framed by the driving question, *Where does the energy to light my home come from?*, and 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 (that shapes the land) during the previous unit of instruction. Students built physical models of a water wheel and windmill and constructed computer-animated models to explain how each of these devices could be used to harness the moving energy of either water or wind to generate electricity. Students were introduced to the concept of a generator and used hand-crank generators to model the components necessary for the conversion of moving energy to electrical energy on a larger scale. When constructing their physical models of windmills, students used an empty thread spool to model the process of spinning a generator using energy from wind.

The topic of renewable energy was chosen as a way to engage students in investigations, discussions, and experiences related to the concept of energy transfer between objects. In addition to building physical models, students created computerized models using *Collabrify Flipbook*, a drawing and animation software application, that allowed students to draw multiple frames that could be animated. The animation feature of *Collabrify Flipbook* supported students to show a process or change over time.

The data sources for this study include video and field notes of whole-class instruction and discussions, students' scientific models, pre- and post-unit assessments, and interviews with a subset of Ms. White's students. Six focal students were selected for interviews prior to the start of the unit, at the end of each minicycle, and after the completion of the unit (see Figure 1); they were chosen to represent a range of prior knowledge of concepts related to energy transfer and renewable energies.

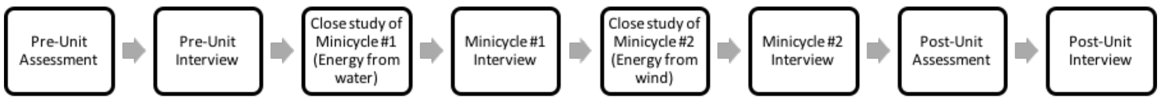

Figure 1. Timeline of focal student interviews.

The unit pre- and post-assessments included the prompt "*Choose one source of renewable energy and draw a model to explain how this source of renewable energy can be used to provide electric power to your home.*" During pre- and post-unit interviews, students were asked to explain their models and were asked follow-up questions to further elicit their sense-making about the concept of energy transfer and their epistemological understandings about models and the practice of modeling. During the post-unit interview, students also engaged in a transfer task. The transfer task consisted of a short video of a person using a pool stick to hit a pool ball that strikes another pool ball and were asked the question, "What causes the pool balls to move?" Data from the transfer task were used to capture students' abilities to transfer their sense-making about energy transfer to a novel context.

Data analysis

To address the research question, this study employed design-based research (DBR) methods to inform revisions to the curriculum. DBR methods seek to design instruction that is theoretically grounded but feasible to enact in the classroom (Brown, 1992; Collins, Joseph, & Bielaczyc, 2004). Therefore, the context within which the instruction occurs is critically important to understanding how learning is actualized in a classroom setting.

Consistent with the design-based research approach, I conducted two minicycles during the unit to study how Ms. White enacted proposed changes to the curriculum and how these changes influenced students' sense-making, in order to inform future change to the curriculum. Cobb, McClain, & Gravemeijer (2003) define minicycles as short cycles of enactment and reflection within the design experiment, often on a daily basis, that lead to pragmatic changes in order to influence learning during the next instructional opportunity. In contrast, macrocycles encompass the entire design experiment; in this case, the entire enactment of the unit, and analyses of this cycle led to changes in the next iteration of enactment and claims regarding the development of students' sense-making with scientific models. The analyses of minicycles can document the research team's learning during the entire macrocycle and contribute to understanding reasons why the macrocycle unfolded in a specific manner (Cobb et al., 2003).

In this study, each minicycle was centered around a different model with which students were engaging. Before and during each minicycle, I worked with the other researchers and Ms. White 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 made adjustments to the activities students were engaged in or provided additional supports that Ms. White could use.

In order to study how the design and enactment of scientific modeling tasks influenced students' sense-making regarding the concept of energy transfer, video and field notes were used to construct a timeline of the unit's enactment and characterize: (a) the conceptual and epistemological ideas introduced during whole-class instruction, (b) the nature of the supports related to scientific modeling that Ms. White provided to students, and (c) the ways in which the teacher and the students interacted with different models. The close study of students' development related to the concept of energy transfer and their interactions with different models and the development of their sense-making across the timespan of the unit were informed by the interviews with focal students at different times in the unit and the pre- and post-unit assessments (see Figure 1).

Findings

Minicycle #1

The enactment of this unit took a total of 25 instructional days. During Minicycle #1, students investigated how the energy of moving water could be harnessed to generate electricity by using a physical model and constructing a computer-animated model of a water wheel. For example, the researcher (who served as a co-teacher) made the decision to emphasize comparisons between models and the phenomena they represent. In addition, the researcher and Ms. White decided to ask students to draw models to explain how a water wheel, as opposed to a hydropower plant, could be used to produce electricity, because students had been working with physical models of water wheels for several classes. The objective was to support student sense-making with the water wheel model and introduce the concept of energy transfer, within the water wheel system, to generate electricity.

During whole-class instruction in Minicycle #1, the class looked at pictures and videos of real water wheels and compared them to their water wheel model. This excerpt from a class-wide discussion led by the researcher (MM) illustrates the connections students made between the model and the phenomenon and the struggles they faced regarding their interpretations of models as an analog for the phenomenon. To maintain confidentiality, focal students were assigned pseudonyms and other students were identified using their initials.

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	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!

Five of the six focal students included electrical energy as a product of the turning water wheel. Caleb was the only focal student to include and discuss the generator in his model and interview (see Figure 2). He explained,

> So it is showing the water wheel and it's 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…The generator, um, when this moves the generator is getting power from it and it's turning and making the electricity to light up the light bulb (Caleb Unit 2 Interview #2).

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. In addition, his explanation of his model suggests that he understood that the turning of the water wheel caused the turning of the generator. This idea could serve as a foundation for energy transfer, but it is unclear how he was thinking about the role of energy in this process because he did not include it in his explanation. Furthermore, he specified that the turning of the generator is what produces the electricity. Caleb's specificity in the language he used regarding his model was also apparent when he described that his model explained "how the water wheel is turning and making the electricity go to the lightbulb." This explanation of his model suggests that Caleb was developing an emergent understanding of the process of generating electricity from moving water.

Many of the focal students demonstrated that they were considering the conventions of their models and how they could use conventions to improve their models' communicative power. All focal students used yellow to denote electricity (as can be seen in the lightbulb in Figure 2). Several students also provided reasons for this choice related to the common convention of using yellow to show electricity. For example, Nick explained that he used yellow, "cause yellow is the general color of electricity, that's how people see it" (Nick Interview #2). In addition, Esther included arrows to show the direction of the movement of energy. These elements of students' models suggest that they were considering how to use their models as explanatory tools and the ways in which components within the models could increase their explanatory power.

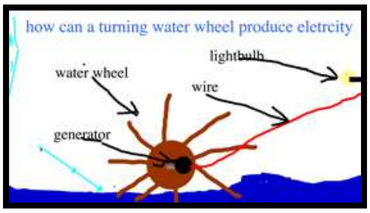

Figure 2. Screenshot of Caleb's Water Wheel Model.

The use of *Flipbook* also provided students the opportunity to use animation. 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. The use of animation provided the opportunity for students to demonstrate their sense-making with respect to the mechanism through which energy from moving water was transferred to the water wheel and harnessed to generate electricity.

Students' individual models and interviews also provided insight into their struggles related to their sense-making of 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 still ambiguous for students. Similarly, students did not understand how the mechanical energy in the turning water wheel was transferred to the turning generator. In addition to not discussing the process of energy transfer, students also 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. In Minicycle #2, the researchers made design decisions to address students' struggles with the process of energy transfer.

Minicycle #2

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, energy was transferring 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. This minicycle began on Day 18 of Unit 2 and lasted six days of instruction.

During this minicycle, students worked in small groups to plan, build, test, and revise their windmill models. On Day 18, Ms. White introduced students to the representation of the generator that they would be using to test the efficacy of their windmill designs. She explained, "[the generators] won't actually work, but you have to find a way to have your wind turbine hook up your wind turbine 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" (Day 18 video). The use of the thread spool was intended to support students' sense-making about the function and motion of the generator. Ms. White's introduction of the thread spool introduced the idea that another object could represent the phenomenon being modeled (e.g., a spinning generator). Unlike the water wheel minicycle, Ms. White did not conduct whole class instruction during this minicycle. Instead, she circulated around the classroom and supported students in building, testing, and revising their windmill models.

Focal students demonstrated 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. 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. The invisible nature of both wind and energy could account for students' difficulty in understanding that energy was present in the wind and was transferred to the windmill.

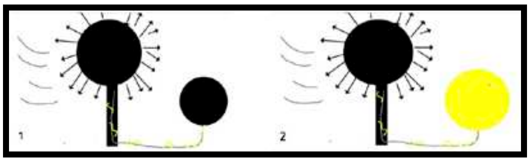

Figure 3. Esther's windmill model

After constructing physical models of windmills, students created models in *Collabrify Flipbook* to explain how their windmill design could light a light bulb. Students' *Flipbook* models reflected different levels of abstraction from students' windmill designs to the 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. Caleb and Nick's models incorporated some specific components from their windmill designs, but also included components that referenced the phenomenon of lighting the bulb. Caleb's interview suggests 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 was generalized to explain the phenomenon of lighting the bulb (see Figure 3). Despite missing components, such as a generator, Esther's explanation and the question for her model (How does electricity get to somewhere else?) suggested 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 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.

The analysis of Minicycle #2 revealed the ways in they could draw on their own investigations and experiences to inform the construction of models, which represented 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 can feel wind, and 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 in contrast to 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. The other focal students indicated that electricity emerged directly from the water wheel. These continued challenges underscore the difficulty of this concept.

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. Because of the materials students were using, there were fewer similarities to real windmills than when students engaged with the water wheel model, resulting in higher cognitive requirements for students to make sense of this model (Lehrer & Schauble, 2012). This was also their first experience with a syntactic model, or a model that maintains functional similarities and not physical similarities with the phenomenon of lighting the bulb (Lehrer & Schauble, 2012).

Macrocycle analysis

In order to determine students' endpoints in the unit and the development in their sense-making regarding energy transfer, I analyzed focal students' post-unit interviews and assessments and the two minicycles to make claims regarding how the curriculum may have supported their sense-making. Five of six focal students identified that energy was present in the renewable source of energy that they chose to model. 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. The development of this understanding can be observed across the two minicycles and may have been supported through Ms. White's prompts to students regarding using their models to answer questions, as well as the sharing of students' models with the class.

Students also demonstrated a range of understandings regarding energy transfer in the transfer task during the post-unit interview. For example, Esther was able to describe, in detail, the path of energy to explain why the pool balls move. She explained, "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" (Esther Unit 2 Interview #5). However, Caleb was not able to use apply the word "energy" in the transfer 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 pool ball task (Wagner, 2010).

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 post-unit 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.

Conclusions and implications

The aim of this study was to investigate how the features of the design and enactment of scientific modeling tasks influence 4th grade students' (a) sense-making of the concept of energy transfer and (b) epistemological ideas related to the use and construction of scientific models. Using DBR methods, analyses of the minicycles within the unit and macrocycle of the entire unit revealed how the design of the use of physical models and the construction of computer-animated models influenced and provided insight into students' sense-making regarding energy transfer.

Students demonstrated increased understanding regarding the use of a generator in the process of generating electricity, but several students did not include generators in either their drawn water wheel or windmill models. 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 in order to make the generator spin. While some students did include generators in their models or discussed their models during their generators, 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 (Lehrer et al., 2008). 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 on 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.

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 the length of 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 than in Minicycle #2, there were no sustained conversations about energy transfer during either minicycle. 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.

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 conventional 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.

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