Simulations and Sensemaking in Elementary Project-Based Science

by

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DEDICATION

For my Grandparents, who taught our whole family to love to learn

Margaret Tracy Feeney
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ABSTRACT

In recent years, there have been many calls for engaging students in sensemaking while interpreting computerized representations. The US Department of Education has called for educators to close the "digital use divide" by supporting all learners to actively engage in sensemaking while working with technology. Literacy scholars have called for students to spend more time working with multimodal, digital, and interactive texts (Dalton & Proctor, 2008; Jewitt, 2008; Kress, 2009). The *Next Generation Science Standards* have called for students to spend more time interpreting models, including dynamic simulations. All these calls support the integration of computer-based simulations into science instruction. However, we still have much to learn about the enactment of simulation-based lessons in elementary classrooms. In this dissertation study, I investigated the enactment of simulation-based lessons in an elementary project-based science curriculum. The following research questions guided this study: (1) How do teachers support student sensemaking while working with simulations in the context of 3rd grade project-based science? Does this support, or student response to this support, shift across the three simulations? (2) What are the teachers' perspectives regarding the use of simulations as sensemaking tools?

This study took place in two third-grade classrooms with a total of 2 teachers and 54 students across a full semester of project-based science instruction. The focal curriculum, *Multiple Literacies in Project-based Learning* (MLs) integrates science, language arts, and math

while addressing all NGSS standards and select CCSS standards. Both teachers were experienced elementary school teachers with prior experience in the ML project.

I used case study methods (Dyson & Genishi, 2005; Stake, 1995) to investigate how teachers supported student sensemaking while working with simulations. Data sources for this study included videos of classrooms observations, interviews with teachers, content assessments, artifacts, and the designed curriculum materials. Focal students were selected to represent the range of demographics and reading levels present in each class.

With respect to the first research question, findings indicated that teachers used a variety of strategies to support student sensemaking during simulation-based lessons. These included: (a) identifying both conceptual goals and potential learning challenges prior to teaching with the simulation, (b) supporting students to articulate and share observations, predictions, reasoning and claims while working with the simulation, (c) supporting students to plan and conduct investigations using the simulation, (d) supporting students to interpret complex visual representations found within the simulations, (e) supporting student understanding of key scientific concepts, (f) repeating and extending student sensemaking, (g) guiding student use of the simulation by setting specific challenges or goals, (h) publicly recording student learning from the simulations, and (i) varying participation structures. With respect to the second research question, findings indicated that both teachers found simulations to be an engaging and beneficial learning opportunity. These findings have implications for curriculum design, simulation design, and teacher decision making while enacting simulation-based lessons.

CHAPTER 1: Introduction

In recent years, there have been a growing number of calls within the literacy community to integrate more multimodal and digital texts into literacy instruction (Dalton, 2012; Dalton & Palincsar, 2013; Siegel, 2006). There have been calls within the science education community to integrate more interpretation of models into science instruction (National Research Council, 2012; NGSS Lead States, 2013). There have also been calls to provide students with more opportunities to interact with technology in active, rather than passive, ways (Baker-Doyle, 2017; US Department of Education, 2016). Online, interactive science simulations have the potential to address all three of these opportunity gaps because they (a) are both digital and multimodal in nature (Adams et al., 2008b; Dalton & Proctor, 2008), (b) are a form of scientific model (National Research Council, 2012; NGSS Lead States, 2013), and (c) can provide opportunities for students to actively engage in scientific sensemaking (Rehn, Moore, Podolefsky, & Finkelstein, 2013)

Simulations and the Call for Students to Interact with Multimodal and Digital Texts

For a text to be considered a multimodal text, it must incorporate more than one mode of communication (for example, writing, images, gesture, and animation). Digital texts are a similarly flexible genre: they may include texts that are linear in nature, texts using hyperlinks, texts with integrated media, and texts that are primarily visual or auditory (Dalton & Proctor, 2008). According to these definitions, simulations can be considered both a multimodal text and a digital text. They are multimodal because they incorporate more than one mode of communications (Jewitt, 2008; Kress, 2009). They are digital because they incorporate hyperlinks, integrate media, and are primarily visual in nature (Adams et al., 2008b; Clark, Nelson, Sengupta, & D'Angelo, 2009)

Calls for more digital and multimodal texts in literacy education frequently refer to the changing nature of texts in recent years. Dalton (2012) writes, "One of the biggest communication changes happening today is the shift from the printed word on a page to multiple modes of image, sound, movement, and text on a screen" (p. 334). In a similar vein, scholars studying multimodality point to an ever-increasing demand for both the production and consumption of multimodal texts, a trend they consider likely to continue into the foreseeable future (Jewitt, 2008; Kress, 2003).

Advocates for increased use of multimodal and digital texts consistently call for the teacher to support students' comprehension as they interpret such texts. For example, Jewitt (2008) found that the teacher needed to play a key role in supporting students to interpret multimodal representations. Similarly, Dalton and Proctor (2008) argue that students may need teacher support in order to engage with digital texts in meaningful ways. In this dissertation, I will argue that teachers supporting students to work with online scientific simulations is one way to answer the call for more supported use of multi-modal and digital texts in classroom settings.

Simulations and the Call for Students to Interpret Scientific Models

Embedded within *The Next Generation Science Standards* (NGSS) is a call for students to have the opportunity to both develop and interpret models. (NGSS Lead States, 2013). The NCR *Framework for K-12 Science Education*, makes a similar call, describing models as important because they "allow scientists and engineers to better visualize and understand a phenomenon under investigation or develop a possible solution to a design problem" (National

Research Council, 2012, p. 56). These calls build on a long line of research that has demonstrated both the importance of models to scientists' daily work and the importance of supporting student to develop and interpret models (Furberg, Kluge, & Ludvigsen, 2013; Kozma, 2003; Lemke, 2004).

Models use surface features (e.g. images, animation, labels) to represent an underlying conceptual model of a scientific phenomenon (Kozma, 2003). Online simulations are explicitly named both in the *Next Generation Science Standards* and the *NRC Framework* as one type of model that students should become familiar with interpreting (National Research Council, 2012; NGSS Lead States, 2013). The NRC specifically mentions simulations as a type of model used by professional scientists and recommends that simulations be used in science education (National Research Council, 2012). In a similar vein, the NGSS frequently points out specific Disciplinary Core Ideas that could be explored using simulations.

As in the case of multimodal and digital texts, advocates for the use of models in scientific education consistently call for teachers to provide support as students interpret models. In particular, research has found that it is important for teachers to students to make connections between different modalities present in the same model (e.g. between text and images) (Jian, 2016; Prain & Waldrip, 2006). Making connections across different parts of a model plays a key role in developing conceptual understanding of models (Bodemer, Ploetzner, Feuerlein, & Spada, 2004; Prain & Waldrip, 2006). In this dissertation, I will argue that supporting students to work with online scientific simulations is one way to answer the call for supporting students to interpret scientific models.

Furthermore, since simulations can be considered to be a type of both (a) multimodal, digital texts and (b) interactive scientific models, the use of simulations in elementary science classrooms can also help answer calls to integrate science and literacy instruction (e.g.National Research Council, 2014; Osborne, 2002; Palincsar, 2013). Scholars have argued that integrating science and literacy instruction is essential, given that literacy practices are fundamental to communication within science (Lemke, 2004; Osborne, 2002).

Simulations and the Call to Close the "Digital Use Divide"

Concurrent with calls to increase students' access to both multimodal texts and conceptual models are calls for students to spend more time using technology in active, rather than passive, ways. The *Future Ready Learning Report* calls for educators to support equity by working to close the "digital use divide," between "learners who are using technology in active, creative ways to support their learning and those who predominantly use technology for passive content consumption" (US Department of Education, 2016, p. 9). This call echoes many educators who have advocated for using technology to support students to actively participate in learning. One of the earliest such calls was made by Bransford, Sherwood, Hasselbring, Kinzer, and Williams (1990) who proposed that technology can help educators bring critical thinking into the classroom by providing shared experiences that can be act as an "anchor" for students to engage in joint problem solving. More recently, in a Transformative Teacher Development Framework, Baker-Doyle (2017) makes a case for using technology to create social learning opportunities.

The *Future Ready Learning Report* suggests that one way to close the digital divide is by promoting increased use of games and simulations in educational contexts (p. 20 & 22). Simulations can provide opportunities for students to actively engage with technology: for example, using simulations students can set and monitor goals (Manlove, Lazonder, & de Jong, 2006), discuss science content (Stephens & Clement, 2015), make predictions, plan investigations, and interpret results (Rehn et al., 2013)

This goal of this study

Since simulations can simultaneously support students to (a) interpret digital and multimodal texts, (b) interpret scientific models, and (c) actively engage with technology, they have potential to play an important role in science education. However, there is currently little research that examines *how* teachers or curricula can support students to engage in scientific sensemaking while using simulations (Rutten, Van Joolingen, & Van Der Veen, 2012). Furthermore, there is almost no research that considers whether and how simulations can be used to support scientific sensemaking with lower elementary students (D'Angelo et al., 2014; Scalise et al., 2011; Smetana & Bell, 2012). There is still much to learn about whether -and how - simulations can support elementary students to engage in scientific sensemaking. This study seeks to address this gap in the literature, by presenting a case study of how two third-grade teachers support their students to engage in scientific sensemaking while working with simulations.

Research Methods and Design

This study uses case-study methods (Dyson & Genishi, 2005; Stake, 1995) and examines the case of two teachers supporting student sensemaking in the context of multiple simulation-based lessons. The instructional context is two third-grade classrooms in rural Michigan where the teachers are teaching a project-based learning curriculum that incorporates several simulations. Data sources include: transcripts of lesson enactment, interviews with teachers, photographs of teacher and student writing, student assessments, and screen captures of student work with simulations.

Organization of the Dissertation

The second chapter of this dissertation presents a literature review that summarizes what we know about (a) using simulations to support student learning; (b) how teachers, curriculum, and simulation features can support student learning from simulations; and (c) user attitudes towards simulations. The second chapter also identifies how this study addresses gaps in existing research and introduces the research questions of the study. The third chapter introduces the theoretical framework, the instructional context, the data sources, and the methods of data analysis. The fourth, fifth, and sixth chapters present case studies of the enactment of three different simulations. The seventh chapter is a cross-case comparison of the findings in chapters four through six. The eighth chapter is a discussion chapter that considers implications for teaching, teacher preparation, and curriculum design as well as reflections on limitations of this study and suggestions for future research.

CHAPTER 2 Literature Review

This literature review begins with a brief description of my process for selecting the research to include. The literature review itself is organized according to six overarching questions; these questions consider what current research has to say about (a) evidence of student learning from simulations, (b) the potential for simulation features to support student learning, (c) the potential for curricular context to support student learning from simulations, (d) the potential for teachers to support student learning from simulations, (e) research-based strategies for teachers to support student sensemaking, and (f) user attitude towards simulations. The final section of the literature review will identify gaps in the current research on simulations, introduce the research questions of this study, and identify how the research questions address the identified gaps in the literature.

Inclusion Criteria for Literature Review

This literature review examines trends in findings from both (a) recent literature reviews and a recent meta-analysis and (b) individual empirical pieces. I included literature reviews and meta-analyses that focused on the use of simulations in science education and were published in the past decade. This resulted in three literature reviews and one meta-analysis. I identified empirical work to review through multiple methods including searching databases, following citations in literature reviews or meta-analyses, following citations in empirical work, and consulting lists of studies archived by PhET and the Concord Consortium (the developers of the simulations at the centerpiece of this study). The studies I review met the following criteria:

- The study involves a simulation, which I defined using D'Angelo et al. (2014) definition of simulation as a computer-based interactive environment with an underlying conceptual model and no built-in rewards.
- The simulation was used to teach science (as opposed to mathematics or any other content area).
- The study included empirical data (e.g. student interviews, teacher interviews, pre/posttests, mouse-click data).

Using these criteria, I generated an initial list of simulations-related literature that contained hundreds of studies. To reduce the size of this list, I noted that the most common type of study compared learning outcomes in conditions with or without a simulation. I reviewed a number of these studies, but as the results were fairly consistent, I determined I had reached a point of saturation and did not review all of these studies. On the other hand, I reviewed every study I could find that: (a) focused on elementary students, (b) focused on teacher moves or social context when using a simulation, (c) focused on the impact of the representations within a simulation, or (d) focused on the impact of using learning supports. This resulted in a literature review aligned to my goal of studying the enacted use of simulations in a third-grade classroom.

Using these criteria, I identified 38 studies, which I read and took notes on using a chart with the following columns: participant age, participant (other details), setting, topic of simulation, time, study design, study details, findings, theoretical orientation, and reflections. See Figure 2.1, below for one exemplar.

Citation	Participant Age	Participant Number	Participant (other details)	Setting	Topic of Simulation	Time	Study Design	Study Details	Findings	Theoretical Orientation	Reflections
(Henderson, Klemes, & Eshet, 2000)	2nd grade	27	27 students in class. 6 focal students (3 same sex pairs.)	Plano, Texas 2nd grade class	Message in a Fossil – paleontology simulation.	Daily for 6 weeks	Pre/Post	Data sources triangulated included Pre/post interviews in which students 1) sorted fossils from stones 2) explained formation of fossils 3) classified picture cards. Pre/post written surveys. Pre/post open-ended structured interview of focal students.	Improvement in basic recall of facts, classification skills, making inferences, and usage of scientific language. Students didn't just treat simulation "as a game" but also learned from it.	Cognitive – talks about internalization of cognitive skills. Less focus on social interaction.	Different types of learning from simulations (facts, scientific language, inferences).

Figure 2.1 Sample entry from literature review chart

Of the 38 studies I examined: one study investigated participants in lower elementary (1st-3rd grade), 7 studies examined participants in upper elementary (4th & 5th grade), 14 studies examined participants in middle school, 13 studies examined participants in high school, and 6 examined participants who were post-high school (university or trade school). The most common country where research occurred was the United States of America. Other countries where research occurred included: Finland, Germany, Israel, Kenya, Korea, Sweden, Taiwan, and Turkey. Simulation foci included topics from both physical sciences and life sciences. The duration of the studies ranged from one hour to one year. The most common theoretical orientations were cognitivist, constructivist, or cognitivist-constructivist. However, about a fifth of the studies took a perspective that was socio-cultural, social-constructivist, or socio-cognitive. Study designs included: pre/post design, quasi-experimental (with matched assignment to different conditions), experimental (with random assignment to different conditions), and qualitative case studies.

What Does Research Tell Us about Using Simulations to Support Student Learning?

Findings from literature reviews and meta-analysis. I begin this section by sharing overarching findings from four recent literature reviews and meta-analyses considering the impact of simulations on student learning. While each of these reviews surveys a different slice of the literature (for example, they set different limits regarding ages of participants), the reviews concur that there is strong potential for simulations to support student learning.

Scalise and colleagues (2011) published a literature review that examined 93 studies focusing on the use of simulations or virtual laboratories in 6th to 12th grade classrooms. This literature review had the goal of considering where the most progress is being made in designing effective simulations and identifying directions for future simulation development Researchers defined simulations using De Jong and van Jooligern (1998)'s definition: "a program that contains a model of a system (natural or artificial) or a process" (p.1053). Researchers defined virtual laboratories as "simulating on screen the experiments that are traditionally performed in real school laboratories as part of biology, chemistry, and other science subjects" (p. 1053). In this literature review, researchers found 42 studies showing unqualified gain in content knowledge resulting from use of a simulation, 20 studies showing mixed results, 14 studies showing gain under the right condition, and three studies that showed no gain at all (Scalise et al., 2011).

In 2012, Smetana and Bell published a literature review that examined 61 studies focused on the use of simulations in K-12 classrooms. This literature review had the goal of investigating the impact of computer simulations on science teaching and learning. Researchers defined simulations as "computer generated dynamic models of the real world and its processes" (p.1338). In this literature review, 49 out of 61 studies found gains in content knowledge after the use of simulations. Studies that included comparison with control groups showed simulations to be equally or more effective than traditional instruction with regard to both promoting science content knowledge and science process skills (Smetana & Bell, 2012).

In 2012, Rutten and colleagues published a literature review that examined 48 studies focusing on the use of simulations among students aged 12-20. This literature review had the goals of examining the potential for computer simulations to enhance traditional education, improve learning processes, and improve learning outcomes. Researchers defined simulation using de Jong & van Joolingen's (1998) definition of simulation as "a program that contains a model of a system (natural or artificial, e.g. equipment) or a process" (p.136). Additionally researchers stipulated that simulations needed to be interactive models, rather than passive animations. Researchers found that all reviewed studies comparing conditions with and without simulations found positive results for the simulation condition.

In 2014 D'Angelo and colleagues published a meta-analysis that examined 59 studies focusing on the use of simulations among students aged K-12. The meta-analysis had two goals: (a) to examine the difference in outcome measures between K-12 students taught through simulations and K-12 students taught through other means, and (b) to examine the difference in outcome measures between K-12 students taught through simulations with and without instructional enhancement (e.g. metacognitive supports.) Researchers defined simulations as computer-based interactive environments with an underlying conceptual model and no built in rewards. Researchers found that students who worked with simulations made greater gains in knowledge of science content and achieved higher non-cognitive outcomes (attitudes & self-efficacy) compared to students who did not work with simulations.

Across these literature reviews and meta-analysis, there is a consistent finding that simulations have strong potential to support student learning of science content. To explore these findings in greater detail, I reviewed individual studies presenting empirical research on simulations.

Findings from empirical work. A number of studies have found that simulations have the potential to support learning for students in middle school, high school, and university. In a study comparing middle-school students designing cars physically and virtually, Klahr and colleagues found that students made consistent learning gains on a posttest measuring both (a) knowledge of causal factors, and (b) ability to optimize car design, regardless of whether they worked with the physical materials or the computer simulation (Klahr, Triona, & Williams, 2007). Similarly, in a study of 9th grade students studying chemistry, Geban, Askar, and Özkan (1992) found that students working with simulations either outperformed or performed comparably to students working with a physical lab depending on what pedagogical methods were used in the lab. Performance was measured using a chemistry achievement test and science process skills test. In a landmark study, White (1993) studied the learning of sixth graders who spent two months studying force and motion using simulations in the ThinkerTools curriculum. White found that sixth graders who worked with the ThinkerTools curriculum outperformed high school physics students on a test of content knowledge of force and motion.

In addition to the studies described above, other researchers who used experimental or quasi-experimental designs to study the use of simulations in middle and high school have found that students who worked with simulations had higher scores on content assessments than students taught using methods that are more traditional. These studies have focused on diverse content areas including: watersheds (Eskrootchi & Oskrochi, 2010), electrostatic induction (Çığrık & Ergül, 2009), frog anatomy (Akpan & Andre, 2000; Akpan & Strayer, 2010), cell division (Kiboss, Ndirangu, & Wekesa, 2004), Le Chatelier’s Principle (Trey & Khan, 2008), and molecular genetics (Marbach-Ad, Rotbain, & Stavy, 2008). Students learning from animations even outperformed the control group when the control group had access to static models (Trey & Khan, 2008) or models incorporating computer animations (Marbach-Ad et al., 2008).

Similar results have been obtained by researchers working with university students. For example, Winberg and Berg (2007) found benefits to science majors working with a simulation representing acid-base titration. When compared to control students, students who had worked with the simulations (a) asked more questions that were theoretical during their laboratory work, and (b) displayed more correct and more complex knowledge of chemistry during follow up interviews.

The majority of research on simulations and learning focuses on older students. I was only able to identify two studies of students in elementary school and only one of these studies examined simulation use among students in first, second, or third grade. Horwitz and colleagues found that 4th grade students who used simulations to study natural selection had higher scores on an assessment measuring understanding of processes underlying evolution, as compared to students who were taught using traditional methods (Horwitz, 2013; Horwitz, McIntyre, Lord, O'Dwyer, & Staudt, 2013; McIntyre, Lord, & Horwitz, 2012). A mixed-method case study by Henderson and colleagues found that a class of second graders working with a paleontology simulation daily for six weeks made pre/post gains on an assessment measuring students' content area knowledge, scientific classification skills, and use of scientific language (Henderson, Klemes, & Eshet, 2000).

Exceptions to general trend of simulations supporting learning. There are, of course, also exceptions to the trend that simulations are generally found to be supportive of student learning. As mentioned above, several literature reviews included multiple empirical studies that did *not* find learning gains associated with simulation use (Scalise et al., 2011; Smetana & Bell, 2012). In one such empirical study Stern and colleagues found that, while 7th grade students studying particles and matter using a simulation outperformed students learning by traditional methods, neither group made substantial learning gains on a content knowledge pre/posttest (Stern, Barnea, & Shauli, 2008). In explaining these results, Stern and colleagues suggest that the simulation was not sufficient to produce meaningful learning, absent other supports (e.g. from the teacher or curriculum). The next three sections of this literature review will examine research findings regarding the role different types of supports may play in facilitating student learning from simulations. These sections will focus on simulation features, curricular context, and teacher facilitation strategies.

What is the Research on Features of Simulations in Relation to Student Learning?

Findings from literature reviews and meta-analysis. Three of the review pieces included in this literature review found a relationship between the quality of a simulation's features and the potential for said simulation to support student learning. Scalise and colleagues (2011) shared that 17% of the studies analyzed in their review found benefits associated with simulation features that promoted scientific inquiry. Scalise and colleagues (2011) also shared that 15% of their studies found a relationship between high quality representations in simulations and gains in student content knowledge.

Similarly, Smetana and Bell (2012) found that the quality of a simulation's features impacted the potential of a simulation to support gains in student content knowledge. Effective support structures included those that encourage students to engage in meta-cognition and self-reflection. Smetana and Bell (2012) also found that, regardless of the quality of supports provided within the simulation itself, the classroom teacher played a critical and irreplaceable facilitative role in supporting students' use of the simulations.

D'Angelo and colleagues (2014) reported two trends related to simulation support features. First, simulations with metacognitive support features were more likely to promote student content learning than were simulations without such support features. Second, simulations that were highly structured, on average, had higher effect sizes for student learning outcomes than simulations that were designed to be flexible.

In sum, the three review pieces described above collectively identify the following types of simulation features as useful for promoting student learning: (a) features that support scientific inquiry, (b) features that support meta-cognition, (c) high-quality representations, and (d) features that provide structure. However, these categories of useful simulation features are somewhat broad and non-specific. For more specific descriptions of simulation features that have been found to be supportive of student learning, I turn to specific empirical studies.

Findings from empirical work. A series of studies have found that different types of supports may help students to learn more effectively from simulations. These include: different types of embedded prompts, a metacognitive tool for setting and monitoring goals, informational audio, icons, divided screens, and attention-directing avatars.

Embedded informational prompts. Hulshof and De Jong (2006) found that embedded informational prompts supported student learning of science content. In a study of 19-year-old students working with an optics simulation, students were randomly divided into two groups. The experimental group received access to just-in-time support through information tips provided within the simulation itself, while the control group did not have access to these tips. The experimental group outperformed the control group on the posttest, which measured science content knowledge.

Embedded prompts supporting investigation design and hypothesis testing. In a quantitative study focused on junior high students working with an optics simulation, Chang, Chen, Lin, and Sung (2008) found benefits to prompts supporting investigation design or hypotheses testing. In their quasi-experimental study with a pre/posttest design, students were assigned to a control group or to one of three experimental groups. In one experimental group, the simulation provided step-by-step instructions: this group was told exactly what to do and when to do it. In the second experimental group, the simulation provided prompts advising how to set up experiments; for example, users were encouraged to change only one variable at a time. In the third group, the simulation supported users to develop hypotheses and then test them. All three experimental groups outperformed the control group on a content measure assessing understanding of optical lenses. However, of the three experimental groups, the students given step-by-step guidance made the smallest pre/post gains. Researchers concluded that the prompts supporting hypothesis testing or investigation design were most effective at promoting learning, because they encouraged students to engage in critical thinking while using the simulation. In contrast, prompts that provided step-by-step guidance encouraged compliance rather than reflection.

Embedded prompts supporting students to make connections across representations. In a study focused on high school and vocational education students working with a physics simulation, van der Meij and de Jong (2011) found benefits to students making connections between variables in simulations across multiple representations. Students were randomly assigned to receive one of two kinds of support: general self-explanation prompts or prompts that supported making connections across different representations within the simulation. On the posttest, students prompted to make connections across representations outperformed students who were given the general self-explanation prompts. The posttest assessed (a) procedural and conceptual knowledge related to the content of the simulation, (b) transfer items, and (c) items that asked students to interpret representations.

Metacognitive tool for setting and monitoring goals. In a study focusing on high school students studying fluid dynamics, Manlove, Lazonder, and de Jong (2006) examined the impact of a tool that helped students set, monitor, and evaluate goals. This tool contained sets of goals and sub goals, strategies for how to reach goals, prompts to monitor progress, and prompts to support notetaking. Students who had access to both the simulation and the self-monitoring support outperformed students who only had access to the simulation both in terms of (a) initial planning while working with the simulation, and (b) learning from the simulation. Learning outcomes were assessed based on the number of correctly specified variables and relations students included in the fluid dynamics model that students were asked to generate following their time working with the simulation.

Informational audio component. In a study of middle-school students working with a simulation of oxidation-reduction reactions, Liu and Chuang (2011) used a 2x2 between-group factorial design to compare the relative impact of (a) student prior knowledge, and (b) the modalities used in the simulation. Pre- and post-assessments measured students' content knowledge of oxidation-reduction reactions. Researchers found that students who used the simulations that used animation and audio to convey information performed better on the posttests, as compared to students who used the simulations with animation and text. These differences in modality had a higher impact on posttest scores than initial differences in student prior knowledge. Researchers hypothesized that the presence of audio narration lightened the cognitive load because it would be easier for students to listen to audio while watching animation than for students to read text while watching animation.

Icons. Plass and colleagues (2009) found that icons played an important role in supporting learners to engage in particularly challenging tasks. In two studies, the researchers assigned high school students to use a simulation about the kinetic theory of heat that either (a) used symbolic representations only, or (b) used both symbols and icons. In the first study, students engaged in a relatively simple task while using the simulation. In this study, students in both simulation conditions performed equally well on the content posttest. In the second study, students engaged in a more complex task. In this study, students who had access to both symbols and icons had higher scores on the posttest, as compared to students who only had access to symbols. This effect was strongest for the learners who entered the study with the lowest scores on the content pretest.

Divided screens. Lee and colleagues (2006) found that both icons and divided screens could support increased student comprehension. In a study of 257 middle-school students working with a simulation of the ideal gas law, researchers used a 2x2 factorial design to compare low- and high- visual complexity and optimized- and non-optimized visual representation. In the low-visual complexity condition, the information in the simulation was divided into two screens. In the high-visual complexity condition, the information in the simulation was combined into one screen. In the non-optimized visual representation, important information was only represented with symbols; sliders were separate from the simulation, and only the most recent graphed results were shown. In the optimized visual representation, important information was represented with both icons and symbols, sliders were integrated with the simulation, and all graphed results were shown. Researchers found that that students working with thee low-visual complexity and optimized-visual representation had higher scores on a posttest measuring content knowledge of the ideal gas law, as compared to their peers in the other three conditions. This was especially true for students with low prior knowledge. Researchers used cognitive load theory to explain why changes in the simulation multimodal text features impacted levels of student learning from the simulation.

Attention-directing avatars. Moreno, Reislein, and Ozogul (2010) identified another way that changes in simulation design could support increases in student learning. In a study of middle-school students working with a simulation focused on Ohm's Law, they compared students who had their attention guided to specific parts of the simulation using an arrow, students who had their attention guided using an avatar, and students who did not have their attention guided at all. The group of students guided by the avatar outperformed both other groups on the posttest, which assessed students' ability to solve electrical circuit problems. Furthermore, this group self-reported fewer difficulties with the simulation, as compared to the other two groups.

The following table summarizes support features that empirical research has identified as supporting students to learn science content knowledge from simulations. I will return to this chart in the methods section, to examine which of these features are incorporated into each of the simulations examined in this study.

Table 2.1

Simulation Features that are Supportive of Student Learning

Simulation Feature	Empirical Work
Embedded prompts: Providing information	(Hulshof & De Jong, 2006)
Embedded prompts: Designing investigations	(Chang et al., 2008)
Embedded prompts: Testing hypotheses	(Chang et al., 2008)
Embedded prompts: Making connections across representations	(van der Meij & de Jong, 2011)
Metacognitive tools: Setting and monitoring goals	(Manlove et al., 2006)
Audio information	(Liu & Chuang, 2011)
Icons	(Lee et al., 2006; Plass et al., 2009)
Divided Screens	(Lee et al., 2006)
Attention-directing avatar	(Moreno et al., 2010)

Limitations of simulation support features. Several empirical studies found limitations related to the capacity of simulation features to support student learning. These limitations included both (a) simulations features omitting some aspects of complex phenomenon, and (b) students choosing not to engage with simulation features.

Some limitations of simulation features stem from the simulation simplifying a complex phenomenon, which can in turn influence student understanding of the phenomenon. For example, researchers (Neulight, Kafai, Kao, Foley, & Galas, 2007) working with 6th-grade students using a simulation on infectious disease found that most students thought of infectious disease as being only caused by human behavior (e.g. standing close to one another), and did not understand the role microscopic agents (e.g. bacteria or viruses) play in transmitting disease between humans. The researchers posited that this incomplete understanding may have been related to the fact that the simulations' images and animation focused entirely on macroscopic processes: there were no images or animations of microscopic processes.

In other cases, the ability of simulation features to support student learning may be constrained when students choose to ignore some of its features. Hsu and Thomas (2002) conducted a study with undergraduates using a simulation based on meteorology. Students were assigned to two simulation conditions or a control condition. At the end of the study, all participants took a content knowledge posttest that measured knowledge of condensation aloft, adiabatic temperature change, and other meteorological concepts presented in the simulation. Contrary to their hypothesis, researchers found no significant difference between the posttest results of students in the simulation and control conditions. To investigate this unexpected result, researchers chose five focal students to interview about how they had used the simulations. In the course of these interviews, researchers learned that four out of the five students had struggled to interpret some of the representations included in the simulation and chose to ignore the representations that they did not understand. Only one student examined all three different types of representations (graphs, digital displays, and animations) to determine the relationship between the variables presented in the simulation. Researchers speculated that students in the simulation condition might have shown greater growth on the content posttest if they had received instructional support to help them interpret all the representation types present in the simulation. This aligns with the conclusion drawn by Smetana and Bell (2012) in their literature review, which suggested that simulation features will be most effective when supported by strong teaching; this study also supports the use of observational data to study closely students' uses of simulations.

In the following two sections, I explore the potential for both curricula and teaching to support students' learning from simulations.

What does Research tell us about Embedding Simulations within Curricula?

Findings from literature reviews and meta-analysis. None of the review pieces included in this literature review shared findings related to the potential impact of curricular context on student learning from simulations. Indeed, Rutten and colleagues (2012) specifically comment that most research does not take into account either the lesson scenario or the role of the curriculum, and calls for more research to fill this gap.

Findings from empirical work. While simulations alone can support student learning, they may be even more powerful when integrated with other learning opportunities. While there is little research examining the impact of integrating simulations into a larger curriculum, several empirical studies have examined the potential for synergy between simulation-based lessons and other related learning opportunities.

In a study of 6th grade students working with an ecosystem simulation, Riess and Mischo (2010) found benefits for combining simulation-based instruction with lessons focused on systems-thinking. Researchers compared students who: (a) participated in lessons on systems thinking, (b) worked with an ecosystem simulation, (c) participated in lessons on systems thinking and worked with an ecosystem simulation, and (d) were taught using traditional methods (business as usual). The students who both worked with the simulation and participated in lessons on systems thinking were the only students who made measurable learning gains on the assessment measuring systems thinking. Researchers concluded that the simulation was more effective at prompting systems thinking when paired with additional lessons introducing and supporting systems thinking. However, a limitation of this study was that the instructional time was not the same across all four groups: students in the condition with both simulation and systems thinking lessons received substantially more instructional time,

In a study that did control for instructional time Jaakkola and Nurmi (2008), working with 10 and 11 year-old students who were learning about electricity, compared learning outcomes for students who: (a) first investigated using the simulation and then investigated using the physical lab, (b) students who worked only with the simulation, and (c) students who worked only with the lab. Students in the combined simulation and lab condition (condition a) had the highest scores on a subject knowledge post-test. The researchers hypothesized that the simulation may have been helpful in isolating and understanding the theoretical principles at play, whereas the lab may have helped demonstrate that these principles also apply in the physical world. In a follow-up study, Jaakkola, Nurmi, and Veermans (2011) compared the performance of 5th and 6th grade students studying circuits in four conditions: (a) simulation with only procedural guidance, (b) simulation with both procedural and conceptual guidance, (c) simulation and physical lab with only procedural guidance, and (d) simulation and physical lab with both procedural and conceptual guidance. All students took pre and posttests that assessed their subject matter knowledge. Again, the researchers found that the greatest pre/post gains were made by students who worked with both the simulation and the physical lab.

When simulations and labs are combined, it may be important to teach the simulation first. In a study by Akpan and Andre (2000), 7th grade students who were learning about frog anatomy were assigned to four different conditions: simulation only, simulation followed by dissection, dissection followed by simulation, and dissection only. The students in the simulation-only condition and the simulation-followed-by-dissection condition learned more anatomy than the students in either of the two conditions that began with physical dissection work. This suggests that it may be most beneficial for students to work with simulated environments before working in a physical lab. One reason for this could be that simulated environments are often simpler, more consistent, and easier to interpret than real world environments.

In summary, while most research on simulations disregards lesson or curricular context (Rutten, Van Joolingen, & Van Der Veen, 2012), the existing research suggests that there is a benefit to pairing simulation-based lessons with (a) hands-on investigations and (b) conceptual discussions about ideas introduced in the simulation. The table below summarizes these findings.

Table 2.2

Curricular Experiences that can Supplement and Reinforce Student Learning from Simulations

Curricular Experience	Empirical Work
Lessons that introduce key science concepts	(Riess & Mischo, 2010)
Lessons that contain hands-on investigations	(Akpan & Andre, 2000; Jaakkola & Nurmi, 2008; Jaakkola et al., 2011)

In the next section, I consider research regarding the impact of the teacher on students' learning from simulations.

What does Research tell us about the Facilitative Role of the Teacher During Simulation-Based Lessons?

Findings from literature reviews and meta-analysis. Only one of the review pieces included in this literature review shared findings about the role of the teacher. Smetana and Bell (2012) found that teachers could support student learning by (a) providing time for familiarization with the simulation, (b) providing directions, asking questions and providing feedback while using the simulation, (c) creating assignments to be used in conjunction with the simulation, and (d) facilitating debriefing conversations following use of the simulation. The other three review pieces did not share findings regarding the role of the teacher. Indeed, Rutten and colleagues (2012) reported that most research on simulations did not take into account the role of the teacher when studying student learning from simulations, and called for more research to address this gap. This current study is designed to be responsive to this call.

Findings from empirical work. I was not able to find a large number of empirical pieces that focused on the role of the teacher in supporting student learning from simulations. Of those pieces that I found, some documented variations in the nature of teacher support while others examined the potential impact of teacher support on student learning.

Variations in the nature of teacher support. Several case studies examined variations in ways that teachers supported students to learn from simulations. In a naturalistic case study of middle and high school physics teachers' approaches to using physics simulations in the classroom, Hennessy, Deaney, and Ruthven (2006) identified two different approaches teachers used to structure simulation-based lessons. In the dialogic approach, the whole class worked together to collaboratively discuss and test student ideas using the simulation. In the authoritative approach, students were given a highly guided work sheet and were instructed to work through it in pairs. Researchers noted that students in the dialogic approach were more involved in the process of generating hypotheses and figuring out how to test them using the simulation. In contrast, students using the worksheet worked step-by-step through an investigation pre-designed by their teacher.

Like Henessey and colleagues (2006), Rehn and colleagues (2013) also found variations in teacher pedagogy while using simulations. In a study that compared a middle school science teachers enactment of a simulation focused on molecules and a university instructor's enactment of a simulation focused on quantum tunneling, Rhen and colleagues found variations in both (a) teacher instructional moves and (b) the amount of productive discussion and co-construction of new ideas that occurred in each classroom (Rehn, Moore, Podolefsky, & Finkelstein, 2013). By comparing the two cases, Rehn and colleagues identified multiple instructional moves with the potential to support productive discussion and co-construction of ideas. These included: (a) supporting students to compare multiple forms of representation within the simulation, (b) using simulations to mediate discussion, (c) encouraging students to make predictions and then observe and explain results, (d) setting up game-like situations and challenges to engage student interests, (e) focusing on illuminating cases, and (f) asking students to represent simulation features (e.g. through sketches in their science notebook) (Rehn et al., 2013)

Impact of teacher support on student learning. The naturalistic case studies described above identify different types of practices used by teachers, but do not consider impact on student learning. However, I also identified three studies that used experimental designs to investigate the impact of teachers' support on student learning. All of these studies found greater evidence of student learning in conditions where teacher guidance was present.

In a study of 9th grade students working with a chemistry simulation, Ardac and Sezen (2002) compared a control condition (no simulation) to two experimental conditions. In the teacher-guided condition, the teacher introduced the simulation, discussed its variables, and showed the students how to manipulate variables. In the unguided condition, students worked independently with the simulation. All participants took pre and posttests that measured both content knowledge and science process skills. On the measure of process skills, students in both simulation conditions made greater pre/post gains than students in the control condition.

However, on the measure of content knowledge, only students in the guided simulation condition and the control condition showed significant pre/post gains. Researchers concluded that teacher guidance may play a key role in supporting students to learn content from simulations. Stephens compared high-school students who worked with a physics simulation in whole-class and small-group participation structures. They examined eight classes taught by two teachers: each teacher taught four classes using whole-class teacher-guided pedagogy and four classes using small-group student-guided participation. Somewhat to their surprise, researchers found that students in the teacher-guided whole-class condition made greater gains on pre/posttests that measured students' ability to apply the content covered during instruction in new contexts. After conducting qualitative data analysis, the researchers found that the teacher-guided whole-class condition typically included: (a) more discussion of key concepts, (b) more support for students who had difficulty understanding, and (c) more support in interpreting key visual features of the simulation. In contrast, students working in small groups tended to: (a) cut conceptual discussions to save time, (b) focus on getting and reporting data rather than on understanding data, and (c) only support each other in interpreting simulation visuals when the teacher was nearby.

In a study focused on 9th grade students working with a force and motion simulation, Wu and Huang (2007) also compared students working with the simulation in a whole-class, teacher-guided condition versus a small-group, student-guided condition. Researchers found that lower-achieving students received a significant benefit from working with the simulation as a whole class. In the whole-class condition, all students made equal gains on a pre/posttest measuring knowledge of force and motion. In the small-group condition, only the higher-achieving students made gains; the higher-achieving students made equal gains in the small-group and whole-class conditions. Although students reported preferring the small group condition, this study suggests that the whole-class, teacher guided condition provided more equitable learning opportunities for all students.

Benefits to teachers providing unstructured exploration time. Although the three studies presented above all suggest benefits to teachers guiding students' experiences with simulations, other research indicates there may also be benefits to teachers providing students with a period of unstructured time for exploration. Podolefsky, Rehn, and Perkins (2013) conducted a quasi-experimental study of two fifth-grade classes working with an optics simulation where one class began with eight minutes of open play while the other class did not. The researchers found that students who had eight minutes to play with the simulation were able to use that time to learn how to work the simulation. Subsequently, during the teacher-led portion of the class, the discussion in the play condition was more focused on the conceptual elements of the simulation while the discussion in the no-play condition was more focused on procedural elements of the simulation. The use of open exploration will play a part in the current study as well.

In sum, the existing research on the role of the teacher in simulation-based lessons suggests that teachers' instructional decisions may play a key role in determining how students will engage with a simulation and what students will learn from a simulation. The table below summarizes types of teacher support that research has suggested might be helpful when facilitating simulations.

Table 2.3

Teacher Moves for Facilitating Simulation-Based Lessons

Teacher Move	Empirical Work
Providing time for students to explore simulations	(Podolefsky et al., 2013; Smetana & Bell, 2012)
Supporting students to interpret simulation representations	(Stephens & Clement, 2015)
Supporting students to compare different simulation representations	(Rehn et al., 2013)
Inviting students to create representations of simulations (e.g. sketches)	(Rehn et al., 2013)
Supporting students to make predictions	(Rehn et al., 2013)
Supporting students to interpret results	(Rehn et al., 2013)
Using challenges to engage student interest	(Rehn et al., 2013)
Focusing on illuminating cases	(Rehn et al., 2013)
Discussing key concepts from the simulation	(Rehn et al., 2013; Stephens & Clement, 2015)
Providing additional support to students who are having difficulty understanding	(Stephens & Clement, 2015)

As Rutten and colleagues (2012) noted in their literature review, most research on simulations does not consider the role played by the teacher. The six studies presented above are the exception to this general trend. However, even in the case of these six studies, there was often minimal description of what teachers were saying and doing in order to support students to engage in scientific sensemaking. Given the relative lack of literature exploring how teachers can support student sensemaking while teaching with simulations, I chose to also examine literature that explored how teachers can support student sensemaking while teaching science.

What does Research Tell Us about How Teachers can Support Student Sensemaking while Teaching Science?

Although there are currently relatively few studies that shed light on how to support student sensemaking while working with simulations, there is a considerable body of literature that provides guidance on how to support student sensemaking across many different academic domains (Fitzgerald & Palincsar, 2019), including science (Windschitl & Calabrese Barton, 2016). In the section that follows, I provide a conceptual review (Kennedy, 2007) of key themes from the literature on teaching practices that support student sensemaking. For a more in-depth review of this literature, see Fitzgerald and Palincsar (2019).

Establishing classroom communities where sensemaking can occur. A positive and respectful class culture is a necessary precondition to supporting student sensemaking. Many researchers have examined how teachers can establish respectful and mutually-supportive class communities, as well as the academic benefits of such communities (Gillies, 2008, 2016; Mercer, Dawes, Wegerif, & Sams, 2004; Mercer, Wegerif, & Dawes, 1999). These types of positive communities can be supported by the teacher introducing and reinforcing norms for productive discussion including: turn-taking, attentive listening, building off of other students' ideas, or respectfully challenging other students' ideas (Mercer et al., 2004).This norm-setting talk is not sensemaking in and of itself; however, it can help establish classroom communities where sensemaking talk can flourish (Michaels, O'Connor, & Resnick, 2008; Michaels, O'Connor, Hall, & Resnick, 2010).

Providing opportunities for students to share their ideas. Another key practice that supports sensemaking is providing opportunities for students to share their ideas. Windschitl and Calabrese Barton (2016) argue that "eliciting student ideas" is a key part of science teaching, because it allows teachers to meet students where they are at and to tailor their instruction to the students in front of them. There are many different participation structures that can support students to share ideas. These include: whole-class conversations, small-group conversations, and partner-based conversations. Grossman and colleagues argue that alternating between these different participation structures is a form of differentiation that can help support all students to learn (Grossman, Loeb, Cohen, & Wyckoff, 2013). In addition to supporting students to share their ideas, it is also beneficial for teachers to explicitly teach students how listen to and build off of each other's ideas (Mercer et al., 2004; Mercer et al., 1999).

Revoicing student contributions. Another practice that can support student sensemaking is revoicing student contributions. By revoicing, teachers can position students as knowers while adding complexity to students' statements (O'Connor & Michaels, 1993). Research has found that there are instructional benefits when teachers reframe a student's ideas in a way that uses scientific, rather than every day, language (Puntambekar, Stylianou, & Goldstein, 2007). Revoicing can also serve to rebalance power dynamics in a classroom, by assigning competence to students who are not considered "academic" by their peers (Cohen, 1994; Cohen, Lotan, Scarloss, & Arellano, 1999).

Asking questions and making connections. Two more ways that teachers can support sensemaking are by asking questions and making connections. There are many kinds of teacher questions that have been found to support sensemaking. These include: (a) asking questions that press students to expand or clarify their thinking (Hogan, Nastasi, & Pressley, 1999), (b) asking conceptual questions that help frame the class conversation (Cervetti, DiPardo, & Staley, 2014), (c) and asking questions that press students to support their ideas with reasoning (Puntambekar et al., 2007). All the questions described above help students make connections among their ideas.

Teachers can also support sensemaking by explicitly pointing out connections to help make connections salient for students. This can include both (a) making connections between different parts of a science unit, and (b) making connections to physical experiences students have witnessed (Puntambekar et al., 2007).

Supporting scientific practices. Teachers can also support sensemaking by supporting students to engage in scientific practices. This often begins by supporting students to make careful observations (Manz, 2016; Manz & Renga, 2017) and predictions (Herrenkohl & Cornelius, 2013). It can be particularly beneficial for students to develop multiple predictions and theories and then develop investigations that will provide confirming or disconfirming evidence (Herrenkohl & Cornelius, 2013). It is also beneficial for the teacher to help guide students to identify what counts as evidence (Manz, 2015; Manz & Renga, 2017) and decide whether or not their evidence supports their theories (Herrenkohl & Cornelius, 2013). Teachers can then help foster class conversations in which students both generate and critique claims (Engle & Conant, 2002; Manz, 2016; McNeill & Pimentel, 2009).

Supporting meta-representational competence. Another way to support student sensemaking is to support their meta-representational competence. diSessa (2004) characterizes meta-representational competence as the ability to select, interpret, and create representations as needed to complete desired tasks and goals. Supporting meta-representational competence is particularly important in science education, since scientists frequently work with representations (Lemke, 2004), yet research has found that novices often struggle to interpret representations effectively (Furberg et al., 2013; Jian, 2016; Kozma, 2003; Prain & Waldrip, 2006).

The following table, Table 2.4, summarizes the teacher moves for supporting student sensemaking that are presented in this section. Note that the moves in Table 2.4 are consistent with the moves presented in Table 2.3, which examined research-based strategies for teacher facilitation of simulations. However, as compared to Table 2.3, Table 2.4 provides a broader repertoire of pedagogical strategies. This makes sense, given that there is currently much more research on supporting student sensemaking than there is research that specifically addresses teacher facilitation of simulations.

Table 2.4

Teacher Moves for Supporting Student Sensemaking

Teacher Move	Empirical Work
Introducing and reinforcing norms for productive discussion	(Mercer et al., 2004)
Supporting students to engage in turn taking	
Supporting students to listen attentively	
Supporting students to build off of each other's ideas	
Supporting students to challenge each other's ideas	
Using varied participation structures to support students to share ideas	(Grossman et al., 2013)
Providing opportunities for whole class conversations	
Providing opportunities for small group conversations	
Providing opportunities for partner-based conversations	
Revoicing student contributions	(Cohen, 1994; O'Connor & Michaels, 1993; Puntambekar et al., 2007)
Asking questions	
Using conceptual questions to frame class conversation	(Cervetti et al., 2014)
Pressing students to expand or clarify their thinking	(Hogan et al., 1999)
Asking students to support their ideas with reasoning	(Puntambekar et al., 2007)
Making connections	(Puntambekar et al., 2007)
Making connections across lessons in a science unit	
Making connections to real-world experiences	
Supporting students to engage in scientific practices	
Supporting students to make detailed observations	(Manz, 2016; Manz & Renga, 2017)
Supporting students to make predictions	(Herrenkohl & Cornelius, 2013)
Supporting students to develop investigations	(Herrenkohl & Cornelius, 2013)
Supporting students to evaluate evidence	(Manz, 2016; Manz & Renga, 2017)
Supporting students to generate and critique claims	(Engle & Conant, 2002; Manz, 2016; McNeill & Pimentel, 2009)
Supporting meta-representational competence	(diSessa, 2004)
Supporting students to select representations appropriate to a given goal	
Supporting students to interpret representations	
Supporting students to create representations	

The past several sections of this literature review have examined how research has studied the potential impact of simulation features, curricular context, and teacher pedagogical moves, respectively. The final section of this literature review will turn towards considering teachers and students reflections on their experiences with simulation-based learning.

How have Researchers Studied User Attitude towards Simulations?

Findings from literature reviews and meta-analysis. Two review pieces mentioned user attitudes towards simulations. Smetana and Bell (2012) found that all studies that examined user perceptions found that both students and teachers thought simulations supported student understandings of science content. D'Angelo and colleagues (2014) found that students generally showed positive non-cognitive outcomes (including more positive attitude towards science learning) following work with simulations, but cautioned against generalizing these findings due to the small number of effect sizes analyzed.

Findings from empirical work. Of the empirical work I examined, several pieces shared findings related to student attitudes toward learning with simulations. However, the existing research is less than conclusive.

Several studies have found that students who work with simulations have a more positive attitude toward science learning than peers who learn by more traditional methods. Kiboss and colleagues found that high school students who studied cell division through simulations subsequently gave higher scores on the Pupil Attitude Questionnaire, as compared to students who studied cell division through traditional means (Kiboss et al., 2004). In a study by Akpan and Strayer (2010) researchers administered an attitude assessment, which measured student attitudes towards dissection, computers, science, and school, both before and after a frog anatomy lesson. Students who participated in traditional physical dissection showed a drop in their attitude scores, whereas students who studied frog anatomy through a simulation did not show a drop in attitude scores.

Other studies have found that students who work with simulations have similar attitudes compared to students who learn with more traditional methods. Klahr and colleagues found that middle school students building and testing physical cars and middle school students working with a car-building simulation both showed similar gains in confidence about their knowledge of how to optimize car design. “Confidence in knowledge” was self-reported for each item on the content posttest, using a Likert scale of one to five (Klahr et al., 2007). Similarly, Çığrık and Ergül (2009) found that 7th grade students learning about electrostatic induction from a simulation displayed comparable attitudes toward learning when compared with students learning about electrostatic induction through traditional methods, as measured on a Science Education attitude scale.

Still other studies have found students to have negative attitudes towards learning with simulations. For example, in a study of 9th grade students working with a chemistry simulation, Ardac and Sezen (2002) reported that some students shared objections to learning chemistry through a simulation during informal discussions with the researchers. For example, students claimed that computer-based instruction was difficult or not of much use. Some complaints indicated that computer-based learning was difficult, in part, because it was unfamiliar. For example, one student stated “working with computers was demanding, because we are used to traditional methods” (p. 47). Similarly, a recent study, which is not yet published but which was presented at the 2018 ICLS conference, found its participants had a highly negative perception of simulations. Researchers working with Latinx emerging bilinguals in two 6th grade science classes collected qualitative data through participant observation, field notes, audio recordings, artifacts from the classroom, structured/semi-structured interviews, and personal and group dialogues with students. Some of the researchers’ initial findings specific to the use and benefits of simulations were later challenged by participants during focal group interviews. Interviewees reported that they considered simulations to be an inferior learning opportunity, compared to hands-on investigations. For example, one student shared “I do not know teachers are getting lazy thinking to use a technology. Just sit there. Good luck learning it.” Another student emphasized inaccuracies in how simulations representation phenomena, “On the computer, it takes 3 seconds for water to boil, in reality it takes about 10 minutes. Most of us do not believe most of the science, why would we believe it? Not everything that you can do or see virtually is real in life, you know, some of it is imagination.” These student concerns about simulations provided a sharp contrast to potential assumptions about how technically-savvy youth would respond to incorporating technology into science instruction (Kayumova & Cardello, 2018).

Looking across the Simulation Literature

There is significant empirical evidence that simulations can support student learning in different content areas of science (D'Angelo et al., 2014; Rutten et al., 2012). Furthermore, research indicates that simulation design (D'Angelo et al., 2014; Scalise et al., 2011), curricular context (Jaakkola & Nurmi, 2008; Riess & Mischo, 2010), and teacher instructional practices (Ardac & Sezen, 2002; Smetana & Bell, 2012) all may impact how much students learn from simulations. However, the research on the impact of curricular context and teacher practice is still in a nascent stage: most studies of simulations still disregard the potential role of the teacher or the curriculum (Rutten et al., 2012).

Based on my review of literature reviews, meta-analyses, and empirical work, I have identified three gaps in the existing research on simulations in science education. First, there is little work focusing on students working with simulations in the early years of elementary school. In all my searching, I only identified one article that examined the use of simulations in

1st – 3rd grade. This gap is problematic because we know that the students at different grade levels may benefit from different types of supports, tailored to where they are at in the developmental progression of different aspects of scientific sensemaking (Berland & McNeill, 2010; Songer & Gotwals, 2012; Songer, Kelcey, & Gotwals, 2009). Therefore, we cannot assume that the findings that simulations are supportive of the learning of middle, high school, or university students necessarily imply that simulations should have a place in the lower elementary classroom. On the contrary, the hypothesis that simulations can be supportive of lower elementary students' sensemaking needs testing.

Second, there is little research focusing on how teachers begin to implement simulations in classrooms settings. What Rutten and colleagues wrote in 2012 remains true today; in most research, "the use of computer simulations has been approached without consideration of the possible impact of teacher support, the lesson scenario, and the computer simulation's place within the curriculum" (p. 136). There is little research that chronicles the challenges that teachers face when beginning to use simulations in their classrooms. Research on teachers taking up new pedagogies and tools can provide images of practices that reveal strategies that may be transferrable to other classrooms (Cervetti et al., 2014; Herrenkohl, Tasker, & White, 2011). Yet, to date, there are few studies that present images of the practice of teachers who are beginning to use simulations to support their teaching of science. This is particularly true in lower elementary grades, where any research on simulations is rare. This is problematic because it means that there are few resources available to support lower elementary teachers who may be interested in using simulations to support scientific sensemaking.

Third, most research on simulations does not attend to the perspectives of teachers. It is rare for researchers to consider whether teachers consider simulations to be (a) supportive of learning, and (b) a valuable part of science curriculum (D'Angelo et al., 2014). The research on user perspectives that does exist is mostly focused on students in middle or high school. However, curriculum designers, such as those on working on the MLs project need to be able to consider teacher feedback when determining whether (and how) to incorporate simulations into elementary science curriculums (Fishman, 2014). Therefore, the lack of studies exploring how teachers evaluate simulations is problematic.

This study proposes to address all three research gaps through a descriptive case study of how two 3rd grade teachers take up the teaching of simulations during science instruction. The research questions of this study will be:

(1) How do teachers support student sensemaking while working with simulations in the context of 3rd grade project-based science? Does this support, or student response to this support, shift across the three simulations?

(2) What are the teachers' perspectives regarding the use of simulations as sensemaking tools?

CHAPTER 3 Research Methods and Design

Overview of Methods Chapter

This chapter begins with an introduction to the theoretical framework that undergirds this study. I next provide my rationale for designing this research as a case study, describe my role and positionality as a researcher, and introduce setting and participants. Then, I introduce the instructional context, including: the MLs units, the simulations, and the ML curricular supports for simulation-based lessons. Finally, I present my data sources and analytical methods.

Theoretical Framework

This study uses the theoretical framework of social constructivism (Palincsar, 1998), which views learning as occurring both through internal cognitive processes and external social processes. Social constructivism has strong roots in Vygotskian-based sociocultural theory and Piagetian-based socio-cognitive theory. One Vygotskian concept that supports social constructivism is the Zone of Proximal Development (ZPD), which argues that when learners are given social support, they are able to achieve more than they would be able to achieve without support (Vygotsky, 1978). Another essential concept drawn from Vygotsky is the idea that human interactions and communication can be mediated by signs and tools, including both written language and other visual symbols (Vygotsky, 1978; Wertsch, 1991). From Piagetian theory, social constructivism draws on the idea of socio-cognitive conflict, which suggests that social interaction can drive cognitive change, by exposing people to ideas that are different from their own (Perret-Clermont, 1980).

More specifically, this study draws from the RAND model of reading comprehension, which emphasizes the role played by sociocultural context in mediating the interactions among reader, text, and activity (Rand Reading Study Group, 2002). It also draws from recent advances in the field of reading research that indicate the important role classroom dialogue may play in supporting student comprehension of text (Wilkinson & Son, 2011).

Influence of social constructivism on this study's research questions. The research questions of this study were both generated based on a social constructivist theory of learning.

The first research question (and its subquestion), *How do teachers support student sensemaking while working with simulations in the context of 3rd grade project-based science? Does this support, or student response to this support, shift across the three simulations* focuses on the social interactions between teachers and students. Empirical research in classrooms, designed and conducted within the context of a social perspective on learning, has found that individual student learning can be impacted by the nature of talk in science classrooms (Mercer et al., 2004). Repeated research has found that, when students have the opportunity to discuss new science concepts while building on each other's ideas, there are benefits both to students' scientific knowledge and to their reasoning ability (see e.g.Mercer, Dawes, Wegerif, & Sams, 2004; Mercer, Wegerif, & Dawes, 1999; Webb & Treagust, 2006).

By emphasizing the role played by the classroom teacher in facilitating discussions that support student sensemaking, this study departs from the research paradigm that has been most commonly used to study simulations. The majority of research on simulations examines interactions between the simulation features and student use of simulations, but does not consider classroom social interactions or curricular context (Rutten, Van Joolingen, & Van Der Veen, 2012). This previous research demonstrates the strong potential of simulations as a learning tool

(D'Angelo et al., 2014), but does not consider how simulations may be used as a learning tool within a specific social context. My research builds on this previous research by considering how the social context of the classroom may support students as they interact with simulations (see Figure 3.1, below).

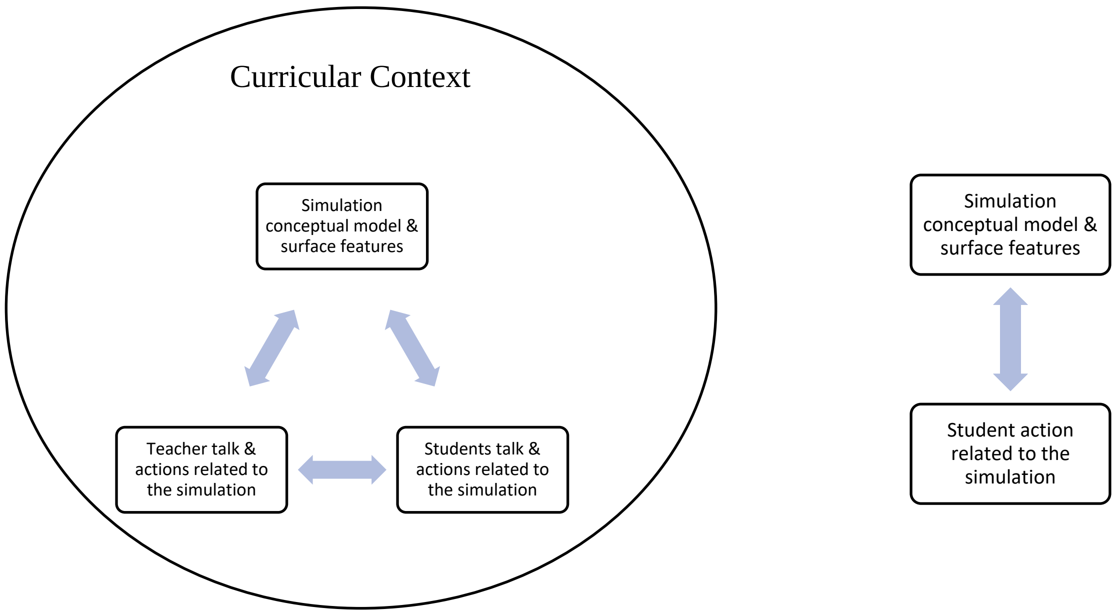

Figure 3.1 Comparing studying simulations through a social constructivist (right) and cognitivist (left) perspective

The second research question, *What are the teachers' perspectives regarding the use of simulations as sensemaking tools?* also draws from a social constructivist perspective, as it emphasizes the value of the simulation as a semiotic tool used to mediate conversations about scientific ideas. In the Vygotskian sociocultural perspective, human society has developed semiotic tools for the purpose of supporting communication within social settings. For these tools to remain a part of a given social context, they must in some way facilitate communication between the different social actors in the situation. My second research question asks to what extent some of the social actors in the classroom (the teachers) find the semiotic tool(s) that make up the simulation to support the shared goal of communicating about scientific ideas. This is an important question to consider, because, from a socio-cultural perspective, the simulation is only a useful teaching tool to the extent that it supports the participants to jointly engage in reasoning about the scientific phenomenon presented by the simulation. If the simulation obfuscates or impedes communication, then it is not effectively functioning as a semiotic tool and should not be used to support scientific discussions.

The Case

Rationale for case study methodology. I chose to design this study as a case study because a case study fits well with both my specific research questions and my overarching theoretical framework of social constructivism. As described above, social constructivism focuses on the important role social interactions play in supporting learning (Palincsar, 1998). Case study methods are well matched to the theoretical framework of social constructivism, because they lend themselves to providing a close look at specific social contexts, as well as human interactions, within those social contexts (Dyson & Genishi, 2005). As described, my specific research questions focus on how teachers support students to engage in sensemaking with simulations and what teachers share about the value of the simulation as a tool to support sensemaking. Case study methods are well matched to my specific research questions, because they allow me to closely examine the enactment of simulation-based lessons in a specific educational context. Case studies based on specific-educational contexts benefit both research and practices because they (a) provide illustrative examples of how particular pedagogical techniques or tools unfold “on the ground” in real-world classroom contexts and (b) can help support theory building by identifying both successes and struggles that occur in a particular case (Stake, 1995).

Every case study is “a case” of something (Hesse-Biber & Leavy, 2010). This case study is the case of how two third-grade teachers enact a series of simulation-based lessons, while supporting their students to engage in scientific sensemaking. It examines pedagogical techniques used by the teachers to support sensemaking through discussion. It also examines teachers’ perspectives on simulation-based lessons, including both benefits and challenges.

In the following sections, I provide more detail about (a) my own role in the educational context featured in this case study, and (b) the school, teachers, and students featured in this case study.

Role and position of the researcher. I designed and conducted this case study within the context of the Using Multiple Literacies in Project-Based Learning Project (MLs), funded by a generous grant from the George Lucas Foundation to Joe Krajcik, Annemarie Palincsar, and Emily Miller. For the past three years, I have been part of the literacy team on the MLS project, which is headed by Annemarie Palincsar, a co-PI on the project and my advisor. In this role, I assisted in the development of literacy resources to support the MLS curriculum. I also worked with teachers in one of our pilot schools, Stone Elementary, observing and supporting as they enacted the MLS curriculum. It was through this work that I first met Ms. Lane and Ms. Lawson (note: all participant and place names in this dissertation are pseudonyms).

Ms. Lane was one of the first four teachers invited to pilot the 3rd grade MLS units. When I joined the MLS project, Ms. Lane had already been teaching the third grade MLS units for one year. Ms. Lawson also taught 3rd grade at Stone Elementary, in the classroom down the hall from Ms. Lane. After hearing Ms. Lane talk about the MLS units, Ms. Lawson asked if she could teach them, also. I was one of the MLS team members who provided support in both Ms. Lane and Ms. Lawson’s rooms as they taught the MLS units. It was in this context that I first became interested in the instructional decisions and discourse moves Ms. Lane and Ms. Lawson made while using several simulations that were incorporated into the MLS curriculum.

Throughout the study, my role as a researcher was that of a participant observer (Hesse-Biber & Leavy, 2010) in both Ms. Lane and Ms. Lawson's room. Early in the year, both teachers introduced me to their students as a one of the designers of the MLs science curriculum and told them that I would be observing science class in order to help make the science curriculum better. During whole group instruction, I would sit in the back of the room with my laptop out, taking notes on science instruction and only speaking in the rare event that the teacher asked me a direct question. When students worked individually, or with partners, both the teacher and I would circulate among students. While circulating, we would both help students with their work and ask them questions about what they were learning. After the science lesson was finished, the teacher and I would usually briefly check in, sharing our impressions of what went well and also (if relevant) sharing ideas about any ways that the curriculum could be modified or improved. The teachers and I would also meet during lunch or prep time several times a unit to discuss the pacing of upcoming science lessons, materials needed, important conceptual ideas, and/or logistical concerns.

My "positionality" as a researcher (Hesse-Biber & Leavy, 2010) comes from my own identity and life experiences, which cannot help but influence what I observe in classrooms and how I interpret what I observe. I am a white woman in my early thirties. I grew up in a middle-sized university town in the Midwest, in a family that highly valued education. After graduating from college, I taught in a combined 1st-6th grade Montessori School for four years, then moved to New York to get my Masters as a Literacy Specialist at Teachers College. For the past four summers, I have taught project-based science to third graders at a summer camp in New York

City. I have worked as a staff developer, led professional development, and taught undergraduate teaching interns. My experiences as a teacher and as a teacher educator have shaped my desire to observe experienced teachers to help articulate and describe teaching practices that support student sensemaking.

Setting. I conducted this study during the 2018-2019 school year at Stone School in rural Michigan. The district revenue per pupil is $11,000, the pupil to teacher ratio is 32:1, and the graduation rate is 82%. The student population is approximately 60% white, 25% African American, 5% “two or more races” and 5% Hispanic/Latinx, and 2% Asian. Approximately 45% is considered low income and approximately 20 % is considered “students with disabilities.” Finally, only 25% of third-grade students attained proficient performance on state-wide measures of reading.

Participants. I purposefully selected (Patton, 2002) Ms. Lane and Ms. Lawson’s classrooms as the context for this study because, over the prior years, I had opportunity to observe the passion, dedication, and skill that they both brought to the teaching of science. I was confident that both of them would teach science on a regular basis and have well-managed classrooms conducive to student learning. Also, during the previous year(s) I had worked with each teacher, they were willing and excited to participate in ongoing conversations about their professional practice. Both teachers were willing to extend our collaboration for an additional year, beyond the timeline of the original MLs project, so that I could collect dissertation data.

During the year that this study was conducted, Ms. Lane was in her 20th year teaching and her 4th year teaching the MLs units. There were twenty-eight students in her class (12 were male, 16 were female). Four of Ms. Lane’s students moved mid-year. The demographics of her class reflected the overall school population. At the beginning of the school year, the reading levels in Ms. Lane's class ranged from pre-K through 8th grade. I have written parent consent to collect written work, video recordings, and audio recordings for all students in Ms. Lane's class.

During the year that this study was conducted, Ms. Lawson was in her 10th year teaching and her 2nd year teaching the MLs units. However, she was teaching the Plant Unit for the first time, because she had not taught it during her first year of enactment. There were twenty-six students in her class, twenty-five of whom were present for science instruction (13 were male, 12 were female). The demographics of her class reflected the overall school population. At the beginning of the school year, the reading levels in Ms. Lawson's class ranged from 2nd to 6th grade. Several of Ms. Lawson's students did not have written parent consent for me to collect written work, video recordings, and/or audio recordings. These students were either fully or partially excluded from this study, depending on the levels of consent provided by their parents.

Within each class, I selected six focal students whose individual work with the simulations I recorded using ScreenCastify. These focal students were selected to (a) represent a range of reading abilities and (b) be diverse with respect to gender and race/ethnicity. The goal behind both these selection criteria was to provide for maximum variation in the sample, since more diverse samples may lead to research that can be applied in a wider variety of contexts (Merriam, 2009). The following table summarizes demographics of the 12 focal students.

Table 3.1
Focal Participant Demographics

Name	Gender	Race/Ethnicity	Reading Level (As identified by classroom teacher)	Classroom Teacher
Kajuan	Male	Black	Lower 33% of class	Ms. Lane
Lashauna	Female	Black	Lower 33% of class	Ms. Lane
Kaiyana	Female	Multiracial	Lower 33% of class	Ms. Lawson
Owen	Male	White	Lower 33% of class	Ms. Lawson
Jett	Male	White	Middle 33% of class	Ms. Lane
Kendra	Female	Black	Middle 33% of class	Ms. Lane
Jada	Female	Black	Middle 33% of class	Ms. Lawson
David	Male	White	Middle 33% of class	Ms. Lawson
Mary	Female	White	Upper 33% of class	Ms. Lane
Davon	Male	Black	Upper 33% of class	Ms. Lane
Christine	Female	White	Upper 33% of class	Ms. Lawson
Jarius	Male	Black	Upper 33% of class	Ms. Lawson

The Multiple Literacies Curriculum

The Multiple Literacies in Project Based Learning (MLS) project has the goal of developing, piloting, assessing, and improving project-based curriculum units that integrate science, literacy, and math learning opportunities in alignment with the Next Generation Science Standards (NGSS) and the Common Core State Standards (CCSS). Both Ms. Lawson and Ms. Lane enacted the Multiple Literacies curriculum for between three and five days a week, for between 45 and 60 minutes per day, during the 2018-2019 school year. Typically, science was taught four days a week. Over the course of the school year both teachers taught all four of the project-based units, designed by the MLs project. Each unit was six- to nine- weeks in length and framed by the following driving questions: (a) *Why do some animals survive while others die out?*, (b) *How can we help the birds around here grow up and thrive?*, (c) *How can we design fun moving toys that any kid can build? (The "Toy Unit"),* (d) *How can we grow plants for food in our community? (The "Plant Unit").*

The MLs units address all three dimensions of the *Next Generation Science Standards* (NGSS Lead States, 2013) while also addressing certain literacy and mathematics standards from the *Common Core State Standards* (National Governors Association Center for Best Practices Council of Chief State School Officers, 2010) and drawing on students' funds of knowledge (Moll, Amanti, Neff, & Gonzalez, 1992). The units incorporate key features of project-based learning including: (a) each unit is framed by an engaging driving question that both captures students' attention and is anchored in real-word problems relevant to students' everyday lives, (b) each unit provides opportunities for students to collaborate with peers and teachers while engaged in scientific sensemaking, and (c) each unit culminates in the creation of a final artifact that reveals student learning from the unit.

In this dissertation, I focus exclusively on the Toy Unit and the Plant Unit, as these were the two units that included simulations.

The Toy Unit synopsis. The Toy Unit focused on the driving question: *How can we design fun moving toys that any kid could build?* In the Toy Unit, students learn about force and motion as they design and re-design a moving toy. The Toy Unit is divided into five learning sets, each with its own focus.

The first learning set is focused on the relationship between unbalanced forces and motion, with a particular focus on how unbalanced forces can cause toys to start moving. In the first learning set, students observe toy rockets, build a toy, and then draw a model to show how an unbalanced force starts their toy moving. While drawing models, the class discusses different ways to represent force (e.g. by drawing arrows.) At the end of this learning set, students use a physical model of a car and a simulation to explore the relationships between unbalanced forces and motion.

The second learning set is focused on the engineering design process. In the second learning set, students interview kindergarteners to find out what kind of design features the kindergarteners might like to see in a fun moving toy. Then, the class reads and discusses a case study focused on how Lonnie Johnson designed the Super Soaker.

The third learning set is focused on the relationship between friction and motion, with a particular emphasis on how friction can cause toys to stop moving. First, the class reads a text about the design of a toy called a "balloon rocket" and performs an investigation with a balloon rocket. As part of this learning experience, students are introduced to the idea of conducting "fair tests" in which only one variable is changed at a time. Next, students use both physical toy cars and a simulation to explore the relationship between friction and motion. Then, students draw models showing how friction can cause a car to stop moving. While drawing these models, the class discusses how to represent forces (e.g. using arrows of different direction or length.) Teachers then have the option of allowing students to make a digital, animated model based on their paper-and-pencil model. Finally, students re-design their car based on what they have learned about friction and then test to see whether their original or improved car can move farther.

The fourth learning set is optional, and focuses on forces of gravity, magnetism, and electricity. Both Ms. Lane and Ms. Lawson skipped this learning set, due to losing 11 instructional days to snow days. The fifth learning set consists of students preparing and presenting a design portfolio describing how they created, tested, and improved their toy.

The above synopsis shows that both of the simulation-based lessons in the Toy Unit support central learning goals of the Toy Unit. That is to say, the curricular learning goals that are supported in the simulations are also supported through other learning opportunities. The Net Force Simulation lesson has the curricular learning goal: "Students use models to identify the sum of forces acting on objects and predict the motion of objects caused by these balanced and unbalanced contact forces."[1] Before working with the Net Force Simulation, students have already (a) observed balanced and unbalanced forces operating on their moving toys and (b) drawn models representing the forces acting on their toys. The Friction Simulation lesson has the curricular learning goal "Students develop models to explain how friction affects the motion of toy cars." This goal of understanding the relationship between friction and motion is also supported by the MLs lessons where students (a) conduct multiple hands-on investigations with friction, and (b) create models of friction using both paper and pencil and digital technology.

Selection of simulations for inclusion in the toy unit. The Net Force and Friction Simulations[2] were selected to be included in the MLs curriculum for several reasons. First, the conceptual terrain of these simulation matches closely with the learning goals of the Toy Unit. The Net Force Simulation reinforces ideas from learning set one, which focuses on balanced and

[1] Note: MLs learning goals are color coded to match three dimensional NGSS standards, with orange used to mark disciplinary core ideas, blue used to mark science and engineering practices, and green used to mark cross-cutting concepts.
[2] The Net Force Simulation and the Friction Simulation are separate pages of the same overarching simulation entitled "Force and Motion: the basics," designed by PhET.

unbalanced forces. The Friction Simulation reinforces ideas from learning set three, which focuses on friction. Therefore, adding the simulations to the Toy Unit allowed for synergy between simulation-based learning activities, conceptual discussions, and hands-on learning activities. As discussed earlier in the literature review, this type of synergy has been found to be supportive of student learning (Jaakkola & Nurmi, 2008; Jaakkola, Nurmi, & Veermans, 2011; Riess & Mischo, 2010).

These simulations were structured in a way that allowed students to design and carry out investigations. The design team valued these simulations for their ability to reinforce scientific practices associated with conducting investigations (such as making predictions, designing tests, interpreting results). As discussed earlier in the literature review, research has repeatedly found benefits to simulations that support students in engaging in scientific practices (Scalise et al., 2011; Smetana & Bell, 2012).

Third, incorporating these simulations into the unit allowed students to have additional practice interpreting visual representations. Both these simulations represented information in visually complex ways that required interpretation on the part of the viewer. As discussed earlier in the introduction chapter, science and literacy scholars have called for more time spent interpreting representations during science and literacy instruction (Dalton & Proctor, 2008; Jaakkola et al., 2011; National Research Council, 2014; New London Group, 1996; NGSS Lead States, 2013; Riess & Mischo, 2010). Given that the MLs curriculum has the stated goal of bringing together science and literacy instruction in the context of project-based learning, the curriculum designers value opportunities to incorporate the interpretation of visual representations into the curriculum.

The Plant Unit synopsis. The Plant Unit is organized around the driving question *How can we grow plants for food in our community?* In the Plant Unit, students learn about weather and climate as they design and grow a garden. Like the Toy Unit, the plant unit is divided into different learning sets, each with its own focus. In the first learning set, students learn about the needs of different plants and plant seeds for their class garden. In the second learning set, students investigate how the environment affects the traits of plants. In the third learning set, students learn about different plants that grow in different climates around the world. Students read a case study about winter wheat and learn that sometimes, one variety of a particular plant is better able to survive in a given climate, as compared to other varieties of the same plant. At the end of the third learning set, students use the Mystery Plant Simulation to explore the question "How do variation in traits affect plants' survival and reproduction?" In the fourth learning set, students learn about how hazardous weather can affect their plants' survival and growth. In the fifth learning set, students design a plan for their class garden.

The two simulations in the Toy Unit were both connected to multiple other learning experiences in the Toy Unit. This is not the case for the simulation in the Plant Unit. The simulation in the Plant Unit is only connected to one other learning experience: the Winter Wheat Reading. There are two reasons that the Plant Unit simulation is less connected to the rest of the unit, as compared to the Toy Unit simulations. First, the learning goals of the Toy Unit simulations are more central to the overall unit, as compared to the learning goal of the Plant Unit simulation. Second, the learning goals of the Toy Unit simulations can be supported by hands-on investigations. The learning goal of the Plant Unit does not easily lend itself to hands-on investigation. Therefore, the plant simulation lesson was not connected with hands-on investigation lessons whereas the toy simulation lessons were connected with hands-on investigation lessons.

The learning goal of the Mystery Plant Simulation lesson is “Students construct an argument using evidence from a simulation to describe patterns in how a group of similar plants can survive differently in the same environment because of differences in their traits.” In other words, students will learn that environmental conditions may impact which plants survive and which plants die, based on the differences in plant traits. This learning goal cannot easily be supported by a hands-on investigation, as such an investigation would require raising many generations of plants, which is not feasible within the scope of a six-nine-week science unit. The curriculum designers could only think of two different ways to support this learning goal: (a) an informational text that described an actual case of plants with certain traits surviving better than plants with other traits and (b) an interactive simulation. Both of these ideas were incorporated into the Plant Unit via the Winter Wheat case study and the Mystery Plant Simulation, respectively

Selection of simulation for the plant unit. The Mystery Plant Simulation was chosen because it was the only simulation that we could identify addressing the phenomenon of how differences in traits among a species of plants may impact plant survival. The design team felt there were two potential advantages to including the Mystery Plant Simulation. First, it would complement the concepts presented in the Winter Wheat text, allowing for potential synergy between the lessons. Second, it would provide students with an additional opportunity to interpret scientific representations. The benefits of both (a) synergy between simulations and other lessons (Jaakkola et al., 2011; Riess & Mischo, 2010) and (b) giving students opportunities to interpret scientific representations (Dalton & Proctor, 2008; National Research Council, 2014;

New London Group, 1996; NGSS Lead States, 2013) are discussed further in the literature review and introduction.

A Detailed Look at the Three Simulations included in the MLs curriculum

The following section presents a detailed look at the design and features of each of the three simulations included in this study. It includes information about who designed the simulations, why the simulations were designed, what features each simulation includes, and how these features compare to the set of supportive features introduced in the literature review. This section is followed by a detailed look at the resources provided by the MLs curriculum to support enactment of each simulation.

Design and features of the Net Force Simulation. The first simulation included in the ML curriculum focuses on Net Force. The Net Force screen was the first of four screens in a simulation entitled "Force and Motion: Basics" (See Figure 3.2, below), which was created and distributed by PhET. For the sake of brevity, in this dissertation I abbreviate "The Net Force Screen of the Force and Motion: Basics Simulation" to "The Net Force Simulation."

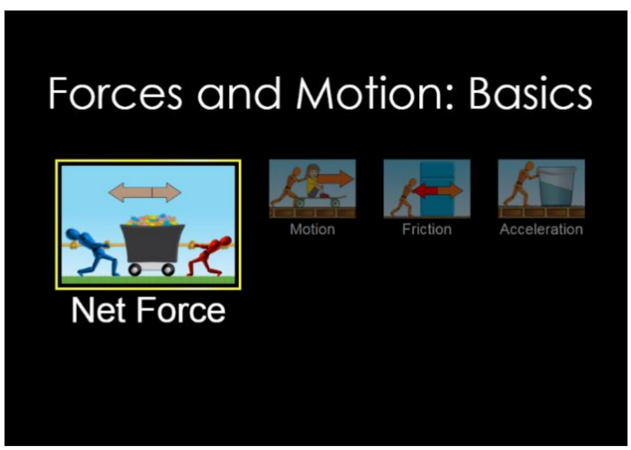

Figure 3.2 The four screens of the PhET "Force and Motion: Basics Simulation"

PhET Interactive Simulations is a non-profit project at the University of Colorado that designs, develops, and shares interactive simulations designed to support the teaching of physics, chemistry, math, earth science, and biology. PhET was founded by Nobel Laureate Carl Wieman, in 2002, to "engage students through an intuitive, game-like environment where students learn through exploration and discovery" (https://phet.colorado.edu). The PhET simulations are intended to be used by teachers and students in the science classroom (as opposed to independent use by students at home). The PhET team recommends that the simulations either be used for guided inquiry during course lectures or independent inquiry during small group work. All PhET simulations are open source and licensed under Creative Commons (https://phet.colorado.edu).

Like all PhET simulations, the PhET Net Force Simulation is a "targeted" simulation designed to be flexibly implemented into many different curricula (Clark, Nelson, Sengupta, & D'Angelo, 2009). In other words, it is designed to be easily transplanted into many different educational contexts. This intended flexibility is underlined by the fact that the PhET website recommends this simulation for use by elementary, middle school, high school, and university students (https://phet.colorado.edu/en/simulations/category/by-level).

The PhET Net Force Simulations is designed according to PhET's design principles and includes multiple features designed to promote interactivity (see Figure 3.3 below). The PhET design principles and simulation tools were drawn from many years of extensive field testing of simulations, including both classroom observations and interviews with student users (See Table 3.2 below).

More About PhET's Design

To help students engage in science and mathematics through inquiry, PhET simulations are developed using the following design principles:

- Encourage scientific inquiry
- Provide interactivity
- Make the invisible visible
- Show visual mental models
- Include multiple representations (e.g., object motion, graphs, numbers, etc.)
- Use real-world connections
- Give users implicit guidance (e.g., by limiting controls) in productive exploration
- Create a simulation that can be flexibly used in many educational situations

Several tools in the simulations provide an interactive experience:

- **Click and drag** to interact with simulation features
- **Use sliders** to increase and decrease parameters
- Choose between options with **radio buttons**
- Make measurements in your experiments with **various instruments –** rulers, stop-watches, voltmeters, and thermometers.

As users interact with these tools, they get immediate feedback about the effect of the changes they made. This allows them to investigate cause-and-effect relationships and answer scientific questions through exploration of the simulation. For more information, visit our research page.

Figure 3.3 PhET design principles, as shared on PhET website

Table 3.2

PhET Findings on Features Supporting Engagement and "Intuitive Use"[3]

Ways to Support Engagement	Ways to Support "Intuitive Use"
User action triggers motion	Intuitive tools (e.g., Click & Drag, grabbable objects, sliders, radio buttons, & checkboxes) that are consistent across different simulations
Embedded puzzles	Starting simulation with little or no animation
Legends and labels	Using everyday objects and cartoon features in the simulation
Fun features	Using color & other visual cues
No long written instructions.	Simple layout with "play area" and "control panel" each containing no more than 3 groups of 3 controls.
	Simulation "breaks" under extreme conditions

In the Net Force Simulation, students manipulate how many pullers are on each side of the rope. As they change the number and size of the pullers, the brown arrows representing left and right force will shift accordingly. Students can then hit "go" to find out which direction the cart will move, once the pullers start tugging. Students have the additional option of toggling on (a) numerical labels that indicate the strength of each force, (b) a "sum of forces" arrow that represents the net force, and (c) a speedometer that measures how quickly the cart is moving (See Figures 3.4 and 3.5).

[3] For more details, see (Adams et al., 2008a, 2008b)

Figure 3.4 Starting screen of Net Force Simulation

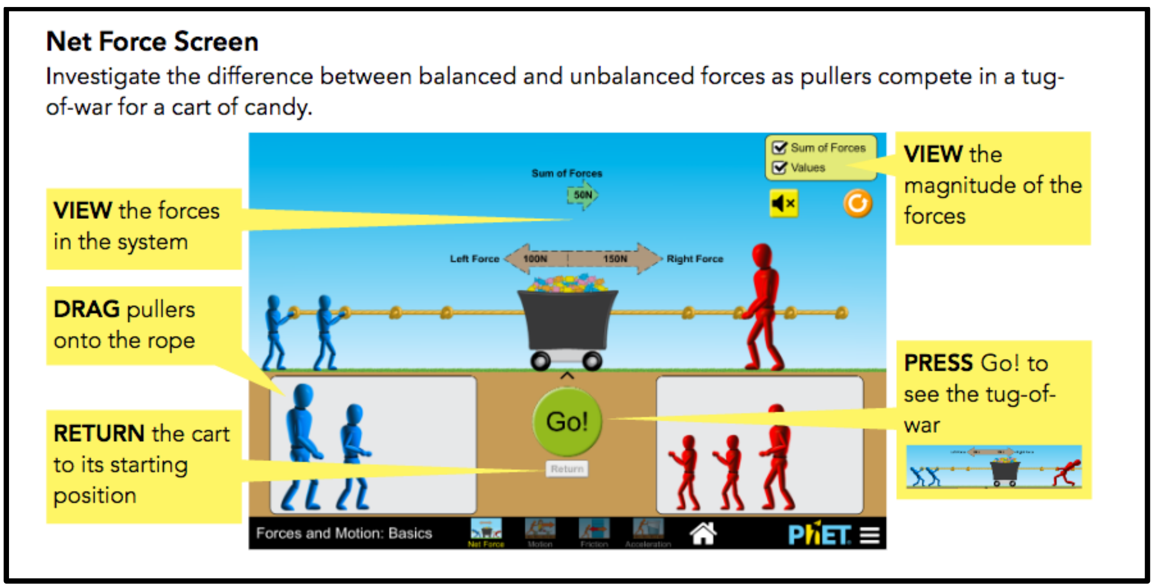

Figure 3.5 PhET teacher support material for Net Force Simulation

Design and features of the Friction Simulation. The second simulation experience included in the MLs curriculum focuses on friction. The friction screen was the third of four screens in a simulation entitled "Force and Motion: Basics" (see Figure 3.6, below). For the sake of brevity, in this dissertation I will abbreviate "the friction screen of the force and motion: basics simulation" to "the Friction Simulation."

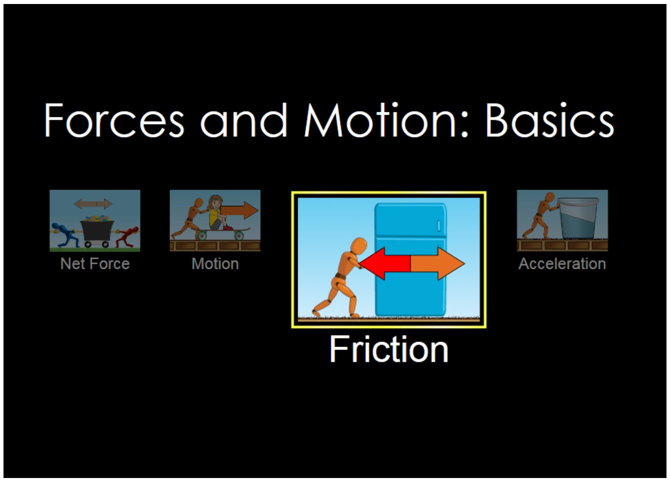

Figure 3.6 The four screens of the PhET “Force and Motion: Basics Simulation.”

The Friction Simulation, like the Net Force Simulation, is an open-source resource designed by PhET according to research-based principles intended to support inquiry learning. (For a review of PHET design principles see Figure 3.3 and Table 3.2., above.) Like the Net Force Simulation, the Friction Simulation is a targeted simulation (Clark et al., 2009) that is designed to be flexibly integrated into classroom settings ranging from elementary school through University classes.

In the Friction Simulation, students manipulate (a) the mass of the object(s) that is pushed, (b) the amount of force with which the object is pushed, (c) and the amount of friction between the object and the ground. Students have the additional option of toggling on (a) arrows that represent the forces and sum of forces, (b) numerical labels that indicate the strength of each force and the mass of each object, and (c) a speedometer that shows the speed at which the object is moving (see Figures 3.7 and 3.8).

Figure 3.7 Starting screen of Friction Simulation

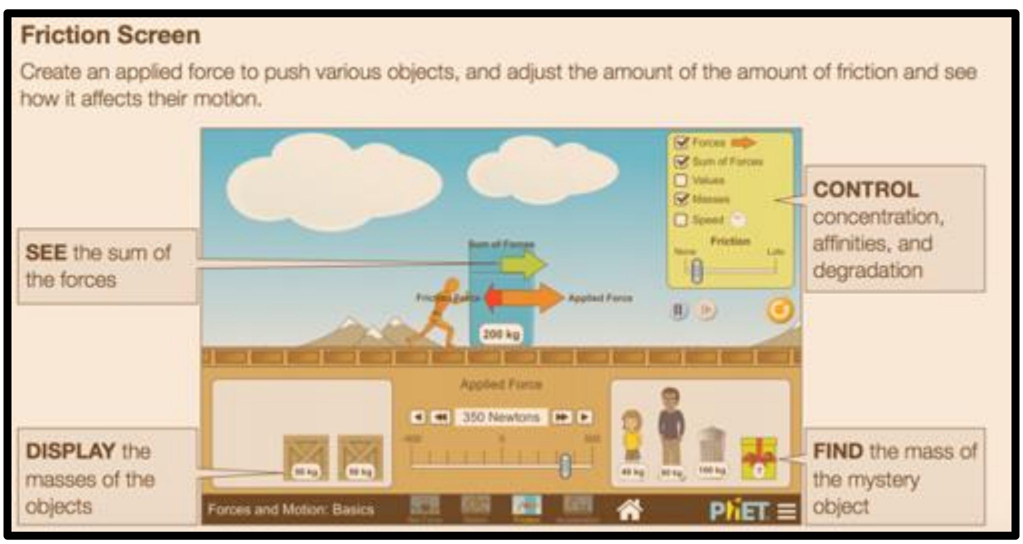

Figure 3.8 Teacher support material for Friction Simulation

Design and features of the Mystery Plant Simulation. The third simulation experience included in the MLs curriculum is the Mystery Plant Simulation. This simulation was created by the Evolution Readiness Project and is available online through the Concord Consortium. Like the simulations designed by PhET, the Mystery Plant Simulation is licensed for reuse under a Creative Commons license. However, unlike the PhET simulation, the Mystery Plant Simulation was designed to fit in a specific curriculum: the Evolution Readiness curriculum. This curriculum is a 3-4-week curriculum and includes 10 computer-based learning activities and six hands-on activities. Its goal is "to introduce students in the fourth grade – 10 years old – in the United States to the concept of evolution by natural selection." It was developed in part in response to survey results showing that about 50% of adults in the United States do not believe in evolution. The Evolution Readiness project had the goal of teaching students 11 "big ideas" related to evolution and introduces concepts related to natural selection (see Figure 3.9, below). The Mystery Plant Simulation is the third online activity in the Evolution Readiness curriculum (Horwitz, 2013; Horwitz, McIntyre, Lord, O'Dwyer, & Staudt, 2013; McIntyre, Lord, & Horwitz, 2012).

Note that the learning goals of the Evolution Readiness curriculum are not exactly the same as the learning goals of the MLs plant unit. The Evolution Readiness curriculum seeks to present ideas related to natural selection to elementary students in the hopes that understanding the mechanisms of natural selection might make them less likely to reject evolution when they study it in middle or high school. On the other hand, as discussed above, the MLs Plant Unit seeks to help students understand the relationship between environmental conditions and plant survival in order to design and create a class garden. The MLs Plant Unit does not have a focus on natural selection or evolution readiness. For this reason, some aspects of the Mystery Plant Simulation are not a perfect fit with the MLs curricular goals (e.g. the screen focused on Darwin's Finches, shown below.)

1. Basic Needs of Organisms
2. Life Cycle—Birth and Death
3. Organisms and Their Environmen
4. Classification of Organisms
5. Interspecific Differences
6. Interactions Between Species
7. Intraspecific Differences
8. Adaptation/Evolution
9. Heritability of Traits
10. Reproduction
11. Descent with Modification

Figure 3.9 The 11 "Big Ideas" from the Evolution Readiness curriculum

The Mystery Plant Simulation is set up as a series of consecutive screens. The first screen makes connections to the previous activity in the Evolution Readiness curriculum (see Figure 3.10). The second screen, the virtual greenhouse, shows a picture of the three planter boxes (see Figure 3.11). Students have the option of placing a seed in the planter box with full sunlight, medium sunlight, or little sunlight. The plant will only grow in the box with medium sunlight. After the plant is grown, it dies and leaves behind three seeds. One of the seeds grows into a small-leafed plant that can only survive in the full sunlight condition. One of the seeds grows into a medium-leafed plant that can only survive in the medium sunlight condition. One of the seeds grows into a large-leafed plant that can only survive in the little sunlight condition. Students move around the different plants until they discover the best place for each plant. Note that students may not be able to tell the difference between the small, medium, and large leaf plants simply by looking at them: they may need to use the magnifying glass tool to ascertain the leaf size. (See Figures 3.12 and 3.13).

Figure 3.10 The first screen of the Mystery Plant Simulation

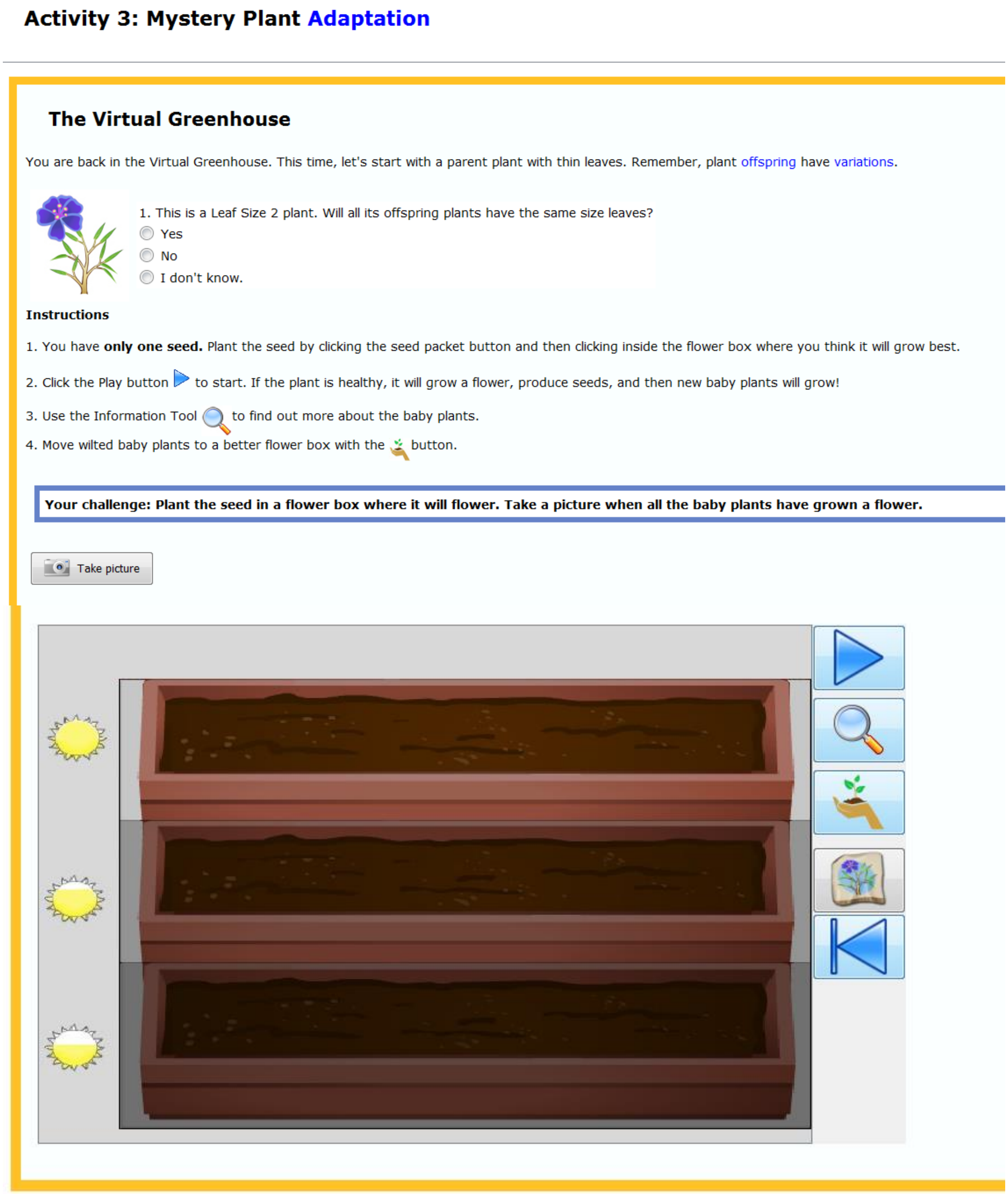

Figure 3.11 The second screen of the Mystery Plant Simulation

Figure 3.12 Wilted small-leaf plant, medium-leaf plant, and large-leaf plant (left to right)

Figure 3.13 Small-leaf plant, medium-leaf plant, and large-leaf plant (top to bottom)

The third screen has a diagram that shows how a plant with medium size leaves might produce offspring with small, medium, or large leaves. It asks students to make a prediction about which of these plants might grow well in the shade (see Figure 3.14).

Figure 3.14 The third screen of the Mystery Plant Simulation

The fourth screen makes a connection to other plants and asks a multiple-choice comprehension question (see Figure 3.15).

Figure 3.15 The fourth screen of the Mystery Plant Simulation

On the fifth screen, students drop seeds onto the virtual field (see Figure 3.16). The original parent plants can only survive in the middle of the field where there is a medium amount of sunlight. However, over time, the parent plants produce offspring that are adapted to live in other parts of the field. As in the virtual greenhouse, plants with larger leaves need less sun and plants with smaller leaves need more sun. And, as in the virtual greenhouse, it may be hard for students to tell the difference between different leaf sizes. For this reason, each different leaf size corresponds to a different color petal. There is also a bar graph to the right of the simulation that documents how many plants of each leaf size are growing in the field at a given time.

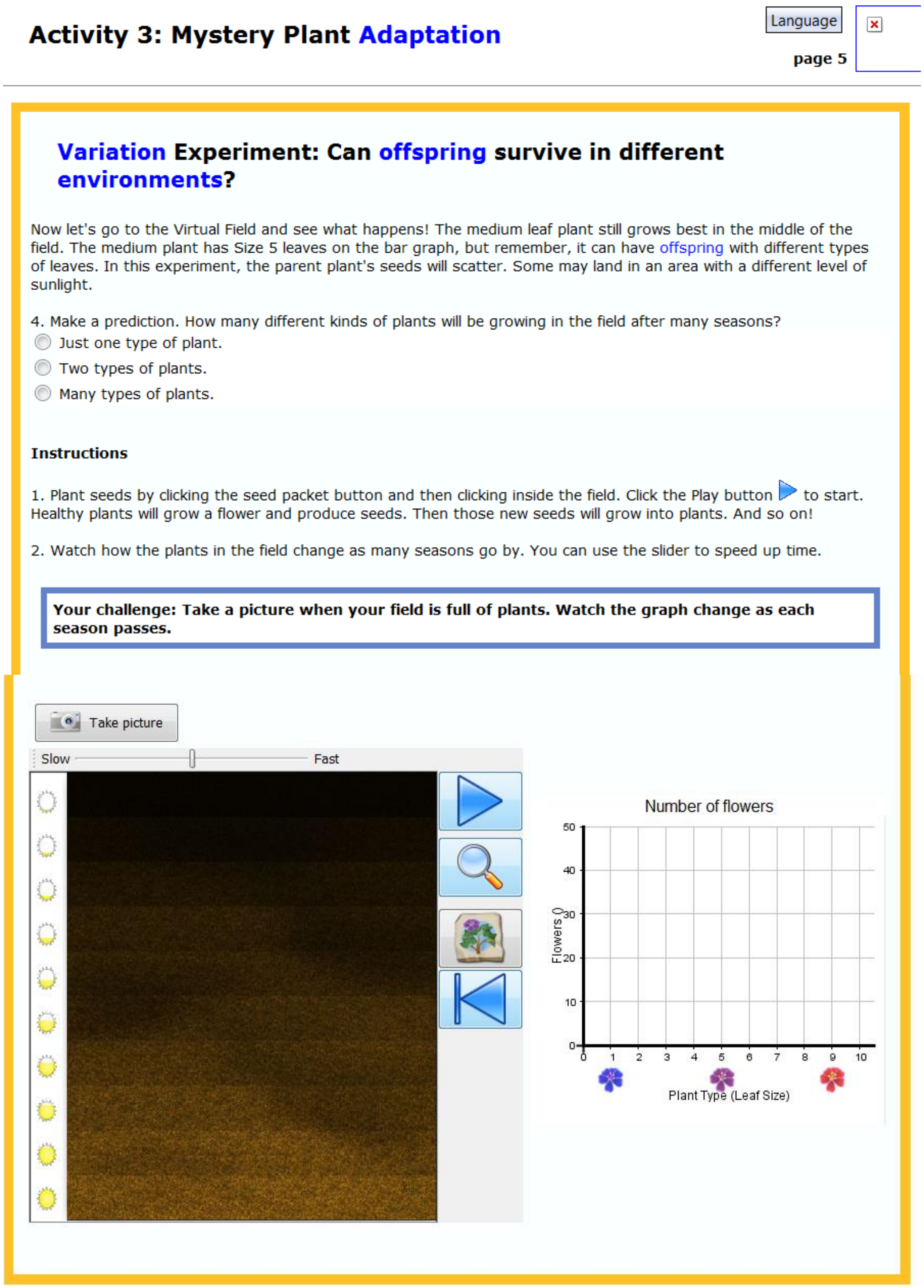

Figure 3.16 The fifth screen of the Mystery Plant Simulation

The sixth screen has multiple choice questions that ask students to interpret bar graphs and explain why many types of plants eventually grew in the field, even though there was initially only one type of plant (see Figure 3.17). The seventh screen makes connections to Darwin's finches (see Figure 3.18), and the final screen summarizes the main idea of the simulation (see Figure 3.19).

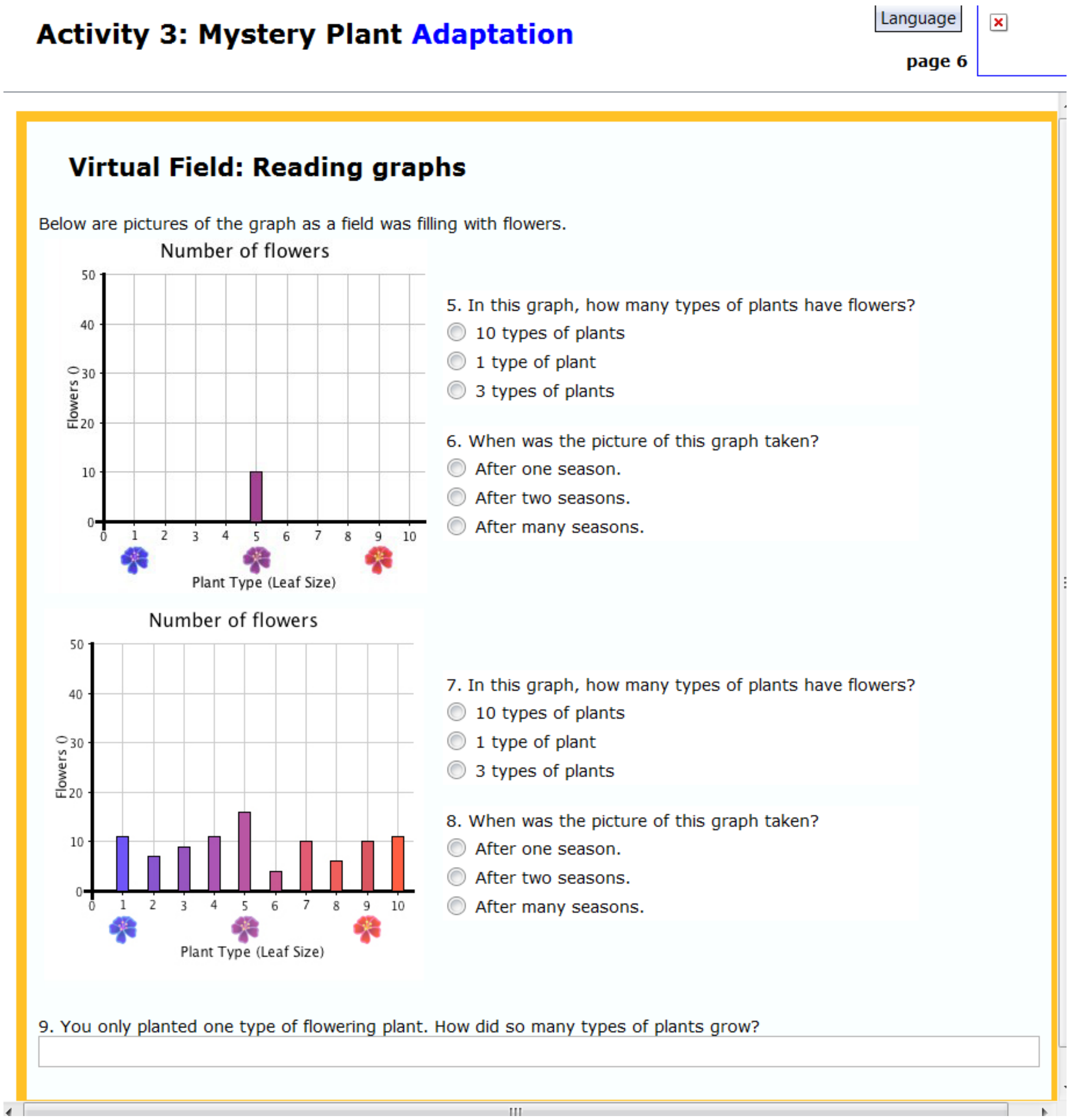

Figure 3.17 The sixth screen of the Mystery Plant Simulation

Figure 3.18 The seventh screen of the Mystery Plant Simulation

Figure 3.19 The eighth screen of the Mystery Plant Simulation.

Note that, unlike the PhET simulation, there are very few choices that students can make while using the Mystery Plant Simulation. In the virtual greenhouse, the only choice is where to move the seeds and plants. In the virtual field, the only choice is where to initially drop the seeds. In contrast, the Net Force and Friction Simulation both allowed students to change three variables (NF: number of pullers, size of pullers, and position of pullers; FR: mass, friction, and applied force.)

Reviewing features of each simulation using the literature review. In the following section, I return to the list of simulation features introduced in the literature review and I consider which of these features are present in the PhET and Concord simulations. The table below summarizes which features each simulation contains.

Table 3.3

Simulation features of PhET and Concord Simulations Examined in this Study

Simulation Feature	Empirical Work	Net Force	Friction	Plant
Embedded prompts: Providing information	(Hulshof & De Jong, 2006)			yes
Embedded prompts: Designing investigations	(Chang, Chen, Lin, & Sung, 2008)			
Embedded prompts: Testing hypotheses	(Chang et al., 2008)			yes
Embedded prompts: Making connections across representations	(van der Meij & de Jong, 2011)			yes
Metacognitive tools: Setting and monitoring goals	(Manlove, Lazonder, & de Jong, 2006)			
Audio information	(Liu & Chuang, 2011)			
Icons	(Lee, Plass, & Homer, 2006; Plass et al., 2009)	yes	yes	yes
Divided Screens	(Lee et al., 2006)	yes	yes	yes
Attention-directing avatar	(Moreno, Reislein, & Ozogul, 2010)			

Of the different supportive features identified in the literature review, the two simulations designed by PhET contain icons and divided screens. In both the PhET Friction Simulation and the PhET Net Force Simulation, the screen is divided into three sections: one section that contains controls, one section where the investigation takes place, and one section that adjusts which output measures are displayed. Research suggests that dividing the screen in this manner can have the effect of reducing cognitive load for the user (Lee et al., 2006). The PhET simulations also contain visually intuitive icons, which research has also shown to reduce cognitive load (Plass et al., 2009).

The PhET simulations do not use embedded prompts to provide information, embedded prompts to support investigation design, embedded prompts to support hypothesis formation, embedded prompts to support making connections across representations, metacognitive tools to support goal setting, audio voiceovers, or attention directing avatars. However, while supporting student sensemaking, the teacher supported students in many of the areas *not* supported by simulation features. This will be discussed further in the findings chapters.

The Mystery Plant Simulation contains prompts that fulfill three of the four prompt types identified in the literature review: providing information (Hulshof & De Jong, 2006), testing hypotheses (Chang et al., 2008), and making connections across representations (van der Meij & de Jong, 2011). There are no prompts that support students to design investigations.

One prompt that "provides information" is a small bubble that pops across the virtual greenhouse and suggests that the user might want to use the magnifying glass to examine the leaf size of different plants. One prompt that "supports forming hypotheses" is a prompt that asked students to predict what the virtual field will look like after several seasons have passed. One prompt that supports "making connections across representations" is a question that invites students to compare the information presented through icons with information presented via a bar graph.

The Mystery Plant Simulation does use icons, as recommended by research (Lee et al., 2006; Plass et al., 2009), but some of the icons were challenging for users to interpret. This will be discussed further in the findings section. Also, as recommended by research (Lee et al, 2006), the Mystery Plant Simulation used divided screens (with controls and output in separate parts of the simulation). The Mystery Plant Simulation did not include audio narration, meta-cognitive support for goal setting, or attention-directing avatars. However, as with the PhET simulations, the teachers fulfilled some of these functions while supporting student sensemaking. This will be discussed in later chapters.

MLs Curricular Supports for Simulation-Based Lessons

In addition to the supportive features provided within the simulations themselves, teacher's enactment of the simulation was also supported by the MLs curriculum. The MLs supportive material included materials designed by the Multiple Literacies project as part of the official MLs curriculum, open-source materials designed by PhET, and materials designed by myself and Miranda Fitzgerald specifically to support the two teachers at Stone Elementary. For complete copies of all supportive materials, see Appendix I.

The first level of support was provided by summary documents that helped teachers to see coherence across units. The "Year at a Glance" document provided a conceptual overview of each of the four MLs units and included links to the "Week at a Glance" documents. The "Week at a Glance" documents provided conceptual overviews for each week of science instruction, and also included links to individual lesson plans and resources. (These documents included brief references to each simulation and showed how the concepts presented in each simulation were connected to concepts in other MLs lessons.)

The next level of support was provided by lesson plans and embedded resources. Each of the three simulations were introduced in a MLs lesson; however, there was significant variety in (a) the amount of emphasis placed on each simulation, (b) the amount of time suggested for the enactment of each simulation, and (c) the level of detail provided regarding the suggested enactment of each simulation. The Net Force Simulation was supported by a full-length lesson plan that was estimated to take between 40 and 50 minutes. The lesson plan begins with an investigation of balanced forces that uses a physical toy car. Then, a slide show introduces the simulation and supports students to make predictions about the simulation. The slide show includes (a) definition of contact force, (b) questions about contact force and the toy car investigation, and (c) questions about the Net Force Simulation. Next, students interact with the simulation (including making predictions, conducting investigations, and interpreting results). Finally, students revisit and edit models that they drew in a previous lesson, which represent how their toy begins to move. Students add labels for balanced and unbalanced forces.

The Net Force Simulation lesson plan[4] supports teachers to engage in many of the practices that have been identified as helpful for supporting student to work with simulations including: supporting students to make predictions, supporting students to interpret results, using challenges to engage student interests, focusing on illuminating cases, and discussing key concepts from the simulation (Rehn, Moore, Podolefsky, & Finkelstein, 2013). It also supports practices that have been identified as helpful for supporting students' sensemaking in the context of science learning including: using conceptual questions to frame class conversations (Cervetti, DiPardo, & Staley, 2014), asking students to support their ideas with reasoning (Puntambekar, Stylianou, & Goldstein, 2007), making connections to previous experiences (Puntambekar et al., 2007), supporting students to make predictions (Herrenkohl & Cornelius, 2013), and supporting students to develop claims (Engle & Conant, 2002). Additionally, it provides guidance suggesting that teachers vary participation structures and support students to build off of

[4] Appendix I shows an annotated copy of the Net Force Simulation lesson plan that indicates where it supports each of the teaching practices described below.

classmates' ideas. Research has suggested that both these practices can help support conditions where sensemaking can occur (Fitzgerald & Palincsar, 2019; Grossman, Loeb, Cohen, & Wyckoff, 2013; Mercer et al., 2004).

Unlike the Net Force Simulation, the Friction Simulation was not supported by a full-length lesson. Instead, it was described as one out of five steps in the final section of the lesson. Figure 3.20, below, shows the portion of the MLs lesson plan supporting enactment of the Friction Simulation. Furthermore, using the Friction Simulation was marked as "optional." The reason that the Friction Simulation was allocated less time in the MLs curriculum, as compared to the Net Force Simulation, is that the overall curriculum was running too long, and the concept of friction was already supported by two different hands-on investigations.

4. If time permits, the teacher can show the simulation from L1.5 (found in the powerpoint for this lesson) which allows students to manipulate the amount of frictional forces by changing the texture of a surface. Click on both the sum of the forces and values. Make sure that students notice that once the figure stops pushing the only horizontal force acting on the object is friction in the opposite direction of the motion. When the object stops moving the sum of the (horizontal) forces is zero.

Figure 3.20 "Optional wrap up" using Friction Simulation

For both the Net Force and Friction Simulations, teachers had access to two different resources provided by PhET. The first resource was an annotated illustration that described the simulation controls. The second resource was a "tip sheet" with suggestions for supporting inquiry while using PhET simulations. This tip sheet suggested that teachers (a) demonstrate the simulation, (b) ask students questions, (c) encourage students to pose new simulation scenarios, (d) solicit student predictions, (e) solicit student reasoning, and (f) test the student-generated scenarios. This resource supported many of the research-based practices previously described in the literature review, including: supporting students to make predictions (Herrenkohl &

Cornelius, 2013; Rehn et al., 2013), soliciting student reasoning (Puntambekar et al., 2007), supporting student exploration (Rehn et al., 2013), and supporting students to develop investigations (Herrenkohl & Cornelius, 2013).

The Mystery Plant Simulation is supported by a full lesson, which is estimated to take around 40 minutes. However, the MLs lesson plan contains minimal detail regarding how to teach the simulation. The lesson plan identifies the goal of the simulation, but does not suggest specific instructional moves to support using the simulation. (See Figure 3.21. below, for screenshot of the Mystery Plant Simulation lesson.)

2 **Mystery Plant Adaptation Simulation** (15-20 min)	1. Tell students that they are going to be using a simulation to gather data to answer the lesson DQ. You may remind them about the two simulations they used in the toy unit and the data that they collected regarding balanced/unbalanced forces and friction. 2. Project the Mystery Plant Adaptation simulation. Work through the simulation together as a class. This simulation introduces students to the ideas that the traits of offspring can vary from their parents (i.e., leaf size) and these variations influence which offspring survive (and reproduce) and which offspring die in the same environment.
3 **Wrap Up** (10 min)	1. Ask students what they learned from the simulation. Invite students to turn and talk about their ideas. Select several students to share. As each child shares his or her ideas, support students to: ○ Identify data from the simulation that supports their idea ○ Share their own reactions to other students' ideas (agree/disagree and why) 2. Invite students to add additional questions or ideas to the DQ Board.

Figure 3.21 MLs lesson details regarding the Mystery Plant Simulation

The 2017-2018 version of the Mystery Plant Simulation lesson was much longer and included an attached step-by-step simulation guide. However, in my observation, I noted teachers becoming confused as they tried to cross reference (a) the instructions in the simulation, (b) instructions in the MLs simulation guide, and (c) instructions in the MLs lesson plan. Therefore, I simplified the ML-provided materials in the 2018-2019 version.

Table 3.4 below summarizes the different supports available for each simulation.

Table 3.4

Curricular Supports Available to Teachers

Curricular Material	Which simulation(s) the material supports	Description of the curricular material	Design & Rationale for the curricular material
Year at a Glance	All three simulations	Provides a conceptual overview of the entire MLs Force and Motion Unit in which the Net Force and Friction Simulations were embedded, with a focus on how students explore key scientific concepts across the entire unit. *Includes hyperlinks to the "Week at a Glances."*	This resource is a modified version of the MLs created Unit Summary Documents (entitled "Table of Contents.") It differs from the official MLs Table of Contents in that it (a) is shortened, to account for limits on the time available for science instruction at Stone school and (b) it includes embedded hyperlinks. I designed this resource specifically to support Ms. Lane and Ms. Lawson.
Week at a Glance	All three simulations	Conceptual overview for the week of science instruction containing the Net Force Simulation. *Includes hyperlinks to the Lesson Plans and other supporting materials (described below)*	Initially designed by Miranda Fitzgerald for the 2016-2017 school year. Modified by me for the 2018-2019 school year.
Lesson Plan	All three simulations	Identifies learning goals, connections to NGSS standards, and sequence of lesson activities.	The lessons associated with the Net Force and Friction simulation were written by Deborah Peek Brown, the lead designer of the MLs Force and Motion Unit. I drafted the 2018-2019 version of the Mystery Plant Simulation Lesson, with help from Annemarie Palincsar, Miranda Fitzgerald, and Deborah Peak Brown, adapting and revising the 2017-2018 version of the

			lesson, which was written by Meredith Baker.
Slide Show	Net Force Simulation only	Includes images, definitions, and discussion prompts to support enactment of the lesson plan	Designed by Deborah Peek Brown, the lead designer of the MLs Force and Motion Unit.
Explanation of simulation controls	Net Force and Friction Simulations only	Explains how to use the different features of the PhET Simulation	Designed by PhET to support teachers in using the simulation controls.
Tips for Supporting Inquiry	Net Force and Friction Simulations only	Provides tips for supporting inquiry while using PhET simulations	Designed by PhET to support teachers in using the simulation in inquiry-based ways.

Research Design

Overview of data sources. Primary data sources for this study included: (a) classroom observations, (b) semi-structured interviews with teachers, (c) class- and student- generated artifacts created during simulation lessons, (d) screen recordings of students' individual work with simulations, (e) student attitude surveys, and (f) pre-assessments conducted before and after students worked with each simulation (see Table 3.5, below).

Table 3.5
Overview of Data Sources

Data Source	Duration or number	Participants Involved
Classroom observations	Observed 58 hours	All students whose parents consented
Semi-structured interviews with teachers	4 interviews per teacher	Both teachers
Class- and student-generated artifacts	Collected as enacted	All students whose parents consented
Screen recordings of students' individual work with simulations	Collected as enacted	Focal participants
Pre-assessments	Collected at the beginning and end of each unit	All students whose parents consented

Observations. Dyson and Genishi (2005) explain that spending extended time in the field helps establish the validity of a case study, as it gives the researcher more familiarity with the context and helps the researcher identify patterns over time. While my dissertation focuses only on the MLs science lessons that involve simulations, I made qualitative observations of most the MLs science lessons taught by Ms. Lane and Ms. Lawson during the spring semester of 2019. This consisted of 47 days of instruction in Ms. Lane's class (32 hours) and 37 days of instruction in Ms. Lawson's class (26 hours). Ms. Lane and Ms. Lawson typically taught science at different times during the school day, which allowed me to observe both science lessons on the same day, minus a small overlap. When I was not able to observe science lessons in person, another member of the MLs team observed and took field notes. On the few days when no member of the MLs team was present, I had a brief conversation with the teacher to hear about the lesson I had missed.

Both I and other members of the MLs team used an open-ended observation template to take field notes (see Appendix A). This template focused on the interactions between teachers and students, as well as noting any insights shared by the teacher. All observed lessons were also filmed.

Focal lessons for my dissertation included all lessons where either class worked with the simulation. There were four such lessons in Ms. Lawson's class (two with the Net Force Simulation, one with the Friction Simulation, and one with the Mystery Plant Simulation). There were seven focal lessons in Ms. Lane's class (two with the Net Force Screen of the "Force and Motion" PhET simulation, three with the Friction Simulation, and two with the Mystery Plant Simulation). Note that Ms. Lane would often choose to spend more days working with the simulation, as compared to Ms. Lawson, which is why there are more focal lessons from Ms. Lane's classroom.

Teacher Interviews. I also conducted semi-structured interviews with both teachers four times. (See Appendices B, C, D, and E for interview protocols). The first three interviews occurred before the teachers taught the Net Force, Friction, and Mystery Plant Simulations. These interviews had three parts. First, the teacher and I sat down to work though the simulation together, to make sure that the teacher understood how to use the simulation and to discuss any aspects of the simulation that the teacher thought might present difficulties to her students. Next, the teacher and I discussed findings from the relevant simulation pre-test, which I had analyzed and summarized. We talked together about what ideas from the simulation students already understood and what ideas were not yet clear to students. Finally, the teacher and I had a general conversation about what decisions the teacher planned to make while teaching with the simulation.

The fourth interview occurred at the end of the year, after the teacher had finished with all the simulations. This interview began with a stimulated recall (Peterson & Clark, 1978) in which I showed a series of short video clips taken from different simulation lessons and asked the teacher to comment on the instructional decisions she was making as she taught with the simulation. Following the stimulated recall portion of the interview, I asked the teacher to evaluate the usefulness of each simulation and to make a recommendation as to whether the simulation should remain part of the MLs curriculum.

In addition to the four semi-structured interviews, I conducted a member check after completing the first draft of my dissertation. In the member check, I showed both teachers tables 7.1, 7.2, and 7.3 (the three tables from the cross-case analysis chapter that most succinctly summarize my findings.) In particular, I asked teachers if they saw any inaccuracies or omissions in (a) my representation of the teaching practices they used to support student sensemaking, or (b) my summary of their comments regarding the effectiveness of the simulations as a learning tool. Both teachers shared that they found the tables to be accurate and complete.

Class and student generated artifacts. I took photographs of all artifacts generated by the whole class or by individual students during the entire spring semester. Class-generated artifacts included: collaboratively constructed claims, collaboratively constructed models, and notes documenting class conversations. Student-generated artifacts included: individually written claims, models, or notes that students wrote in worksheets or in their science notebook. Student-generated artifacts also included online, animated models students created using the application *Collabrify Flipbook,* which was designed by Elliot Soloway and team.

As in the case of observation notes, I collected all artifacts from the spring semester, for the sake of thorough and complete documentation. However, this dissertation only analyzes those artifacts that were related to simulation lessons.

Screen recordings of student individual work with simulations. For both the Net Force and the Friction Simulation, I used the program ScreenCastify to take screencasts of what focal students did with the simulations when they were given time to explore the simulations independently using a personal computer or Chromebook. For the Net Force Simulation, I took a screencast while students explored the Net Force Simulation during science class. For the Friction Simulation, I took two sets of screencasts. The first set of screencasts were taken before the students had received any instruction on how to use the Friction Simulation. The second set of screencasts were taken after the students had been instructed in the use of the Friction Simulation.

Assessments. Before students used each simulation, they took a pre-assessment to gauge their knowledge of relevant scientific content. I designed these assessments for use in this dissertation study[5], with assistance from my advisor, Annemarie Palincsar. My dissertation committee also briefly provided feedback on these assessments during my dissertation proposal meeting. I assessed each pretest using a rubric and then generated an overview document that summarized the class's performance on the pre-assessment. The teachers and I looked at this summary document as the teachers prepared to teach each simulation-based lessons.

[5] As of the writing of this dissertation, I do not have psychometric data for the assessments. In this dissertation, I do not use the assessments as a pre-post efficacy measure. Rather, I use them descriptively to describe student prior knowledge before each simulation.

The net force pre-assessment consisted of two items. Each item showed a simulation scenario and asked students to (a) predict whether the cart would move left, move right, or stay still, and (b) explain their reasoning. Using the rubric, I checked whether each student's answer was correct and also how many of the simulation features students incorporated into their reasoning.

The friction pre-assessment consisted of three items that posed scenarios related to the friction simulation and asked students to make predictions. Using my rubric, I gave one point for making a correct prediction, one point for explaining the concept of friction, and one point for using the word "friction.[6]"

The mystery plant assessment began with two items that asked about heredity. A third item assessed students' understanding of the relationship between (a) the level of variation among offspring, and (b) a plant's ability to survive and reproduce in a wide range of environmental conditions. There were also two items that assessed student understanding of fair tests[7]. Again, the assessment was scored using a rubric. For the first two items, I checked whether or not students expected variation of traits and needs among a plant's offspring. For the third item, I checked (a) if students noticed the absence or presence of variation among offspring, and (b) whether students associated variation among a plant's offspring with the ability of the plant to survive in a wider range of environments. For the fair test items, I checked whether students could (a) accurately identify examples and non-examples of fair tests, and (b) clearly explain their reasoning. For copies of pre-tests, and rubrics see Appendices (F, G, and H).

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[6] Because the teachers both chose to emphasize fair tests during the friction simulation lessons, I decided to add two fair test related items to the friction posttest. However, the posttests analysis is not within the scope of this dissertation.

[7] These items were included to observe whether students were able to transfer understanding a fair test from the friction simulation to the plant simulation.

Data Management, Preparation, and Methods of Analysis

I used the University of Michigan M-box site to store my data, which I organized by source (audio files, transcripts, field notes, etcetera). I also made backup copies of data which I stored on secure external hard drives. In the sections that follow, I describe how I organized, stored, and analyzed different types of data.

Time- use analysis. Following Fitzgerald's (2018) lead I created "Enactment Timelines" that documented how teachers spent time during each science lesson of the spring semester. These enactment timelines recorded: the date of each lesson, the topic of each lesson, activities during each lesson, the length of time of each lesson, whether the lesson was recorded, and whole-class and individual artifacts created during the lesson. The purpose of the enactment timelines was to help me see how the simulation lessons fit into the larger context of the overall unit. See Figure 3.22 below for an excerpt of one of my enactment timelines.

Date	Lesson and Activities	Time	Video & Audio	Associated Photos (stored on cloud unless otherwise noted)	Scanned Student Work (stored on box)
1.11.19	**Lesson 1.1: How do toys move?** • Students observed two rockets as a class & shared observations and questions, while teacher recorded on chart paper	35	BOTH	• Photo of "How/ I noticed" class chart. (2 pages) • Photo of teacher making chart with the students. • Photos of each rocket	
1.15.19	**Lesson 1.1: How do toys move?** • Class worked together to record "I notice"/ "I wonder" for one large rocket • In pairs, students recorded "I notice"/ "I wonder" for their own small foam rocket • Whole class discussion of	40	BOTH	• Photo of "I notice/I wonder" chart projected on smart board with teacher sample entry. • Photo of "I notice/I wonder" class list on chart paper.	• I notice/I wonder

Figure 3.22 Excerpt from enactment timeline.

Transcript analysis. For each of the simulation lessons, I used the online service Rev.com to generate a transcript based on the video recording. I read through and double-checked this transcript and then imported the transcript into a database I created in Microsoft

Excel. Every sentence from each transcript was entered into a separate row in Excel[8]. Each sentence was assigned a unique line number and then labeled to show which teacher taught the lesson, which simulation was being used, and what number the lesson was. For example, Figure 3.23 below shows one sentence spoken by Ms. Lane during the third friction lesson.

	A	B	C	D	E	F	G
1	Index	Teacher	Simulation	Lesson Number	Open Coding	Speaker	Transcript
3174	3174	J	FR	3	T reminds student that they need to actually run the test (as part of their fair test.)	Ms. Lane	We have to test it.

Figure 3.23 Screenshot of Excel lesson transcript database

Once all the transcripts were entered into the database, I read through the transcript line-by-line and went through a process of open coding (Corbin & Strauss, 2008) where I noted any ways that the teacher was supporting student sensemaking. This initial process of coding was informal, rather than systematic. In particular, I made notes of places where the teacher was supporting students to engage with or think about the simulation in ways that supported deeper understanding of the simulation content, of processes of scientific inquiry, or of how to interpret the simulation visuals.

After open coding the transcripts, I went through all the transcripts again and engaged in systematic line-by- line coding, this time using a list of codes adapted from Cervetti and colleagues (2014) (See Table 3.5, below.)

[8] I defined sentences based on where the Rev transcribers put punctuation. In a few cases, I added punctuation to the Rev-generated transcript because the transcript had been punctuated in a way that created run-on sentences.

Table 3.6
Codebook for Teacher Talk

Code	Abbreviation	Definition	Example
Directing Attention	DA	Draws attention to a specific part of the simulation	"Look at the arrows"
Conceptual Question	CQ	Asking about a scientific concept; soliciting prediction or reasoning; asking student to interpret representation.	"What happens if the speed goes slower?"
Experiential Question	EQ	Asking about previous out-of-school or in-school experiences, including experiences from within the same lesson.	"What did we do yesterday?"
Procedural Question	PQ	Asking about the procedure for using the simulation.	"If I hit return, is that supposed to happen?"
Inviting	IN	Inviting students to share their thinking.	"Okay, someone else?"
Requesting Information/ Clarification	RI	Asking students to clarify or elaborate on their response	"Can you say more about that?"

Repeating	RP	Exact repetition of student’s contribution.	S: At the top T: At the top
Revoicing	RV	Rephrasing and extending student contribution.	S: Let’s say you move your hands together. It makes your hands feel warm. T: Okay, so – rubbing my hands together. I’m sliding two surfaces over each other, right
Recalling shared events	RS	Referring back to a shared experience, including both experiences from science class and experiences outside of science class.	"What does it mean to scatter? I sometimes tell you guys that at recess time. You look like you're getting involved in something you don't need to be involved in, you're all stressed out, and I say, you need to go scatter."
Directive/Discussion Etiquette	DD	Giving students directions or maintaining norms for classroom conversations	"Come to the rug."
Providing Information	PI	Giving information directly to students.	"The sum of forces is going to be how big that arrow is."

Praising	PR	Giving praise to individual student or to the whole class	"Terrence is one of the first students I've ever heard come up with that."

I chose to use this set of codes because (a) they draw from the literature on how teacher talk can support student sensemaking (Cervetti et al., 2014), and (b) they provided a way of sorting and organizing the data that was consistent with the sensemaking-related observations I had made during open coding. After I coded all of the data, a second trained coder went through and coded a randomly selected 20% of the data. Our agreement was 84.4%.

Interview analysis. I transcribed teacher interviews myself, with some assistance from the automated transcription software Otter.ai. Once the interviews were transcribed, I entered them into an Excel database. This database was sorted by both the name of the teacher and the name of the interview. I was able to use keyword searches to quickly navigate among this database. I also used both open coding and color-coded highlighting to make notes on different ways that the teachers spoke about supporting student sensemaking (see Figure 3.24).

#	Speaker:	Transcript:	Notes:	Conceptual Goals	Student Prior Knowledge	T's experience last year	Participation Structures	Sim. Features	Questions Concerns
1	me	right so do you remember this simulation from last year with the cart in the middle and the pullers on either side?							
2	Ms. Lawson	Yes.							
3	me	So we're just talking about that simulation today.Um, what are you hoping students will understand learn by working with that simulation.							
4	Ms. Lawson	So for this one, they're looking at unbalanced force or balanced and so you want them to be able to see that with the unbalanced force, whether it's the pusher or the pull that the cart will move, I'm going based off memory cause I have not looked at this lesson yet, I'm at 1.3 today.	goal: unbalanced forces (push/pull) --> movement						
5	me	Perfect.							
6	Ms. Lawson	Right?							
7	me	Right. So your goal is that they'll understand that if the forces are unbalanced the cart will move.Yeahand that if it is balanced it will not move, right? What do you plan to do to support them to							
8	Ms. Lawson	so I'm going to give them opportunities.							
9	Ms. Lawson	What did you say?							
10	me	how will you support them to understand that?							
11	Ms. Lawson	I'm going to call up -- I'm going to do some modeling and demonstrations with that --and then I'm going to call students up to interact with it and probably do some kind of turn and talk where they -- like a think pair share and see if we can't get it going. last year my Preston talked about sidewalks --	will support by first doing demonstration and then inviting students take a turn.						
12	me	Yes.							

Figure 3.24 Teacher Interview Database

Artifacts. I used the class-generated and student-generated artifacts I collected to supplement my understanding of what was revealed in the lesson transcript. For example, when the lesson transcript documented the process of students co-constructing a written claim, I cross-referenced that portion of the transcript with the photograph I had taken of the claim the teacher wrote down on chart paper. I did not engage in a systematic analysis of all artifacts. Instead, I used them for triangulation purposes to shed additional light on my analysis of the lesson transcript.

Screencasts. I used the program ScreenCastify to record how focal students used the Friction Simulation both before and during the Friction Simulation lessons. I then compared how many different features of the simulation the focal students used before the lesson and during the lesson, to see if the teachers' instruction influenced how fully the students explored the simulation.

I conclude this methods chapter with a table identifying the data sources used to address each research question, together with the analytical methods used to analyze each data source.

Table 3.7

Data Sources used to Support Research Questions

Data Source	Analytical Method
RQ1: How do teachers support student sensemaking while working with simulations in the context of 3rd grade project-based science? Does this support, or student response to this support, shift across the three simulations?	
Video of lesson enactment	Transcribed and coded to identify patterns in teacher talk
Photos of artifacts created during lesson enactment	Matched to the point in the lesson where they were created and used to examine how participants communicated about the simulation through means other than oral speech
Pre-assessments	Scored using rubric and then described using summary document
Screen recordings of students' individual work with simulations	Analyzed to observe how many simulation features students used both before and after teacher provided support for using the simulation
RQ2: What are the teachers' perspectives regarding the use of simulations as sensemaking tools?	
Teacher Interviews	Transcribed and coded to identify to what extent teachers found simulations to be supportive of learning

The next three chapters present the findings of this dissertation. The next chapter (Chapter Four) will address both research questions by examining both teachers' enactment of the Net Force Simulation.

CHAPTER 4 The Net Force Simulation

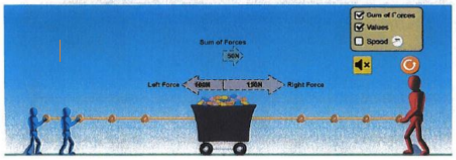
This chapter focuses on the Net Force Simulation. It is organized by the study's two research questions. It begins by considering the first research question: *How do teachers support student sensemaking while working with the Net Force Simulation? How do students respond to this support?* The first part of this chapter constructs a case of how each teacher supports student sensemaking in her classroom. Each case contains the following sections (a) how the teacher prepares to support sensemaking prior to beginning teaching, (b) an overview of how the teacher enacted the simulation-based lesson, (c) a closer look at types of teacher talk that specifically supported sensemaking, and (d) an illustrative example of how student(s) responded to the teacher's sensemaking support. Following the two cases, I consider the relationship between the teacher's instructional decisions and the support provided by both the simulation and the MLs curriculum. The chapter then moves to consider the second research question: *What are the teachers' perspectives regarding the use of the Net Force Simulation as a sensemaking tool?* The chapter concludes with a brief summary of key findings that relate to each of the two research questions.

How Does Ms. Lane Support Student Sensemaking while Working with the Net Force Simulation and How Do Students Respond to this Support?

The following section considers how Ms. Lane supported student sensemaking both through careful pre-planning and through instructional decisions that she made while teaching.

How Ms. Lane prepared to support student sensemaking prior to teaching. Figure 4.1 shows the overview document that I brought to my meeting with Ms. Lane, which summarized how her students had responded to each of the two questions on the pre-test. For each item, the majority of the students correctly predicted the direction of motion (or lack of motion) of the cart. However, (a) none of the students used simulation features (arrows) to support their reasoning, (b) some students supported their prediction using scientifically inaccurate or incomplete reasoning, and (c) some students either made incorrect predictions or left an item unanswered.

1. These people are pulling on opposite sides of a cart. Which way do you predict the cart will move?



Explain why you think this will happen. Give as many reasons as you can.

16 students said that it will move right.

<u>3 students mentioned differences in the **VALUE of the left and right forces**</u>

- "The left force is 100N. The right 150N."

<u>5 students mentioned **UNBALANCED FORCES**</u>

- "Because the red guy is pulling harder"

<u>No one mentioned the left/right/or sum of forces **ARROWS**</u>

<u>Other reasoning included</u>

- "Because the man or woman on the right is so strong, it will shoot to him."
- It is uneven a grown up against a kid."
- "Cause the person is bigger and the string is bigger."

5 students said it will not move

- "They are both pushing the cart on each side"
- "It will not move on grass"

3 students said it will move left

- "There are two knots on the blue on the left side and there are three knots on the right"
- "because 2 is better than one and if one gets tired the other one will still pulling. The left side has less weight."

2. These people are pulling on opposite sides of a cart. Which way do you predict the cart will move?

Explain why you think this will happen. Give as many reasons as you can.

13students said it will not move.

<u>2 students mentioned the **VALUE of the left and right forces**</u>

- *They're both 100 N*

<u>4 student mentioned that the forces were balanced</u>

- *they are pulling the same amount*

<u>**No one mentioned the left arrow, right arrow, or sum of forces arrow.**</u>

<u>Other reasoning included</u>

- *it never move on grass*
- *they have the same weight*
- *It will not move because they both have no force*

6 students said it will move left.

- "cuz it is 2 people on the left and one on the right"
- "There are two knots on the left side or the blue side and on the right side has three knots on the red side."

5 students said it will move right.

- "Cuz the person is bigger and the cart is more on his side"
- "It is causing friction and the left has two people pulling the cart"

Figure 4.1 Pretest Overview for Ms. Lane's class

Ms. Lane consistently approached her teaching by trying to understand what students observed and how they interpreted their observations. After seeing the summary sheets, her first response was to be impressed that some of the students had noticed “100 N” on the simulation and used it to support their answers. She said: “I mean right off the get go. Just the fact that three notice that the left force is 100!” (Lane, NF[9]). Ms. Lane then quickly moved to fill a gap in her own knowledge, “What does N stand for?” she asked (Lane, NF). I replied that it stood for “newton” a metric unit of measurement. We then discussed the etymology of the word newton, what newtons measured, and how newtons compare to non-metric units of measure. This discussion was typical of many of the conversations Ms. Lane and I had throughout the year. Ms. Lane continually worked to deepen her own understanding of the scientific concepts she taught and often asked conceptual questions when talking with me and/or Ms. Lawson. Ms. Lawson, for her part, often asked Ms. Lane questions that drew on Ms. Lane’s multiple years of experience teaching with the MLs curriculum.

As we read through the pre-test answers, Ms. Lane mused aloud about how students’ reasoning supported their answers. For example, she considered what life experiences might have led students to provide not-entirely-scientifically-accurate answers. “If they've played with a dog, pulled back and forth or…trying to get something away from someone. It's easier to get something away from someone smaller versus someone that's bigger. Or if you've got two people trying to get it away, it's going to be easier to get it away. . .” (Lane, NF). While Ms. Lane knew that force is not determined by either size of people or number of people, she could imagine how her students might have formed those theories, based on their life experiences.

[9] Net Force Interview

Ms. Lane also noted that since students had presented multiple opposing predictions, this would provide a good opportunity for students to engage in scientific argumentation during the simulation lesson. She made plans to support this argumentation by inviting students to make different predictions and support their predictions with reasoning. “I would want to do some discussion…so we've got three different trains of thoughts: some of you are saying it's going to move to the left, some of you are saying moving to the right, some of you are saying it's not going to move…Somebody tell us why you think that …” (Lane, NF). After all students had a chance to share their predictions and reasoning, Ms. Lane planned to check back in to see if anyone had changed their predictions. “And then I may just say, you know, does this change anybody's mind? Like, is anybody convinced?” (Lane, NF).

During the same interview, before the Net Force Simulation lesson, Ms. Lane also articulated her goals for student learning. Ms. Lane explicitly prioritized student sensemaking, saying that she was less concerned whether students discuss balanced and more unbalanced forces and more concerned that students make careful observations, pose questions, and engage in reasoning. Ms. Lane’s second goal was related to supporting students to interpret representations: she wanted students to be aware of the different features of the simulation and how these features can be adjusted or changed. Table 4.1 below lays out Ms. Lane’s two goals, together with quotations supporting each goal.

Table 4.1
Ms. Lane's Goals for the Net Force Simulation

Conceptual Goal	Quote
Students will make observations, ask questions, and engage in reasoning while working with the simulation.	"I don't think balanced and unbalanced is going to come out. It may it very well may, but ... So just, you know, I guess what do I want to come out of it? Questions! ---- I want them to make. Make some observations. Question Why is this happening? Why is that happening?" (Lane, NF).
Students will notice simulation features such as: size of people, number of people, position of people on the rope, labels, size of arrows, simulation key with toggles that can be clicked	"'Those look like kids and that's an adult', somebody else might say. 'But there's two kids and there's only one adult.' And hopefully they're going to notice, 'But wait, he's pulling on the fourth one, and they're pulling on the third and fourth one.' … I'm hoping that they pay attention to the arrows and notice that one is larger than the other ...and also look up at that key right there" (Lane, NF).

When asked about potential challenges that might occur as students worked with the simulation, Ms. Lane only mentioned one concern. She recalled that in the previous year, students had been thrown by the fact that half of the simulation people were red, while the others were blue (see Table 4.2). The class had discussed multiple potential things that red/blue could symbolize, such as temperature, gender, and sports team affiliation. Ms. Lane felt it was important that student realize that the red/blue divide did not carry any particular symbolic meaning within the context of the simulation.

Table 4.2
Ms. Lane's Concerns about the Net Force Simulation

Potential Challenges/Concerns	Quote
Students become distracted by non-salient features of the simulation	[Last year] they thought it had to do with colors because are these red and blue (Lane, NF).

During the same pre-meeting, Ms. Lane also laid out how she planned to support student sensemaking while working with the simulation, in order to help them reach her aforementioned conceptual goals. The teaching moves that she identified (see Table 4.3 below), are consistent with both the best practices listed by PhET and the curricular supports provided by the MLs project. They are also directly aligned with Ms. Lane's own conceptual goals for student learning.

For example, Ms. Lane's plan to support students to use a think/pair/share format to brainstorm observations before beginning to use the simulation was directly related to her goals of students observing, predicting, and reasoning throughout their work with the simulation. It was also consistent with PhET's emphasis on intuitive simulations that "make the invisible visible." Furthermore, it was consistent with the MLs recommendation that the lesson begin with observation of the simulation. Finally, it gave Ms. Lane an opportunity to intervene if students became overly concerned about the role of color, to the possible detriment of their overall understanding of the simulation.

Table 4.3

Ms. Lane's Plans for Supporting Student Sensemaking

Plan for supporting sensemaking	Quote
Supporting students to make initial observations using a Think/Pair/Share participation format.	"[I'll] give them a minute to look at it. 'I don't want anybody to talk.'… [I'll tell them] …. "I was looking at it and there were at least five or half a dozen noticings that I had.' And I want them to take a little bit longer to look and then I'll maybe let them turn and talk with the partner for a couple of just a few seconds and then say …. 'What are some things that that you notice? What are some questions that you have?"' (Lane, NF).
Modeling one simulation scenario as a whole class while supporting students to make predictions, support their predictions with reasoning, test their predictions, and interpret whether or not their test supported their predictions.	"I think I'd almost only do one together like just one. We're just you know what we're going to do, we're just going to do one because I think if I go through and ask them, what are your thoughts, what do you think's going to happen? Prove it. Why do you think this? Okay, we're just going to pick one of these. And we're going to test it out here. And then based on what happens were we right here we wrong, okay, now look at these other things that we've thought are going to happen" (Lane, NF).
Giving students time to experiment individually with the simulation	"I'd like to do one or two first so that there's some sense of direction. And then, 'okay, I'm going to set the timer. You've got this much time, go back and try different scenarios'" (Lane, NF).
Connecting to student experiences	"[I will ask] how many of you have ever played tug of war? Got the same amount of people on each side?" (Lane, NF).
Encouraging students to carefully listen to and critically consider each other's ideas	"You've got to be thinkers got to be scientists, you've got to listen to each other and hear each other out and see what makes sense" (Lane, NF).

Overview of Ms. Lane's enactment of the Net Force Simulation lessons. Ms. Lane taught the Net Force Simulation over the course of two days. Her first lesson was 41 minutes and her second lesson was 36 minutes. On the first day, the whole class explored together. (Ms. Lane's original plan to model one or two simulation scenarios on the Smart Board and then have students work independently on Chromebooks was thwarted by Wi-Fi issues that incapacitated the Chromebooks but not the Smart Board.)

On the first day, Ms. Lane began by asking students to recall what they had been previously doing in science. During this discussion, Ms. Lane and her students reviewed ideas of balanced and unbalanced forces. Ms. Lane nearly always began her science lessons with a review discussion, in order to support all students to make connections across the science unit, and also to give English Language Learners and students with special needs a review of important vocabulary and concepts (Lane, summer 2019 interview). Following this review discussion, Ms. Lane introduced the idea of contact forces and invited a student to help her demonstrate unbalanced and balanced contact forces by pushing on opposite sides of a toy cart. Ms. Lane then introduced the simulation and gave her students time to make observations. Next, Ms. Lane gave her students the opportunity to set up simulation scenarios, make predictions, justify their predictions with reasoning, test their predictions, and interpret their predictions. Throughout these discussions, Ms. Lane supported students to think about balanced forces, unbalanced forces, and newtons as a measure of force. She also provided students with specific challenges to aim towards while setting up simulation scenarios.

On the second day, Ms. Lane again began with a student-led review discussion that focused on the concepts of balanced and unbalanced forces. Ms. Lane next supported her students to come up with a list of challenges to try to accomplish as they explored the simulation. The class identified the following challenges: make the cart move as fast as possible, make the cart move as slowly as possible, and make the forces balanced without having an identical configuration of people on each side. After identifying challenges, Ms. Lane gave students time to explore the simulation on their Chromebooks. At the end of class, Ms. Lane gave students time to share different ways that they had achieved the challenges and interesting observations students had made while exploring the simulation.

As students explored the simulations, many created a somewhat surprising scenario where the forces were balanced, yet the cart moved. When a student showed me this scenario, I first thought it was a result of a lagging internet connection. However, Jared Tenbrink (a fellow member of the MLs team who was also present in Ms. Lane’s room that day) had been carefully observing and he explained that there was no glitch. Instead, what had happened was that the student had first created an unbalanced force, causing the cart to accelerate to the right. The student had then re-balanced the force, which meant that the cart stopped accelerating to the right but kept moving. Ms. Lane and I briefly checked in about this phenomenon and Ms. Lane correctly predicted that some students would want to share about it during the final debrief conversation.

Table 4.4 shows the breakdown of Ms. Lane’s talk during whole-class instruction with the Net Force Simulation.

Table 4.4
Ms. Lane's Talk during the Net Force Simulation Lessons[10]

Talk Type	Frequency
Directive or Discussion Etiquette	27%
Conceptual Question	21%
Providing Information	15%
Inviting	7%
Revoicing	6%
Requesting Information or Clarification	5%
Repeating	4%
Directing Attention	4%
Praise	4%
Recalling Shared Experiences	3%
Experiential Question	3%
Procedural Question	.01%

During the Net Force lesson, Ms. Lane most frequently engaged in providing directions and discussion etiquette (27% of total teacher talk), which is a type of talk that is important for classroom management. The next most common type of teacher talk was posing conceptual questions (20%). The high rate of conceptual questions might be related to Ms. Lane's ongoing curiosity about student reasoning, as reflected in our pre Net Force interview (see section entitled "Student Prior Knowledge," above.)

Types of teacher talk that supported student sensemaking. While all of Ms. Lane's talk was important and necessary to keeping the lesson up-and-running, in the sections that follow I will be focusing on six types of talk that were particularly generative in supporting student sensemaking and foregrounding student ideas. These were: directing attention,

[10] Does not include one-on-one conversations with individual students

experiential questions, conceptual questions, inviting, requesting information or clarification, and revoicing.

Directing attention. Ms. Lane frequently guided students to make observations of the simulation. This helped support three of her instructional goals: (a) that students would be able to engage in sensemaking processes including making observations, (b) that students would be aware of the many different features of the simulation, and (c) that students would not be distracted by non-salient features of the simulation. Ms. Lane guided students to make observations using general prompts designed to support observation (e.g. “Anything else that you’re noticing?” NFD1[11]), specific prompts guiding students to look at a particular feature of the simulation (e.g. “Do you see those numbers in those arrows?” NFD1), and prompts encouraging student to notice how simulation features changed over the course of a scenario (“What do you notice is happening to the speed?” NFD1). While teaching the Net Force Simulation, Ms. Lane commented to me that she was impressed with the careful observations her students were making. ("And even the fact that they kind of brought up the speed - you know - they're really noticing things” NFD1).

Experiential questions. Consistent with her goal of helping students make connections to their experiences, Ms. Lane asked questions that helped her students connect their previous experiences to what they were currently doing with the simulation. These included questions about general life or out-of-school experiences (“How many of you have ever been in a simulator or on a simulator?” NFD2), to experiences from prior science lessons (“Who else remembers a challenge that we set up?” NFD2), and experiences that occurred earlier within the same science

[11] Net Force Lesson Day 1

lesson. ("Were we both applying a force?") Many of these experiential questions occurred near the beginning of each day's science class, as Ms. Lane helped students connect the day's learning to what they had done in previous classes.

Conceptual questions. Ms. Lane used conceptual questions to support students in: engaging in scientific practices, interpreting representations, and developing understanding of key science concepts, as well as to increase the cognitive demand of generating simulation scenarios. Ms. Lane supported students to engage in scientific practices with questions that encouraged them to make predictions ("Is it going to move to the right or to the left?" NFD1), develop generalizable claims ("Does a contact force always cause an object to move?" NFD1), and support their ideas with reasoning ("Why do you think so?" NFD1). Ms. Lane supported students to interpret representations with questions that pressed students to explain how they interpreted different simulation features ("What's the biggest clue that it's unbalanced?" NFD2). Ms. Lane supported student understanding of key scientific concepts with questions that focused on key concepts and vocabulary (e.g. "'Unbalanced' means what?" NFD2). Concepts and vocabulary that she emphasized included: balanced force, unbalanced force, contact force, friction, model, newtons, and sum.

Ms. Lane also asked conceptual questions that increased the cognitive demand for students. Some of these questions were general in nature, as Ms. Lane asked students to take what they had been observing or describing and discuss its significance. ("If they're balanced and the toy is moving, what does that mean?" NFD1). In other cases, as discussed above, Ms. Lane increased the cognitive demand by providing students with specific challenges to accomplish ("What else do you think you could do maybe to make the speed go faster?" NFD1).

Ms. Lane's conceptual questions followed through on the plan that she made during the pre-interview to have students make predictions, support predictions with reasoning, test predictions, and interpret their investigation results in light of their predictions

Inviting, requesting clarification, repeating, and revoicing. Ms. Lane used a number of talk moves to bring student voices into the class conversation and to extend student ideas. All throughout both days of instruction with the Net Force Simulation, Ms. Lane invited students to share their thoughts, ideas, and wonderings. Most often, she did so by calling on students whose hands were raised. She also had a number of techniques she used to invite all students to simultaneously share their ideas. These included: (a) having students point in the direction in which they predicted the cart would move, (b) having students put their thumb up or down to indicate whether or not they thought the cart would move, and (c) giving students the chance to turn and talk with someone near them.

Ms. Lane valued student contributions and made efforts to make sure that she understood students' ideas correctly. If she was not certain what a student was saying, she might invite students to expand on their idea ("Can you tell me a little more about that?" NFD1). Once ideas were shared, Ms. Lane often repeated or re-voiced them, thus making sure that they would become part of the class conversation. Repeating was particularly important when some students spoke so softly that they could not be heard by everyone. Revoicing allowed Ms. Lane to build off of students' contributions, while also adding new ideas into the conversation. Ms. Lane described the process of revoicing as "getting the kinks out for them a little bit" (Lane, Stimulated Recall Interview). She saw revoicing as a useful technique for two reasons: first, because it showed that she valued the students' ideas and contributions and second because it allowed her to add a little clarity and avoid misconceptions. She also shared that when she repeated and re-voiced, she hoped that students might follow her example and refer back to each other's comments during class discussion ("[I'm] hoping that kids hear that, 'oh, she's restating that. I could do that for someone sometime.'" Lane, SR[12]).

Taken together, the talk moves of inviting, requesting clarification, repeating, and revoicing allowed Ms. Lane to bring student ideas to the discussion, make sure the ideas were as clear and fleshed out as possible, and make sure that all students heard their classmates' ideas. This was consistent with the goal Ms. Lane stated during the pre-interviews, that students would listen to each other's ideas. The combined frequency of these four moves (23%) speaks to the extent to which Ms. Lane valued creating spaces for student voices and extending student ideas.

Considering a student's responses to Ms. Lane's sensemaking support. In the above sections, I have shown how Ms. Lane used a variety of different teaching moves in order to support students' sensemaking. In this final section, I will look at one example of a longer stretch of dialogue, in order to show the way that Ms. Lane's different teaching moves build on each other in order to support sensemaking across the conversation and to shed light on is student responses to these moves.

> *Ms. Lane: Okay, again, give me a thumbs up or thumbs down on whether or not you think the cart is going to move. Okay, so it's a thumbs up or a thumbs down. It's not both. We can't think both. [Most thumbs are up, one is sideways, and a few are down.] Right. Okay. So, anyone have thoughts on why you think it's going to move? Somebody kind of give us some thoughts. Jeremy pass it [the microphone] up to Kajuan, please. Then Kajuan will pass it to George*
>
> *Kajuan: I see that the blue one is bigger than the red one.*
>
> *Ms. Lane: What do you mean the blue one? The blue one what?*
>
> *Kajuan: Is taller.*

[12] Stimulated Recall Interview

Ms. Lane: You think the person is taller?

Kajuan: Yeah.

Ms. Lane: Okay. The question is do you think it's going to move?

Kajuan: Yes.

Ms. Lane: Which way do you think it's going to move, to the left or to the right?

Kajuan: Left.

Ms. Lane: You think it's going to move to the left. Okay. And why do you think so? You said because the person's taller?

Kajuan: No, but the arrow right there, on top of it on the left side, is longer, and the right side is shorter. (NFD1)

At the beginning of the above excerpt, Ms. Lane is providing all of her students an opportunity to make a prediction as to which way the cart will move. When she sees that some students have not yet made a prediction, or have made more than one prediction, she stops to repeat her directions until all students have voted. She then cues students so that they will know when it will be their turn to share. This cueing is a technique that she often used when soliciting student ideas.

Kajuan’s initial contribution is a descriptive statement that does not explicitly answer Ms. Lane’s question of “why” and also uses vague language. Ms. Lane first asks him to clarify what he means by “the blue one.” Instead of clarifying his noun, Kajuan clarifies his descriptors, replacing “bigger” with “taller.” Ms. Lane accepts this contribution, legitimizes it by repeating it, and then prompts Kajuan to repeat his prediction as to which way the cart will move. She then tries to make a connection between his descriptive statement and his prediction, asking Kajuan if he thinks the cart will move to the left *because* the person on the left is taller. Instead of agreeing with this statement, Kajuan changes his reasoning and points out a different simulation feature that could be used to justify his prediction: the arrows.

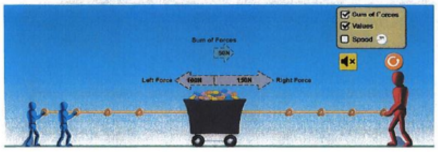
Throughout this conversation, we see that Ms. Lane is helping Kajuan clarify his initial reasoning, without ever taking over or denying him agency. Through prompts, she first supports him to move from a vague descriptive statement to a more specific descriptive statement and then prompts him to turn his descriptive statement into an explanation. At multiple points in the conversation, Kajuan responds in a way that Ms. Lane might not have been expecting. When he does so, she follows his lead. Her flexibility pays off, too: the end result is that Kajuan identifies a new simulation feature that had not previously been discussed. This co-constructive process of teacher and student building an idea together was typical of many exchanges in Ms. Lane's classroom.

How Does Ms. Lawson Support Student Sensemaking while Working with the Net Force Simulation and How Do Students Respond to this Support?

The following section considers how Ms. Lawson supported student sensemaking both through careful pre-planning and through instructional decisions that she made while teaching. Like the previous case study, it begins with the teacher's pre-instructional decisions, then provides a general overview of her teaching, then considers specific teacher talk moves that supported senses making and concludes with an illustrative example of student response to the sensemaking support.

How Ms. Lawson prepared to support student sensemaking prior to teaching. Figure 4.2 shows the overview document that I brought to my meeting with Ms. Lawson, which summarized how her students had responded to the two questions on the pre-test. As in the case of Ms. Lane's class, the majority of the students correctly predicted the direction of motion (or lack of motion) of the cart for both items. As in Ms. Lane's class, no student mentioned the simulation arrows, reasoning for some students was scientifically inaccurate, some students made predictions that were incorrect, and some students left items blank.

1. These people are pulling on opposite sides of a cart. Which way do you predict the cart will move?



Explain why you think this will happen. Give as many reasons as you can.

19 students said that it will move right.

<u>4 students mentioned differences in the **VALUE of the left and right forces**</u>

- "The left force is 100N and the right force is 150N"

<u>4 students mentioned **UNBALANCED FORCES**</u>

- "The people on the left are smaller, so they can't pull as hard."

<u>No one mentioned the left/right/or sum of forces **ARROWS**</u>

<u>Other reasoning included</u>

- "because it looks like on the right side there is an adult so it looks like the right side"
- Because the person on the right is bigger than the two people on the left"

2 students said it will not move

- "I think it will not move because if one person is pulling to the right and people on the left it can not go two directions at once"

1 students said it will move left

- "Because there is two people on the left and one on the right."

2. These people are pulling on opposite sides of a cart. Which way do you predict the cart will move?

Explain why you think this will happen. Give as many reasons as you can.

16 students said it will not move.

<u>6 students mentioned the **VALUE of the left and right forces**</u>

- *"they both have the same number I think it's amount? And they are probably pulling with the exact same strength."*

<u>5 student mentioned that the forces were balanced</u>

- *"There is equal amount of force means just like a game of tug of war equal amount of force no one will win pulling the cart"*

<u>**No one mentioned the left arrow, right arrow, or sum of forces arrow.**</u>

<u>Other reasoning included:</u>

- *"because they're the same weight"*
- *"Because two kids versus grown up. 2 kids = 1 grown up. 2 kids might have the same force."*
- *"because they're all the same size."*
- *"They have the same strength. And if the two blue people get on top of each other, it would be the same height as the red one"*

2 students said it will move left.

- *"Because the people on the left is now still smaller but have bigger muscles."*
- *"Because there are two people on the left side and one person on the right"*

3 students said it will move right.

- *"I think it will go to the right because there is an adult on the other side."*
- *"I think right because it has more force."*

Figure 4.2 Pretest Overview for Ms. Lawson's Class

Ms. Lawson consistently approached her students and her teaching from an asset-based point of view. After seeing the summary sheets, her first response was "Pretty good starting point… I love that they all were trying to support their reasoning" (Lawson, NF). She noted that whether or not students had the "right answer," they were backing up their answer with reasoning. "So even though we know that's incorrect, I think they all tried to support themselves which is great to see…that's really great for being in third grade, you know. I mean, fantastic!" (Lawson, NF). She also identified some misconceptions that would be "easy to tackle" during the lesson, including the idea that two people are always stronger than one person. She also praised her students for sticking with their ideas and thinking through them, "With this group, too, we've got a lot of people who are thinkers [and] love to persevere through some questions" (Lawson, NF).

Ms. Lawson also noted that the simulation is dynamic, whereas the pre-test only had static pictures. She predicted that students would have an easier time interpreting the simulation, as compared to the pretest. "I think I think the simulations are great, because they actually can see on there: 'Oh, the arrows are getting bigger. You know there's an unbalanced force and the cart is heading that way.' That's why I think, maybe some of this didn't show up [on the pretest], just because it's just the screenshot" (Lawson, NF).

During our pre-Net Force lesson conversation, Ms. Lawson also articulated her goals for student learning. Her first goal was that students understand the science concepts presented in the simulation: by the end of the lesson, she wanted to make sure that all her students knew that unbalanced forces cause movement. Her second goal was for students to get better at interpreting visual representations. Her third goal was that students would understand that simulations are, by their nature, limited. They represent real life, but they are not identical to real life. She wanted to make sure that the students understood that the simulation included some over-simplifications. In particular, she wanted to make sure they understood that in the real world neither height nor weight is necessarily proportionate to strength. The table below lays out Ms. Lawson's three goals, together with quotations supporting each goal.

Table 4.5
Ms. Lawson's Goals for the Net Force Simulation Lessons

Conceptual Goal	Quote
Students will understand that unbalanced forces cause movement.	"So for this one, they're looking at unbalanced force or balanced and so you want them to be able to see that with the unbalanced force, whether it's the pusher or the pull that the cart will move" (Lawson, NF).
Students will interpret the representations within the simulation: students will understand that the length of the arrow and the number of newtons (N) indicate the strength of the force	"Once they start messing with it and seeing that the arrows are getting longer, I think that that will be something that they actually mention" (Lawson, NF). "Using these values [newtons] instead of just looking at Well, there are more people on the side. So, it would go that way" (Lawson, NF).
Students will understand limitations of the simulation (e.g. in real life, strength is not proportionate to size.)	"But in real life, your strength is obviously not proportional to your weight necessarily" (Lawson, NF). "You're taller you must be strong - But we know that's not necessarily true at all" (Lawson, NF).

When asked about potential challenges that might come with working with the simulation, Ms. Lawson shared two concerns (see Table 4.6). The first was a concern that her smartboard would malfunction during the lesson, since it had a tendency to freeze up and stop working at inconvenient times. The second was that students might become so excited by the simulation that they would rapidly click on all of the different simulation features, without taking the time to interpret what they were seeing.

Table 4.6
Ms. Lawson's Concerns Regarding the Net Force Simulation

Potential Challenges/Concerns	Quote
Technical difficulties with Smart Board	"My smart board needs to be new!"
Students clicking all over the simulation without focusing	I think last year was -- it was a little bit difficult, because you do have to look at all of these parts of it [the simulation]. You know, for some kids that might be difficult. This year, I think it's going to be much different. I think we're going to see kids …using parts that we didn't want them to use…so making sure that [they] focus in on what we want them.

During the same pre-meeting, Ms. Lawson also laid out how she planned to support student sensemaking while working with the simulation, in order to help them reach the aforementioned conceptual goals. As in the case of Ms. Lane, there was alignment between PhET and MLs recommendations, Ms. Lawson's own goals, and Ms. Lawson's plans to support student sensemaking. Ms. Lawson's plans for supporting sensemaking are outlined in Table 4.7, below.

For example, when Ms. Lawson demonstrated/modeled scenarios, this was consistent with both the PhET recommendation that the teacher model scenarios early in the lesson and the MLs lesson plan description of how to introduce students to the simulation (see Chapter 3 or Appendix I for more details on curricular supports) It also provided Ms. Lawson with the opportunity to support both students' ability to interpret simulation features and students' conceptual understanding of balance forces, without creating a situation where students clicked without focusing. And, because Ms. Lawson identified the potential for Smartboard difficulties ahead of time, she was not thrown when the Smart Board didn't work perfectly during her demonstration.

Instead, she stayed calm and cheerful, promising that the Smartboard would resume working once it was finished being “fussy” (NFD1).

Table 4.7
Ms. Lawson’s Plans to Support Student Sensemaking

Plan for supporting sensemaking	Quote
Demonstrating/modeling scenarios with the simulation	“I'm going to do some modeling and demonstrations.”
Inviting students to come to the front of the class to engage with the simulation and then giving the whole class time to discuss these scenarios.	“and then I'm going to call students up to interact with it [the simulation] and probably do some kind of turn and talk where they -- like a think pair share”
Helping students make connections between the simulation and their lives	“Trying to get though them to connect it to their lives, right, or like instances where they have seen it [balanced forces] -- hoping that will help support their understanding as well.”
Supporting students to make observations	“Start with maybe the simplest, dissecting what the simulation is. And then from there, ‘what do you see out there?’ – having that discussion. ‘Okay, let's take it apart. And what do we see?’
Supporting students to make predictions supported by reasoning.	“And then testing it out and seeing ‘Okay, that cart is going to move.’ ‘Why is the cart moving?’ ‘Okay, well, what if we do this next?’”

Overview of Ms. Lawson’s enactment of the Net Force Simulation lessons. Ms. Lawson taught the Net Force Simulation over the course of two days. Her first lesson was 40 minutes and her second lesson was 45 minutes. On the first day, the whole class explored the simulation together. Ms. Lawson supported her students to make observations of the simulation, demonstrated simulation features, set up scenarios using the Smart Board, invited students to make predictions about these scenarios, invited individual students to set up their own scenarios on the Smart Board, and then invited students to interpret the results of their scenario. As students interpreted scenarios, Ms. Lawson encouraged them to think in terms of science concepts including force, balanced force, unbalanced force, and newtons as a measure of force.

On the second day, Ms. Lawson began with a whole class discussion of the simulation, then gave students the opportunity to explore the simulation individually, using their laptops. Initially, Ms. Lawson had all the students set up the same simulation scenarios on their laptops. As the lesson progressed, she gave students the opportunity to explore the simulation freely. As students were exploring, many made the same surprising discovery as Ms. Lane's students: scenarios could be both balanced and moving. Given the widespread curiosity and confusion, Ms. Lawson brought the class back together to watch a balanced-but-moving scenario on the Smartboard, make careful observations, and discuss and interpret what they saw.

Interestingly, Ms. Lawson's decision to include a second day with time for individual exploration came somewhat at the last minute. Her initial plan, as discussed during the pre-interview, was to only use the Smart Board for the simulation. She planned to give all students a chance to explore the simulation individually by finding time (during the weeks following the simulation lesson) for many different students to go up and experiment with the simulation on the Smart Board. However, at the beginning of the first simulation lesson, Ms. Lawson informed both the students and me that she would be giving time for students to explore the simulation individually on their own laptops. This change in plans might have been related to Ms. Lane's decision to have her students explore the Net Force Simulation on their Chromebook and her reported satisfaction with that decision. Ms. Lawson and Ms. Lane frequently shared stories, insights, and photographs of their science teaching with each other, even sometimes quoting each other's insights while teaching science. They also frequently adjusted their own teaching based on the other's experiences, successes, and challenges. When speaking with me, Ms. Lawson frequently mentioned how she valued Ms. Lane's expertise because Ms. Lane had more years of experience teaching with both the MLs curriculum in general and the simulations in particular (e.g. "…and I would need to talk to Ms. Lane because she's taught this longer than I have.") Ms. Lane, in turn, valued Ms. Lawson's content expertise that came from her experience as a middle school science teacher. Table 4.8 shows the breakdown of Ms. Lawson's talk during whole-class instruction with the Net Force Simulation.

During the Net Force lesson, Ms. Lawson most frequently engaged in providing directions and discussion etiquette (21% of total teacher talk) or providing information (19% of teacher talk.) The frequency of these two talk types is to be expected: the former is a necessary part of classroom management and the latter is a common occurrence any time teachers are introducing new content. The next most common types of talk included talk moves designed to support student sensemaking and to foreground student ideas including: Conceptual Questions, Experiential Questions, Directing Attention, Inviting, Repeating, and Revoicing. Taken together, these types of talk made up a substantial portion of Ms. Lawson's utterances (50%). Furthermore, when Ms. Lawson viewed video clips of herself teaching this simulation, she expressed that she wished that she had done even *more* talk designed to elicit and support student sensemaking. She said that next year, she would like the lesson to be even less teacher led, although she admitted that she might need to balance this goal with practical considerations (e.g. time constraints or the challenges that came with teaching science class directly after lunch.)

Table 4.8
Ms. Lawson's Talk during the Net Force Simulation Lessons[13]

Talk Type	Frequency
Directive or Discussion Etiquette	21%
Providing Information	19%
Conceptual Question	12%
Inviting	10%
Directing Attention	10%
Revoicing	7%
Experiential Question	6%
Repeating	5%
Recalling Shared Experiences	4%
Procedural Question	3%
Praise	2%
Requesting Information or Clarification	1%

Types of teacher talk that supported student sensemaking. In the sections that follow I will be focusing on five types of talk that were particularly generative in supporting student sensemaking and foregrounding student ideas. These were: directing attention, experiential questions, conceptual questions, inviting, and revoicing. (Note: I do not include Requesting Information/Clarification in my analysis below, as it made up only 1% of the total talk.)

Directing attention. Like Ms. Lane, Ms. Lawson frequently directed students' attention towards a particular part of the simulation that she wanted them to consider. As in Ms. Lane's instruction, this included general prompts designed to support observations (e.g. "What do you notice?" NFD2), specific prompts guiding students to look at a particular feature of the simulation (e.g. "Okay, now notice what is the value?" NFD1), and prompts encouraging student to notice how simulation features changed over the course of a scenario ("Do you see what's

[13] Does not include one-on-one conversations with individual students

happening with the speed?" NFD2). By directing students' attention, Ms. Lawson helped work towards two of the goals she had identified before teaching: (a) supporting the scientific practice of making careful observations, and (b) also supporting students' ability to interpret simulation representations by encouraging them to carefully examine the key visual features of the simulation. Furthermore, students' careful observations of the simulation became building blocks that students could draw from later in the lesson when they were interpreting and reasoning about different simulation scenarios.

Ms. Lawson supported students to make observations throughout both simulation lessons. However, she placed particular emphasis on having students make observations of the simulation at the beginning of the first lesson, before students first began to use the simulation. This was consistent with the recommendations in the MLs lesson plan, which suggest that students begin by observing the simulation. Ms. Lawson wanted to start the simulation lesson with a period of extended observation. This period of observation served several purpose: encouraging students to carefully observe text and visual features when preparing to interpret representations, doing an informal pre-assessment, checking if students noticed something that Ms. Lawson didn't, and keeping the start of the lesson open-ended and student-centered (see Table 4.9 below). Ms. Lawson made her goal of encouraging initial observations explicit for her students. She compared this previewing practice to pre-reading habits students were developing in Language Arts. While students made their initial observations of the simulation, Ms. Lawson told them "Look at the whole board because before we experiment with it, just like when we read, we should preview it, right?"

Table 4.9
Ms. Lawson's Reasons for Supporting Student Observations

Reason	Quote
Informal pre-assessment to gauge where students are.	"I also want to gauge where they are that day. [A] starting Point, do you know what I mean?"
Benefits to starting the lesson as open-ended instead of highly structured/teacher led, so that Ms. Lawson can follow up on student ideas.	"I don't want to lead too much. You know, S might raise their hand and say one thing, and then it goes off in one direction…"
Checking to see if students noticed parts of the simulation that Ms. Lawson did not notice.	"I am good with technology, but they are just so more open minded, as we know about kids. So that also is sometimes why I open with, 'tell me what you see'. Because they notice things that maybe I didn't at first glance…"
Encouraging students to get in the habit of observing text and visual features of representations when preparing to interpret representations	"[In language arts], it's so pushed, that pre reading activity. But that [previewing visual and text features] goes for math and science and social studies. And so I want them to take that moment and be that detective and really look at it….I wanted it to become that habitual part of their 'Okay, I'm going to look at this first before I jump in.'"

Experiential questions. Like Ms. Lane, Ms. Lawson used experiential questions to make connections between what was currently happening and previous experiences of students. Again, as in Ms. Lane's room, Ms. Lawson's experiential questions covered a range of experiences from general life or out-of-school experience ("Have you ever played with virtual reality? Maybe you went to a hands-on museum and they had it?" NFD1), to experiences from prior science lessons

(“What did we try [yesterday]?” NFD2), and experiences that occurred earlier within the same science lesson. (“What was the motion of the cart in S’s simulation?” NFD2) Most of these experiential questions made connections to other experiences in science class. However, Ms. Lawson had an explicit goal of making connections to out-of-school experiences (see Table 4.5, above) and deliberately chose to ask some questions eliciting students’ out-of-school experiences.

Conceptual questions. Like Ms. Lane, Ms. Lawson used conceptual questions to support students in engaging in scientific practices, support students to interpret simulation representations, support student understanding, and increase the cognitive demand of generating simulation scenarios. The similarity between Ms. Lane’s and Ms. Lawson’s conceptual questions was striking and may have been related to their frequent conversations with each other, as well as their access to the same MLs curriculum and PhET supports. Like Ms. Lane, Ms. Lawson supported students to engage in scientific practices with questions that encouraged students to make predictions (“Which way do you think the cart will travel?” NFD1), develop generalizable claims (“Listen, I'm taller than maybe one or two people in here and you might be stronger than me. Does size actually determine how strong somebody is?” NFD1), and support their ideas with reasoning (“Why do you think that?” NFD2).[14] Ms. Lawson supported students to interpret simulation representations with questions that pressed students to explain how they interpreted

[14] Note that when Ms. Lawson is trying to support students to make the claim that size is not an indicator of strength, she draws from evidence taken from the real world. (In addition to mentioning that some of her students might be stronger than she is, as shown in the above quote, she also compares the size and strength of several of her family members.) Ms. Lawson needs to use real world evidence, rather than simulation-based evidence to support this claim because the simulation evidence would support the erroneous claim that “bigger people are stronger than smaller people.”

different simulation features ("How did you know how much force each [person] was assigned?" NFD1).

Ms. Lawson checked for student understanding with questions that focused on key concepts and vocabulary. Concepts and vocabulary that she emphasized included: force, balanced force, unbalanced force, value, newtons, predictions, and simulations (e.g. "What does that mean, 'simulation?'" NFD1). Ms. Lawson said that she made a conscious effort to check in with students when introducing new concepts, because there was a wide range within her class in terms of students' vocabularies, and she wanted to make sure all students were able to access the science content. "I want to make sure that the vocabulary is there, because in science and social studies, they're so rich with the vocab and my class is so spread as you know, between like, vocabulary knowledge of kids that have and have not" (Lawson, SR).

Ms. Lawson also asked one conceptual question that increased the cognitive demand of using the simulation by specifically challenging students to set up a new kind of scenario ("Is there a way that we can make the force balanced but the people [on each side] aren't the same? NFD1). This final question was first proposed by me, as a suggestion near the end of day one, based on Ms. Lane's earlier success with giving students challenges to accomplish. Ms. Lawson quickly took up this question and posed it to the class, after briefly thanking me for the reminder and saying she had always planned to pose this challenge ("that's the one I was trying to remember" NFD1). However, as compared to Ms. Lane, Ms. Lawson spent less time posing challenges for students.

Ms. Lawson's use of conceptual questions helped her work towards many of the goals she identified during our pre-lesson conversation including (a) supporting students to understand unbalanced forces, (b) supporting students to interpret simulation representations, and (c) supporting students to make predictions supported by reasoning. It may be that having identified these goals ahead of time helped shape the nature and frequency of the conceptual questions that she asked the students.

Inviting, repeating, and revoicing. Ms. Lawson valued students' ideas and scientific interpretations, and continually worked to use student ideas to fuel the class conversation. Throughout the lesson, she invited students to share their ideas and questions. Most often, she did so by calling on students whose hands were raised. At one point, she specifically asked to hear from someone new and gave a personal invitation to a student who had not yet participated. ("I would like to hear from someone else…. like S, I would love to hear from you if you have an idea." NFD2). She also created multiple opportunities for students to share their ideas by voting with their thumbs ("If you think the cart will travel towards the right, put a thumb up" NFD2) and at one point gave students several minutes to turn and talk with their neighbor (NFD1). Once ideas were shared, Ms. Lawson often repeated them aloud – to make sure that all students could hear them. She also often revoiced student ideas, building and adding to the original idea.

Considering a student's responses to Ms. Lawson's sensemaking support. In the analysis above, I have focused on how different teacher moves supported student sensemaking at the sentence level. However, these different teaching moves did not happen in isolation. On the contrary, Ms. Lawson skillfully wove together different teaching moves to raise the cognitive level of the class discussion, monitor student understanding, and support students to interpret simulation representations.

> *Ms. Lawson: Why doesn't it go anywhere? They're all pulling the force, the force is there, but that cart is not going any-they're not moving, they're frozen and the only way that we know they're being pulled is because somebody noticed that pause needed to be...Sara*
>
> *Sara: 'Cause it's the balanced*

Ms. Lawson: Because it's a balanced force, how do I know that it's a balanced force? How do I know? Addy?

Addy: Yeah?

Ms. Lawson: What do you see up here?

Addy: They're all the same...

Ms. Lawson: That these are all the same size and we decided for our simulation that size did mean how much force was being pulled, and the numbers are the same, right? (NFD1).

In her first utterance, Ms. Lawson asks a conceptual question that presses students to explain why the car is not moving. Sara provides an answer that is accurate, but incomplete, and Ms. Lawson re-voices Sara's answer, changing it from "because it's the balanced" to "because it's a balanced force." The change is slight, but it reintroduces the concept of force into the conversation. Ms. Lawson then proceeds to press students to share what evidence from the simulation they are using to determine that the force is balanced. "How do I know that it's a balanced force?" When Addy seems confused, and only replies by saying "yeah," Ms. Lawson makes her question more concrete. "What do you see up here?" This time, Addy seems to understand the question more clearly and describes what she is seeing in the simulation. Ms. Lawson takes Addy's somewhat vague response, "they're all the same" and re-voices it to add more detail. "These are all the same size." Ms. Lawson then refers back to an earlier exchange with Terrence about size and strength and reminds the class that, within the specific context of this simulation, size is an indicator of force. In her final utterance, Ms. Lawson points out another way that the red and blue sides are the same. Not only are the figures the same size, but the numbers are also the same.

We see in this exchange how Ms. Lawson first asks a question that prompts for student reasoning, and then guides several different students to use evidence from the simulation as they answer. This not only supports scientific sensemaking, but it also supports students' ability to interpret simulation representations. Furthermore, these excerpts show how Ms. Lawson consistently makes connections between current conversations, and conversations from earlier in the lesson (in this case, referring back to Terrence's comment.)

In a later interview, Ms. Lawson reflected that Terrence was one of the smallest students in the classroom, but also likely one of the strongest. She wondered whether, in future years, the small but strong children would likewise speak up for themselves saying, "Wait a minute. Hello! I'm really strong too" (Lawson, SR). In other words, Ms. Lawson noted potential for something that could be a limitation of the simulation (its inaccurate correlation between height and strength) could actually enrich the simulation lesson, by giving students the chance to use their own personal experience to correct the simulation.

Considering the Relationship between Instruction and Curriculum.

Both Ms. Lane and Ms. Lawson engaged in a number of practices to support student sensemaking while working with the Net Force Simulation including: directing student attention, helping students make connections to previous experiences and asking many different types of conceptual questions (e.g. questions designed to support different scientific practices or questions designed to help students interpret simulation representations.) As described in Chapter Three, practices were explicitly suggested in the MLs support material provided to Ms. Lane and Ms. Lawson.

However, Ms. Lane and Ms. Lawson also improvised on the MLs support material in two key ways. First, they chose to teach the Net Force lesson over two days, instead of over one day.

Second, and related, they chose to give students a long period of exploring the simulation on individual devices (Chromebooks) or laptops. They made these decisions so that students would have the opportunity to experience the simulation directly, rather than simply watching the teacher manipulate the simulation.

In addition to drawing from and expanding on ideas provided in the MLs support materials, Ms. Lane and Ms. Lawson both capitalized on advantages provided by the Net Force Simulation design. For example, Ms. Lane gave students engineering style "challenges" to complete using the simulation. (E.g. How fast can you make the rope go?) The Net Force Simulation lent itself well to challenges because the simulation had a definite point when it "ended" – and conditions at the ending point could be observed.[15] Ms. Lane and Ms. Lawson both also used key features from the Net Force Simulation (such as the length of the arrows) to help support students to interpret visual representations.

What are the Teachers' Perspectives Regarding the Use of the Net Force Simulation as a Sensemaking Tool?

So far, the data analyzed have addressed the first research question. In the section below, I turn to my second research question, which addresses teacher perspective on the value of the simulation as a sensemaking tool.

The perspective of Ms. Lane. Ms. Lane had positive things to say about the Net Force Simulation before, during, and after teaching it (See Table 4.10 for full quotations). Before teaching, Ms. Lane commented that her students had taken to the simulation from the very first year that she taught it, even though she had personally struggled with the simulation during her

[15] E.G. which team (if any) won when the simulation ended? How fast was the rope going when the simulation ended? What was the composition of the winning team? The losing team?

first enactment. While teaching, Ms. Lane commented to me that the Net Force Simulation is always “a bit hit.” She also shared that because her own comfort with the simulation was higher this year, she was going to give student time to explore the simulation individually on their Chromebooks. After teaching, Ms. Lane commented that she thought that students had really learned the idea of balanced and unbalanced forces, both from their work with the simulation and from the physical experiments they did in class. She also shared that in future years, she would like to have students write down a claim or a question in their notebook, following their work with the simulation. Ms. Lane felt that the Net Force Simulation was supportive of student learning and recommended that it stay in the MLs curriculum.

Table 4.10
Ms. Lane’s reflections before, during, and after Teaching the Net Force Simulation

Time	Quotation
Before Teaching	“I can't think of anything else. I think that the first year I taught it I struggled. So, they kind of got it . . . I [didn’t]” (Lane, NF)
While Teaching	“Oh, it's always such a big hit. And I felt more comfortable with it this year, so I was hoping they could go on their Chromebooks because they all have some very cool ideas.” (NFD1)
After Teaching	“Balanced and unbalanced, I feel like they really nailed down pretty well… [for next year] an exit ticket [or] it could be in a notebook, do you know what I mean? Like, I'll have to talk to Ms. Lawson about, about doing that a little bit more consistently. Writing a claim or writing at least one question,” (Lane, SR)

The perspective of Ms. Lawson. Ms. Lawson had positive things to say about the Net Force Simulation before, during, and after teaching with it. (See Table 4.11 for Ms. Lawson’s quotes given before, during and after the simulation). In our pre-interview, she reflected on her experience teaching the simulation during the previous year. She said that she particularly valued the simulation because "The kids can actually make something happen… It sticks with them.

They will remember it" (Lawson, NF). While teaching with the simulation, Ms. Lawson made an aside comment to me reflecting on how quickly the students came to the front of the room once they saw the simulation. She said that she had never seen the students move to the front of the room so quickly and efficiently. "I can already tell the engagement level," she said.

After teaching the simulation, Ms. Lawson cited two specific benefits of the simulation. First, she appreciated its interactivity, which she felt made the simulation interesting for students to work with. Second, she reported that working with the simulation helped students to master the concept of balanced and unbalanced forces. While she acknowledged the simulation was not a perfect representation, citing that its treatment of weight was not entirely accurate, she still felt that it helped students learn. Furthermore, Ms. Lawson reported that students who sometimes felt "disenfranchised" had showed a lot of enthusiasm in working with the simulation. In particular, she mentioned that Terrence often felt angry during the day but was highly engaged and happy while working with the simulation. In fact, Ms. Lawson felt that some of the students who were least likely to feel "in their niche" during other parts of the day, were some of the students who were the most engaged and enthusiastic while working with the simulation: "To see that [enthusiasm] out of kids who are sometimes disenfranchised… Is really really cool" (Lawson, SR).

Table 4.11

Ms. Lawson's reflections before, during, and after teaching the Net Force Simulation

Time	Quotation
Before Teaching	"Like I said, loved this unit. And I love the simulations …this lesson and the other lesson are wonderful because the kids can actually make something happen. And I think whenever they can [make something happen], whether it's on a Smart Board, or you know, this authentic experience of a lab or building a toy, it sticks with them. They will remember it, so yeah, I think the simulations are great" (Lawson, NF).
While Teaching	"It's funny because I can already tell like the engagement level cause whenever I do that it's usually like, okay we'll come up to the front, but I actually have a planet sliding out of the way" (NFD1).[16]
After Teaching	"I find the simulations to be very supportive of student learning. . . I think with anything, there are some flaws that we found, right? Like we know that like weight isn't really a factor in the forces one….But I do think that with the forces simulations, them seeing that really gave them a better understanding of balanced and unbalanced…And I think that today's learners, anything that adds that component of technology, but that interactive technology is really, really, really beneficial, because they like grab on to them. So, like, during our, even during our free times, things like simulations can be woven into those free times or during our independent work times. And they're interesting for the kids, because they have the interactive component, but they also are reinforcing the concepts directly that we're setting. Right. So yeah, I absolutely think that simulations are supportive of student learning" (Lawson, SR).
	"Yeah, I did [enjoy teaching with the simulation]. I would, I would probably do it the same way, trying things out at the smart boards. I'm going to work on getting that revamped. In fact, I don't know what's going on with smart boards in our district. But trying it out as best we can on this on board interacting with that, having them up at the carpet, like all the comfortable places they're sitting, and then having them try it on their own computer. I think that that was that's something that I didn't do last year, at least I don't think I did. We just did it on the SMART Board. And I really liked doing it on their computers as well" (Lawson, SR).

[16] Note- here "planet refers to a cluster of student desks. Ms. Lawson is saying that students spontaneously moved their desks to create more space for the whole class to sit at the front of the room and watch the simulation.

After teaching the Net Force Simulation, Ms. Lawson shared that her only concern with teaching with the simulation was Smart Board malfunctions. She had anticipated this problem before teaching the simulation and it did occur when she taught the simulation. She said that she hoped that the district would fix the Smart Boards soon.

Ms. Lawson recommended that the Net Force Simulation stay in the next revision of the MLs curriculum and said that she plans to teach it next year. Her reasoning was that the concepts in the simulation fit conceptually with the rest of the unit, "Well, for forces, I think it goes so hand in hand, that they were able to use what they know. I think that's really important …being able to either test their toys, and then test the simulation - are we seeing the same thing? Or try it out on the simulation, and then use what they've learned for that [testing the toys]. I think that's really important" (Lawson, SR.)

Summary of Key Points in Relation to Research Questions

This chapter first asks *How do teachers support student sensemaking while working with the Net Force Simulation? How do students respond to this support?* Findings in this chapter suggest that Ms. Lawson and Ms. Lane leveraged suggestions in both (a) the curricular supports and (b) key simulation features as they supported student sensemaking through a variety of moves including: directing student attention, asking different types of conceptual questions, and supporting students to make connections with their past experiences. In addition to talk that directly supported sensemaking, the teachers also engaged in talk that helped set conditions that could support sensemaking (for example by setting norms and expectations.) Students and teachers engaged in dialogues where both worked together to co-construct ideas, with the teacher supporting students to both share new ideas and to develop their ideas more fully. The chapter then asked *What are the teachers' perspectives regarding the use of simulations as sensemaking tools?* Both Ms. Lane and Ms. Lawson felt that the Net Force simulation both (a) engaged students and (b) supported student learning.

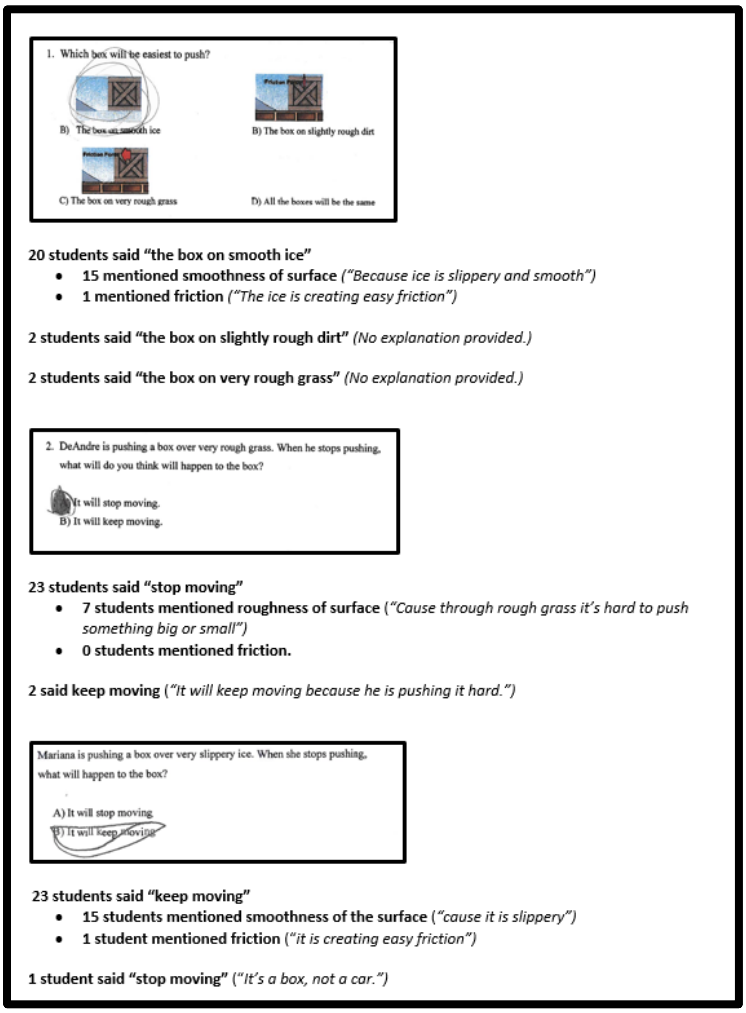
CHAPTER 5 The Friction Simulation

This chapter focuses on the Friction Simulation. It is organized by the study's two research questions. It begins by considering the first research question: *How do teachers support student sensemaking while working with the Friction Simulation? How do students respond to this support?* It constructs a case of how each teacher supports student sensemaking in her classroom. Each case contains the following sections (a) how the teacher prepares to support sensemaking prior to beginning teaching, (b) an overview of how the teacher enacted the simulation-based lesson, (c) a closer look at types of teacher talk that specifically supported sensemaking (d) an illustrative example of how student(s) responded to the teacher's sensemaking support, and (e) the relationship between the teacher's instructional decisions and the support provided by both the simulation and the MLs curriculum. The chapter then moves to consider the second research question: *What are the teachers' perspectives regarding the use of the Friction Simulation as a sensemaking tool?* The chapter concludes with a brief summary of key findings that relate to each of the two research questions.

How does Ms. Lane Support Student Sensemaking while Working with the Friction Simulation and how do Students Respond to this Support?

The following section considers how Ms. Lane supported student sensemaking both through careful pre-planning and through instructional decisions that she made while teaching.

How Ms. Lane prepared to support student sensemaking prior to teaching. Figure 5.1 shows the overview document that I brought to my meeting with Ms. Lane, which summarized how her students had responded to each of the questions on the pre-test. For each item, the majority of the students correctly predicted which box would be easier to move or whether the box would continue to move. However (a) only a few students mentioned friction when explaining their reasoning, (b) students were much more likely to cite “smoothness” as a factor in their reasoning than “roughness,” and (c) some students either made incorrect predictions or left an item unanswered.


1. Which box will be easiest to push?

B) The box on smooth ice

B) The box on slightly rough dirt

C) The box on very rough grass

D) All the boxes will be the same

20 students said “the box on smooth ice”

- **15 mentioned smoothness of surface** *(“Because ice is slippery and smooth”)*
- **1 mentioned friction** *(“The ice is creating easy friction”)*

2 students said “the box on slightly rough dirt” *(No explanation provided.)*

2 students said “the box on very rough grass” *(No explanation provided.)*

2. DeAndre is pushing a box over very rough grass. When he stops pushing, what will do you think will happen to the box?

A) It will stop moving.
B) It will keep moving.

23 students said “stop moving”

- **7 students mentioned roughness of surface** (*“Cause through rough grass it’s hard to push something big or small”)*
- **0 students mentioned friction.**

2 said keep moving (*“It will keep moving because he is pushing it hard.”)*

Mariana is pushing a box over very slippery ice. When she stops pushing, what will happen to the box?

A) It will stop moving
B) It will keep moving

23 students said “keep moving”

- **15 students mentioned smoothness of the surface** (*“cause it is slippery”)*
- **1 student mentioned friction** (*“it is creating easy friction”)*

1 student said “stop moving” (*“It’s a box, not a car.”)*

Figure 5.1 Pretest overview for Ms. Lane’s class.

As with the Net Force Simulation pretest, Ms. Lane read the friction pretests with an eye towards unpacking potential student reasoning. In particular, as she read through answers that were not “correct,” she tried to imagine how students might have come to that answer. For example, two students said that the box on rough grass would keep moving after DeAndre stopped pushing. After reading these responses, Ms. Lane said, “these makes sense… they'd be able to connect some rationale…in real life, if you're pushing something really hard, if you keep pushing really hard, usually, that thing is going to go [for a little bit]” (Lane, FR). Ms. Lane added that looking at the pretest results made her think about how standardized tests can give an inaccurate picture of students’ abilities, because they may focus entirely on accuracy at the expense of giving students credit for thoughtful reasoning.

When Ms. Lane saw that many students mentioned the “smoothness” of the surface as evidence to support their prediction, while fewer students mentioned the “roughness” of the surface, she hypothesized that this might be a vocabulary issue. She said that just the other day, her own daughter had asked her to define the word “rough.” She pointed out that rough could be a challenging word to understand because “it has multiple meanings…that exam was rough. That road was rough.” She thought that students might have an easier time understanding a word like “bumpy.” She said that when teaching the simulation, she did plan to use the word “rough,” but that she was also going to discuss its meaning, to make sure that all students understood.

During the same interview, Ms. Lane articulated her goals for student learning (see Table 5.1). Her first goal was that students would understand the concept of friction and how friction can cause an object to stop moving. While her first goal was related to content, her second goal was related to sensemaking. She wanted to support students to move from concrete to abstract thinking, for example, by making generalizable claims based on the evidence from the simulation.

Table 5.1

Ms. Lane's Goals for the Friction Simulation

Conceptual Goal	Quote
Students will understand that the force of friction can cause an object to stop moving	"What do you think made it stop...there's still a force going against it, friction being that force" (Lane, FR)[17].
Students will have the opportunity to engage in abstract thinking.	"Some of them are still such concrete thinkers. And we want to evolve that" (Lane, FR).

When asked about potential challenges that might occur as students worked with the simulation, Ms. Lane mentioned two concerns, both related to students' focus (see Table 5.2). Her first concern was that students might click their way around the simulation without paying attention or thinking about what they are doing. Her second concern was that students might become distracted by the fact that, under certain simulation conditions, the figurine applying force will do the splits and let go of the box. She was concerned that students would want to have the figure do the splits, over and over again, instead of fully exploring the simulation.

Table 5.2

Ms. Lane's Concerns about the Friction Simulation

Potential Challenges/Concerns	Quote
Students engage with the simulation procedurally but not conceptually	"Hopefully, they're not just moving things without paying attention to what they're doing" (Lane, FR).
Students become distracted by non-salient features of the simulation	"[It's] super distracting because then all they want to do is make the person to the splits, right? It's all they want to do" (Lane, FR).

[17] Friction interview

During the same pre-meeting, Ms. Lane laid out how she planned to support student sensemaking to help them reach her conceptual goals, while avoiding potential concerns. The teaching moves that she identified (see Table 5.3 below) are consistent with her goals of both supporting students to understand friction and supporting students to engage in abstract thinking while working with the simulation. Her plans also go above and beyond the support and suggestions provided by the MLs curriculum for the Friction Simulation, while still remaining consistent with the "spirit" of both the MLs curriculum and the PhET suggestions. In particular, Ms. Lane decided that she would take the idea of "fair tests," which was introduced in a previous MLs lesson, and use it to structure how students interacted with the Friction Simulation. By doing so, Ms. Lane added additional coherence to the MLs unit, while giving students additional time to engage in an important scientific practice. Her incorporation of fair tests is also consistent with the PhET recommendation of supporting students to set up scenarios and then interpret the results, while also "upping the ante" by adding in the additional cognitive challenge of controlling variables while setting up scenarios.

Table 5.3

Ms. Lane's Plans for Supporting Student Sensemaking

Plan for supporting sensemaking	Quote
Support students to observe ways that this simulation is different from the previous simulation	"This is similar to the simulation we did the other day. But what do you notice is different? Somebody's going to notice that you can, you know, change the surface. Or that you can put things on top . . ." (Lane, FR).
Support students to make important observations themselves, rather than simply telling them about important parts of the simulation.	"If it doesn't come, I may mention something, but I'd rather it come from them" (Lane, FR).
Discuss purpose of the simulation	"Have a little bit of conversation about 'Why did we make a simulation for this?' (Lane, FR).
Model a scenario with the simulation and then give students time for individual explorations	"Doing a couple examples .And then probably less whole group examples …the first one we did a lot of whole group and so this one, go back to your seat, kind of play around with it" (Lane, FR).
Support students to engage in fair tests (only changing one variable at a time.)	"We could tie it into, okay, if we're going to do a fair test…[if you change the friction], then the weight and the amount of force has to be the same… do some fair tests and make some observations" (Lane, FR).
Inviting students who are using the simulation successfully to give suggestions/ideas to students who are distracted or confused.	"If I'm starting to see stuff, maybe not go the way it's supposed to, or some kids are really getting it and some kids aren't. We can come together and say, 'okay, so as I'm walking around and seeing… wow, you're really creating some fair test you have some noticings, Let's talk about that for a minute. So that those that maybe aren't seeing it yet, can get some ideas from you" (Lane, FR).
End the lesson with a discussion about what students noticed and learned.	"Ideally, I would like to have a longer science session at the end of science as opposed to the beginning . . . 'what sorts of things were you noticing?' having the simulation up. IF, some people are like, 'No, that's not what happened.' we can go, 'so let's test that out'" (Lane, FR).

Overview of Ms. Lane's enactment of the Net Force Simulation lessons. On the first day, Ms. Lane opened the lesson with a review discussion of the Net Force Simulation, which included a conceptual review of both "forces and "newtons." Then, she transitioned into discussion of the features of the Friction Simulation. This helped support Ms. Lane's plan of having students observe ways that the Friction Simulation differed from the Net Force Simulation.

Also as she had planned, Ms. Lane deliberately let students take the lead in the discussion of the features of the Friction Simulation, so that students could make important discoveries for themselves. During this discussion, students identified and explained many features of the simulation, including several features that Ms. Lane herself either had temporarily forgotten about or had never discovered. (For example, students noted that there were two different ways to increase the applied force – whereas Ms. Lane only knew one way to increase applied force.)[18] After this discussion, Ms. Lane gave students time to explore the simulation individually. At the end of the day, Ms. Lane expressed to me that she was concerned that students might have been clicking at random, rather than making intentional choices. (Recall that Ms. Lane expressed concern about this, during our pre-lesson conversation). Ms. Lane closed the lesson by telling students that the second day of simulation exploration would be more structured. "What I want to make sure is that you understand the connection between the friction, the mass, the forces. There's a reason all of those items are on this simulation, right? It's important that you understand how they kind of work together or against each other. So it's fun to play with it… But I also am

[18] Note: the full PhET teacher explanation page did include an explanation for different ways to increase applied force. However, this explanation was not included in the abridged PhET teacher page made available to Ms. Lane and Ms. Lawson through the MLS project. I remedied this omission in the 2018-2019 materials provided to Ms. Lane and Ms. Lawson: they now have access to the full PhET teacher support materials.

going to try to come up with some challenges between now and tomorrow that force you to kind of see the connection between these items. Okay?" (FRD1).[19]

On the second day, Ms. Lane began with a review conversation that included discussion of friction and of fair tests, consistent with her plans to focus on fair tests while using the Friction Simulation (See Figure 5.2 and Figure 5.3 for the notes Ms. Lane made on the board during this discussion.) She and her students discussed what they had learned in previous lessons about why it is important to only change one variable at a time. Then, the class made a list of the variables that could be changed in the Friction Simulation: mass, applied force, and friction (see Figure 5.4). As a class, they ran several fair tests together. Then, Ms. Lane gave students time to explore the simulation individually while conducting fair tests.

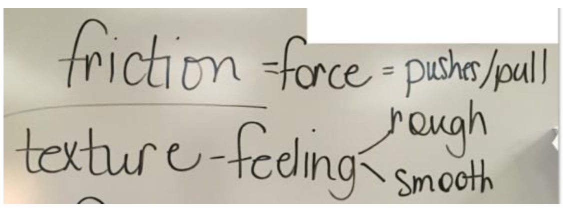


Figure 5.2 Whiteboard notes from day II review discussion

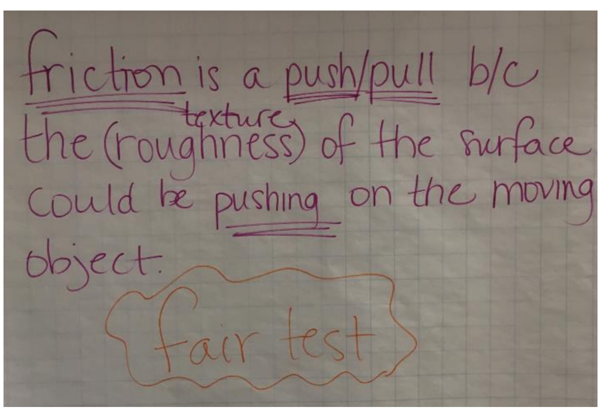


Figure 5.3 Chart paper notes from day II review discussion

[19] Friction lesson, Day 1

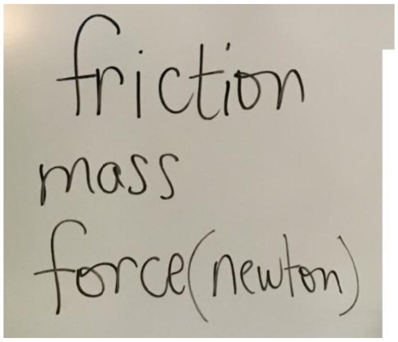


Figure 5.4 List of the three variables that can be changed in the Friction Simulation.

On the third day of science, Ms. Lane began with a review discussion focusing on what the class had done and learned on the past two days. She then supported students to make claims based on what they had learned in the simulation. (See Figure 5.5 for a list of the claims co-constructed by Ms. Lane and her students.) Near the end of the lesson, her students became very interested in determining the mass of the “mystery box” (see Figure 5.6). Ms. Lane supported her students to figure out how they could determine the mass of the box, even though it meant that science ran nearly fifteen minutes over time. Even then, Ms. Lane’s students protested ending science class, and Ms. Lane promised them the option of exploring the simulation the next day, during centers time.

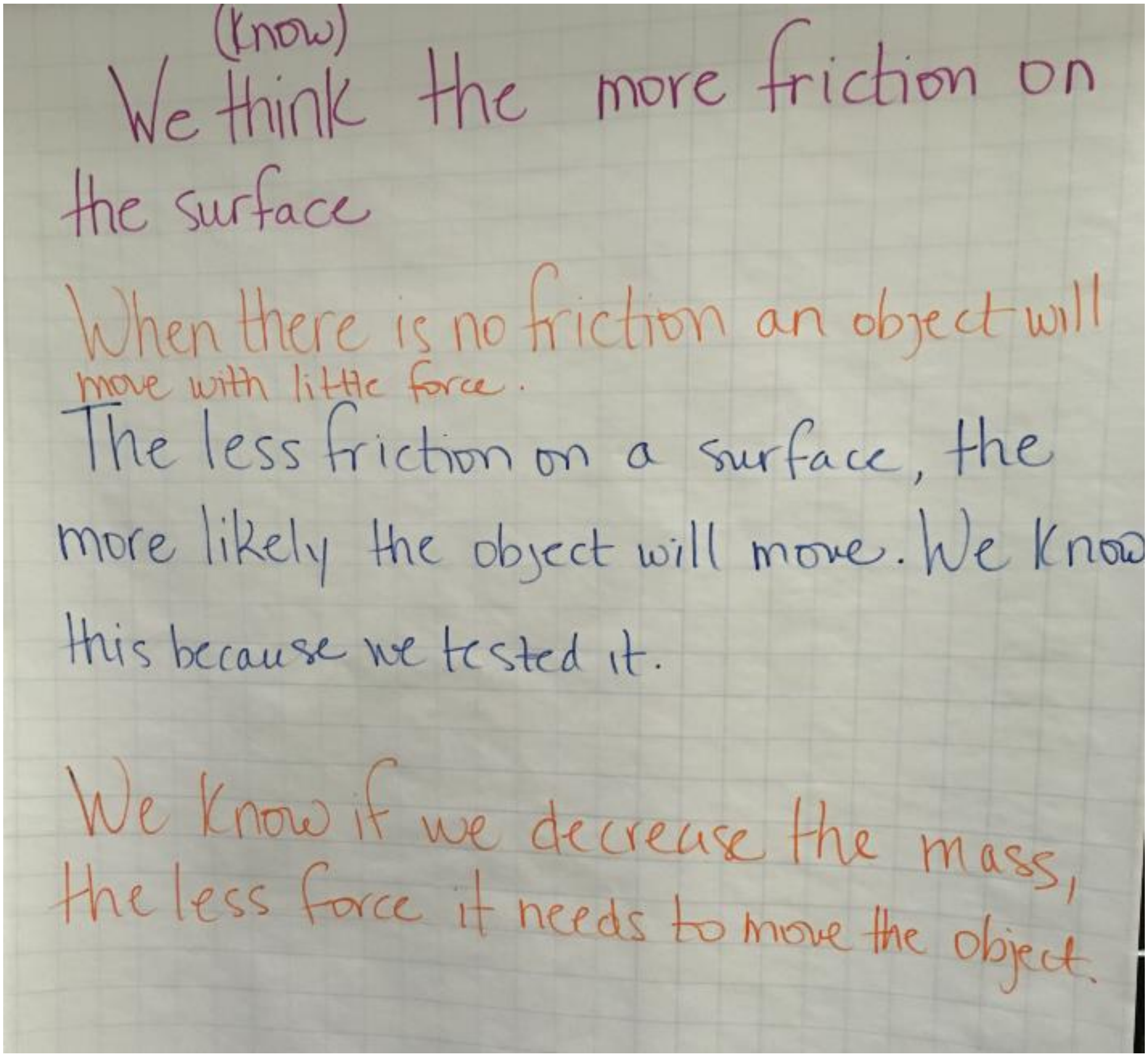


Figure 5.5 Co-constructed claims based on the Friction Simulation

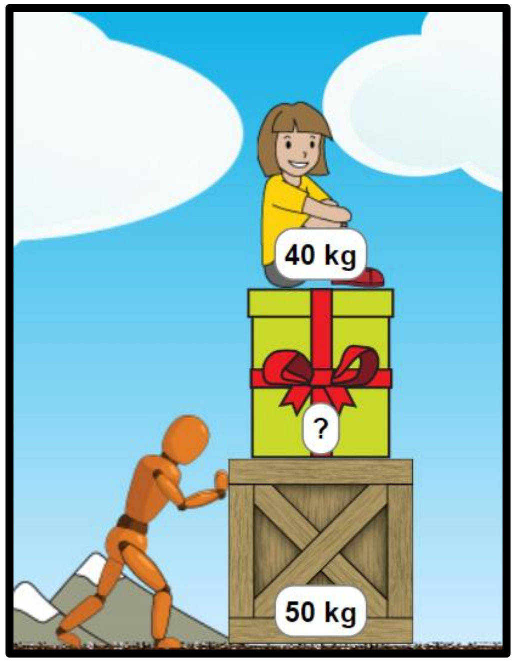
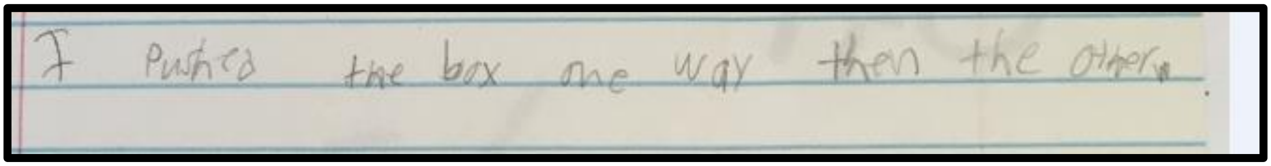


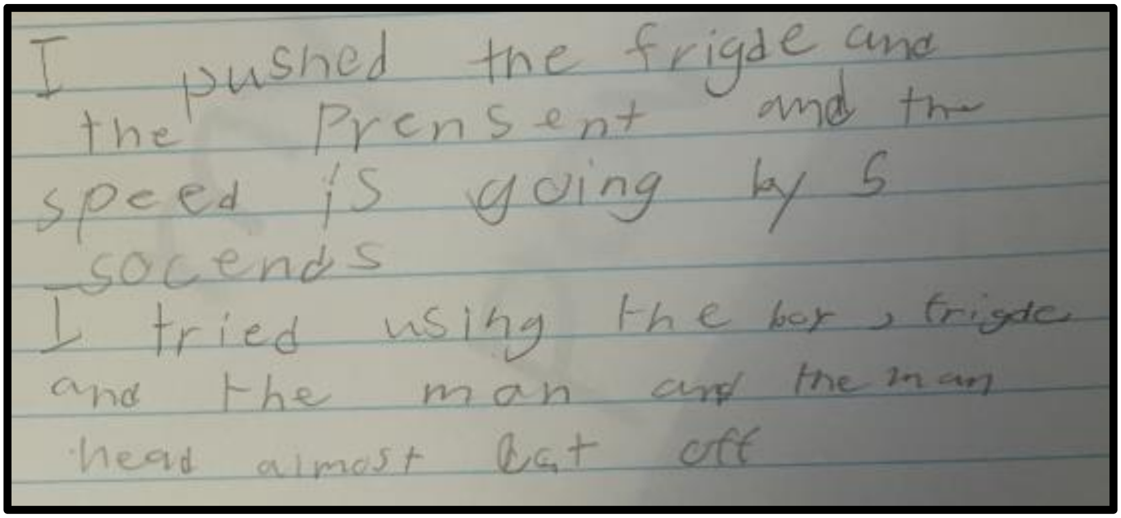
Figure 5.6 The “Mystery Box” in the Friction Simulation has an unknown mass.

On the fourth day, Ms. Lane gave students the option to explore the simulation for up to twenty minutes during centers time, provided they took notes as they worked. Many students took her up on this offer. The pictures below show photos of the notes taken by focal students. Recall that the focal students represented the full range of literacy levels in Ms. Lane’s class, as measured by reading levels. In looking at the focal students’ self-directed note-taking, we see a range of length/complexity that goes from a list of numbers (Kendra), to a short descriptive statement (Jett), to a longer descriptive statement (Davon), to a claim supported by evidence (Mary). When Ms. Lane asked students to write as they used the simulation, every student using the simulation found a way to write. However, the students did not chose to record the same types of information nor did they include the same degree of detail.



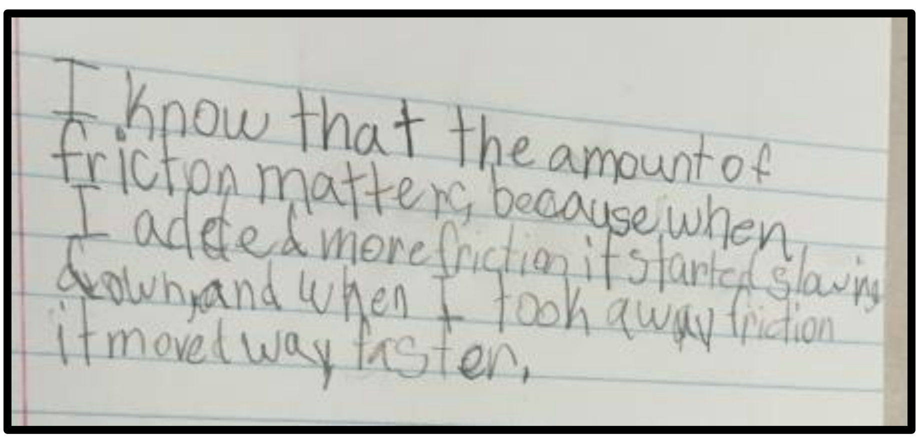
I Pushed the box one way then the other.

Figure 5.7 Jett's notes



I pushed the frigde and the Prensent and the speed is going by 5 socends
I tried using the box, frigde and the man and the man head almost cat off

Figure 5.8 Davon's notes



I know that the amount of fricton matters, because when I added more friction it started slowing down, and when I took away friction it moved way faster.

Figure 5.9 Mary's notes

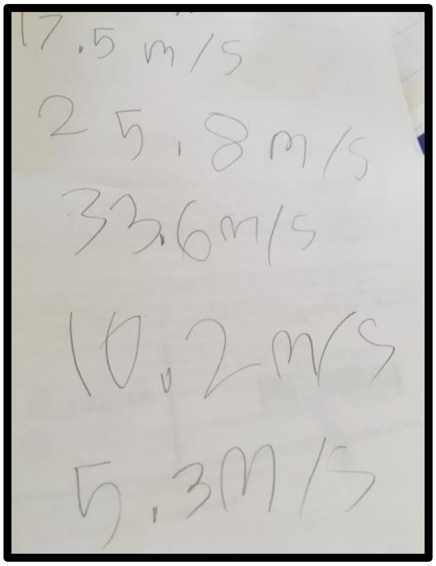


Figure 5.10 Kendra's notes

Table 5.4 shows the breakdown of Ms. Lane's talk during whole-class instruction with the Friction Simulation. Again, we see that conceptual questions are among her most common types of talk. This is not surprising, given how many of Ms. Lane's pre-lesson goals and plans centered around supporting students to engage in sensemaking about science concepts.

Table 5.4

Ms. Lane's Talk during the Friction Simulation Lessons[20]

Talk Type	Frequency
Providing Information	24%
Conceptual Question	17%
Directive or Discussion Etiquette	13%
Experiential Question	9%
Directing Attention	8%
Recalling Shared Experiences	7%
Inviting	6%
Repeating	5%
Requesting Information or Clarification	4%
Revoicing	3%
Procedural Question	3%
Praise	1%

[20] Does not include one-on-one conversations with individual students

Types of teacher talk that supported student sensemaking. As in the previous chapter, in the sections that follow I will be focusing on types of talk that supported student sensemaking: directing attention, experiential questions, conceptual questions, inviting, requesting information or clarification, and revoicing.

Directing attention. As discussed above, Ms. Lane followed her plan to open the Friction Simulation lesson by first inviting students to compare features of the Net Force and Friction Simulations and then encouraging student to take the lead in observing the Friction Simulation. Thus, much of Ms. Lane's directing of student attention occurred near the beginning of the lesson. Ms. Lane also continued to direct student attention throughout the friction lesson, ranging from general prompts designed to support observation ("What else do you notice?" FRD1), to prompts guiding students to look at a particular feature ("look right here" FRD2), to prompts encouraging student to notice how simulation features changed over the course of a scenario ([When] we hit go, what's happening to the speed? FRD1).

Ms. Lane's support of student observations had a measurable effect on how students used the simulations. Before the lesson, I gave focal students time to explore the simulation. During this pre-lesson exploration time, three of the focal students did not ever adjust the friction setting and two of the focal students adjusted the friction, but never set it to zero. Later, after participating in Ms. Lane's guided observation, all five focal students adjusted the friction setting, including turning the friction off. (Note: the sixth focal student wasn't present for the whole lesson.) This indicates that Ms. Lane's whole-class guided observation session substantially changed how students interacted with the simulation, in ways that would increase chances for learning. It would be very difficult for students to use the Friction Simulation to learn about friction if they never adjusted the levels of friction within the simulation.

Experiential questions. Recall that Ms. Lane shared that she liked to begin each science lesson with a student-led review discussion of previous science learning. She felt this discussion supported all students, but especially supported English Language Learners and students with special needs, because it provided a review of key concepts and vocabulary. Because of this practice, she used many experiential questions near the beginning of each lesson. Additionally, Ms. Lane wove experiential questions throughout the lesson to help students make connections between their current work and their previous experiences. As in the case of the Net Force Simulation, these included questions about experiences from prior science lessons ("What did we start talking about on Thursday, guys?" FRD1) and experiences that occurred earlier within the same science lesson ("What did we have before?" FRD3). In particular, Ms. Lane made many connections to a previous science lesson entitled *The Balloon Rocket Lesson*, in which students had both read about and witnessed physical demonstration of the effect of friction. Ms. Lane connected back to the Balloon Rocket both because it introduced the concept of friction and because it introduced the concept of conducting "fair tests" (i.e. controlling variables.)

Conceptual questions. As mentioned earlier, Ms. Lane made many plans for supporting students' conceptual sensemaking, which she then enacted by asking frequent conceptual questions. Ms. Lane shared that the reason that she asked these questions was to focus students on the important concepts to help them interact with the simulation as a learning experience rather than a game. After watching a clip of herself asking conceptual questions, she commented "I think sometimes they see it just as a video game, you know what I mean? So [I'm] trying to get them away from this is a game on a screen. There's actually a purpose here. Let's tie it back into friction" (Lane, SR).

Many of Ms. Lane's conceptual questions were geared towards supporting students to engage in scientific practices including: making predictions ("do you think it will eventually move?" FRD3), supporting their ideas with reasoning ("Why do you think it'll move?" FRD3), and developing generalizable claims ("In order to get an object to move, does there have to be a force?" FRD3). In the post-lesson interview, Ms. Lane described how she moved from asking students to make predictions to running scenarios to test students' predictions. She noted that not all the students had the same predictions and that, as students watched the scenario run, they commented aloud regarding whether their prediction had been accurate. "[I was] asking them questions, and letting them answer and they didn't all have the same answer [prediction]. Some said faster, some said bigger, some said slower . . . Well, this is what actually [happens]… -- you can hear either the [students saying] 'oh, I was right' or 'oh, no, it's doing this instead.'" In the same interview, Ms. Lane commented how important it was for students to be able to support their ideas with reasoning. "[There's] so much of that 'well, because.' So I'm really trying to reinforce that if you're going to if you're going to make a claim, if you're going to say something, [you need to] have proof to back it up not just 'because.'" (Lane, SR).

One scientific practice that Ms. Lane particularly focused on was controlling variables. Before teaching this lesson, Ms. Lane decided that she wanted support students to conduct "fair tests" while working with the simulations. Many of her conceptual questions were focused on how to conduct a fair test and why fair tests are important ("What are some ways we can conduct a fair test?" FRD2). This focus on fair tests increased the cognitive demand for students as they worked with the simulation. As in the case of the Net Force Simulation, Ms. Lane also upped the cognitive demand by giving students specific challenges ("What would I have to do to get it to stop?" FRD3). However, Ms. Lane did not give as many specific challenges for the Friction Simulation as she did for the Net Force Simulation; instead, she focused on "fair tests" as a way to guide students exploration of the simulation.

Inviting, requesting clarification, repeating, and revoicing. The combined frequency of these four moves (18%) speaks to the extent to which Ms. Lane valued student contributions and ideas. As with the Net Force Simulation lessons, Ms. Lane used inviting to bring students into the conversation. In addition to calling on students who had raised their hands, Ms. Lane also invited students to share their ideas through turn and talks and through thumbs up/thumbs down voting ("Who else agrees with Jessica?" FRD3)." Again, as in the Net Force Simulation, Ms. Lane valued understanding students' ideas and would ask for clarification if she wasn't sure what students meant ("What do you mean we didn't use friction?" (FRD1) Ms. Lane used repeating and revoicing to amplify and expand on student ideas, which helped make sure that all students could both hear and understand their classmates' ideas. In the following example of revoicing, we see how Ms. Lane builds off of a student's idea by adding more detail.

S: More force

Ms. Lane: There's more force pulling against it this time (FRD1)

Considering a student's responses to Ms. Lane's sensemaking support. As in the previous chapter, I end the analysis of Ms. Lane's teaching of the Friction Simulation by unpacking a longer stretch of classroom talk.

Mary: Friction could be a push or a pull because … the roughness is kind of pushing on whatever the...whatever thing that's creating friction.

Ms. Lane: Okay, say it one more time.

Mary: Friction is could be a push or a pull because the roughness of whatever surface is could be pushing on the object.

Ms. Lane: Okay. Do you guys understand what Mary's saying?

Students: Yes.

Ms. Lane: Could somebody repeat it? Can somebody kind of say what she said in their own words? Because we said, yeah we understand it. It's one thing to say, yeah we understand it. But do we understand it enough that we can kind of explain it in our own words? Brittney?

Brittney: The softness of...pushing and pulling the thing…will affect how it moves.

Ms. Lane: Okay. Mary, would you agree with that? Does that sum up a little bit of what you said? The softness of what you're pushing it on will affect how it moves? (FRD2)

In the above excerpt, Ms. Lane is checking to make sure that students are understanding a classmate's contribution. Mary is explaining the complicated idea that friction could be considered either a push or pull because the roughness [of the surface] is pushing on whatever is trying to move [across the surface]. Mary's thought is initially a little unclear. When Ms. Lane asks her to repeat her thinking, Mary adds more detail. Instead of saying the roughness, she says "the roughness of whatever surface" and instead of saying "whatever thing" she says "the object."

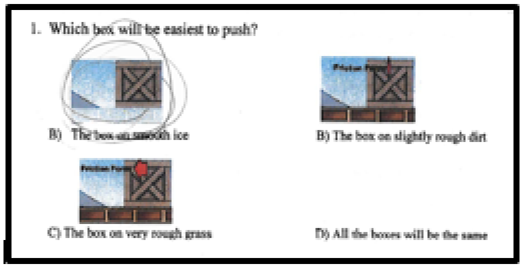
Once Mary's idea is a little clearer, Ms. Lane asks the class if they understand Mary's idea. Everyone says that they do. Ms. Lane cautions them that it's easy to say that you understand something, but one way to test whether you really understand something is whether you can say it in your own words. She then invites Britney to re-voice Mary's contribution. Brittany's rewording is less specific than Mary's statement, but Ms. Lane does not correct Britney. Instead, Ms. Lane revoices Britney's contribution to make it a little clearer and then asks Mary if she agrees that Britney has summarized her contribution.

In this brief exchange, Ms. Lane is (a) supporting students to increase their understanding of what it means to consider friction to be a specific type of force, within the context of the class's definition of force as "a push or a pull," (b) teaching her students the value of repeating their classmates' ideas to make sure that they've understood their classmates accurately. And she does this, (c) treating both Mary and Britney's ideas with respect, and (d) giving the rest of the class the opportunity to hear the same idea stated in several different ways. This is typical of how Ms. Lane supported her students to clarify their own ideas and build off of each other's ideas during all of the simulation lessons, and indeed, during all of science class.

How does Ms. Lawson Support Student Sensemaking while Working with the Friction Simulation and How do Students Respond to this Support?

The following section considers how Ms. Lawson supported student sensemaking both through careful pre-planning and through instructional decisions that she made while teaching.

How Ms. Lawson prepared to support student sensemaking prior to teaching. Figure 5.11 shows the overview document that I brought to my meeting with Ms. Lawson, which summarized how her students had responded to each of the questions on the pre-test. As in Ms. Lane's class, for each item, the majority of the students correctly predicted which box would be easier to move or whether the box would continue to move. However, (a) only a few students mentioned friction when explaining their reasoning, (b) students were slightly more likely to cite "smoothness" as a factor in their reasoning than "roughness," and (c) some students either made incorrect predictions or left an item unanswered.


1. Which box will be easiest to push?

B) The box on smooth ice

B) The box on slightly rough dirt

C) The box on very rough grass

D) All the boxes will be the same

20 students said “the box on smooth ice”

- 13 mentioned smoothness of surface *(“because ice is slippery”)*
- 1 mentioned friction *(“ice has no friction”)*

1 student said “the box on slightly rough dirt” *(“Because it will be easy to push”)*

1 student said “all boxes will be the same” *(“It will make a platform”)*

2. DeAndre is pushing a box over very rough grass. When he stops pushing, what will do you think will happen to the box?

A) It will stop moving.
B) It will keep moving.

21 students said “stop moving”

- 10 students mentioned roughness of surface (*“because rough grass is hard to push on”)*
- 2 students mentioned friction. (*“because there’s a lot of friction on grass”)*

1 said keep moving (*“ice is very slippery”)* – I think that student misread the question?

Mariana is pushing a box over very slippery ice. When she stops pushing, what will happen to the box?

A) It will stop moving
B) It will keep moving

18 students said “keep moving”

- 14 students mentioned smoothness of the surface (*“I think my answer is true because it is smooth and it is slippery and it could keep sliding”)*
- 1 student mentioned friction (*“on ice no friction”)*

3 student said “stop moving”

- *“It will stop moving because if she walks slow that means she will stop the box.”*
- *“because she was on ice so a lump will stop the box.”*

Figure 5.11 Pretest overview for Ms. Lawson's class

After viewing the pretest results, Ms. Lawson's first response was that the students had clearly put effort into their pretest responses and that most of the class had a basic understanding of the key concepts. "So at first glance, I have a lot of kids who really try their best and kind of on target…just a few who maybe were off" (Lawson, FR). She also noted that some students had mentioned friction, even though she had not taught it yet, which implied that they were drawing from prior knowledge from outside of science class. "I think it's interesting that we hadn't taught this yet. But they've mentioned friction. So I'm wondering if they get that in another grade? Or if that's something that they've been exposed to?" (Lawson, FR).

With regard to the incorrect student answers, Ms. Lawson considered multiple potential explanations. She noted that the student who said that the box would stop moving on ice because of a "lump" might have been using critical thinking to justify their answer, "Finding reasons why it would stop - like if the ice is lumpy, like not assuming that it's smooth. I have a lot of critical thinkers" (Lawson, FR). In other cases, Ms. Lawson wondered if the student had been rushing or had not read the question correctly. "May not have read it? Could have rushed" (Lawson, FR). Note that both Ms. Lawson and Ms. Lane read all the assessments out loud, while administering them; however, sometimes students would choose to go ahead faster than the pace that the teacher was reading.

In the same conversation, Ms. Lawson shared her goals for student learning from the simulation (see Table 5.5). Her first goal was related to the science content: she wanted students to understand that friction is a force that affects the movement of objects. Her second goal was related to science practices: she wanted students to know the importance of only changing one thing at a time (i.e., controlling variables). Since Ms. Lawson and Ms. Lane frequently talked together about their science teaching, it is possible that Ms. Lawson's interest in focusing on controlling variables was inspired by Ms. Lane's teaching. It is also possible that Ms. Lawson came to this conclusion independently, especially since the lesson directly before the simulation lesson focused on the importance of controlling variables.

Table 5.5

Ms. Lawson's Goals for the Friction Simulation

Conceptual Goal	Quote
Students will understand that friction is a force that impacts the motion of objects.	"...that friction occurs between the contact [of two objects], that it's a force that we can't see, and that it will affect the motion of an object" (Lawson, FR).
Students will understand the importance of controlling variables.	"I really want them to walk away knowing that you can only change one thing at a time. I feel like they're going to want to change everything. That is part of the learning curve, though" (Lawson, FR).

As in the case of the Net Force Simulation, Ms. Lawson's main concern with the Friction Simulation was that the Smartboard might malfunction (see Table 5.6 below). Because of this concern, she and I ran a complete test of the Friction Simulation on the Smartboard before Ms. Lawson taught the lesson. Ms. Lawson also wondered about the balance between letting students explore the simulation features versus giving students guidance regarding the simulation features. In the end, she decided to first give students time to make observations, and then highlight any important simulation features that students had missed. Note that Ms. Lawson asked what Ms. Lane did, to help decide what she herself would do. This respect for, and learning from, each other's practice was typical of both Ms. Lawson and Ms. Lane.

Table 5.6

Ms. Lawson's Concerns about the Friction Simulation

Potential Challenges/Concerns	Quote
Smartboard malfunction	"I hope this will work on the smart board… maybe we should pull it up on the SMART Board and see [if the touch screen works] … or if they need to use my mouse at my computer" (Lawson, FR).
Simulation controls could be confusing	"When Ms. Lane started, did she introduce the stuff on here? Or does she just like let them [explore] willy nilly? There's so much going on this one that I almost want to review variables and friction" (Lawson, FR).

As part of the same pre-lesson conversation, Ms. Lawson shared how she planned to support student sensemaking while working with the Friction Simulation. Like Ms. Lane, Ms. Lawson planned to go above and beyond the support provided by the MLs lesson plan, in ways that were consistent with the rest of the MLs curriculum and with PhET recommendations for supporting student inquiry while working with simulations. Like Ms. Lane, Ms. Lawson planned to have students run fair tests and make a claim based on what they learned from their investigations, two practices that were not present in the Friction Simulation portion of the MLs curriculum, but were present in other portions of the curriculum. Additionally, Ms. Lawson planned to teach students to use notetaking to keep track of their fair tests. Table 5.7, below, provides a complete list of Ms. Lawson's plans to support student sensemaking.

Table 5.7

Ms. Lawson's Plans for Supporting Student Sensemaking

Plan for supporting sensemaking	Quote
Supporting students to make observations of the simulation. Making sure to introduce the key simulation features.	"I'll open it up as 'Tell me what you see. What are some things that we recognize that we learned before spring break…I definitely think we need to introduce/discuss all the things [simulation features] that we talked about'" (Lawson, FR).
Introducing key scientific concepts/vocabulary, such as "mass."	I'm not sure that they know what mass is… and I remember as a seventh grade teacher when we would get to our chemistry unit, they were very confused by that [mass]… I am going to introduce some terms and ask [the students what they know]…may be new vocabulary for them" Lawson, FR).
Modeling a few scenarios on the smart board, giving students time to explore individually, and then having a whole-class discussion about what students learned.	"I plan to let them experiment with the board up front… and then allowing them time to actually experiment with it on their computer and hoping they gain a deeper understanding. Then I plan to bring it back and have that discussion to see if there are misconceptions, and where those misconceptions are" (Lawson, FR)."
Supporting students to control variables.	"Reminding that you can only change one variable at a time" (Lawson, FR).
Teaching students to take notes to keep track of how they controlled variables in their investigations.	Maybe they could jot down in their notebook what they've tried clicking… to hold them accountable for not just like changing everything... I can write it on the board so they have an example of what I want in their notebook" (Lawson, FR.)
Supporting students to write a claim based on what they learned.	"If they have time, I might have them do a claim - we'll see how long today takes" (Lawson, FR).

Overview of Ms. Lawson's enactment of the Friction Simulation lessons. Ms. Lawson taught the Friction Simulation in one lesson, which lasted 53 minutes. She had originally intended to teach the Friction Simulation in two (shorter) lessons, but logistical scheduling issues interfered. (The logistical issues were related both to (a) my being about to leave the country for a conference and (b) Ms. Lawson's student teacher needed to teach the lesson that followed the Friction Simulation as soon as possible.)

Ms. Lawson began with a whole class discussion about the concept of friction. Then, she showed students the different features of the simulation. As she did so, she wrote down the three variables that could be changed on the board: mass, force, and friction. She led a discussion about "fair tests" and showed students how they could record which variables they were going to keep the same and which variable they planned to change. She invited several students to run fair tests on the white board and gave the class a chance to discuss each fair test. After that, she gave students time to explore the simulation independently. As students worked independently, she asked that they record what kind of fair tests they were doing, using the same system she had modeled on the whiteboard. (She also showed them how they could record with drawing, as well as writing.) At the end of the lesson, Ms. Lawson built off of a student comment to generate a claim about friction. She wrote down this claim, checked to see if the class agreed with it, and then when the class said that they agreed with it, she had students copy it into their science notebooks. (See Figures 5.12-5.16 for photographs of the records and claims that the focal students wrote into their science notebooks. Note, one focal student missed the end of the lesson and did not write in her science notebook.) Ms. Lawson felt it was particularly important to generate a written claim about the effect of friction on an object's motion, in order to carry the learning from the simulation forward into the next science lesson.

When looking at the focal students' science notebook, we see that four of the five focal students followed Ms. Lawson's instructions and copied down the friction claim into their science notebooks. In other words, the class claim became part of (nearly) every student's personal and permanent records of science class. The focal students' science notebooks also show a range of understanding of the concept of fair tests. For example, we see that Christine conducted two different fair tests. In the first fair test, her control variables were friction (set at no friction) and applied force (set at 500 Newtons) and her experimental variable was the mass. In her second fair test, she kept friction and mass constant while changing the force. Similarly, both Jarius and Owen also recorded at least one fair test in which two variables are controlled and the third variable is manipulated. Owen had even already started writing his own claim ("the speed is faster without friction"), even before Ms. Lawson had everyone record the class claim. In other cases, focal students' notebooks demonstrate some confusion about fair tests. For example, in one of Jada's "fair tests" she has mass recorded both as her experimental variable and as one of her control variables.

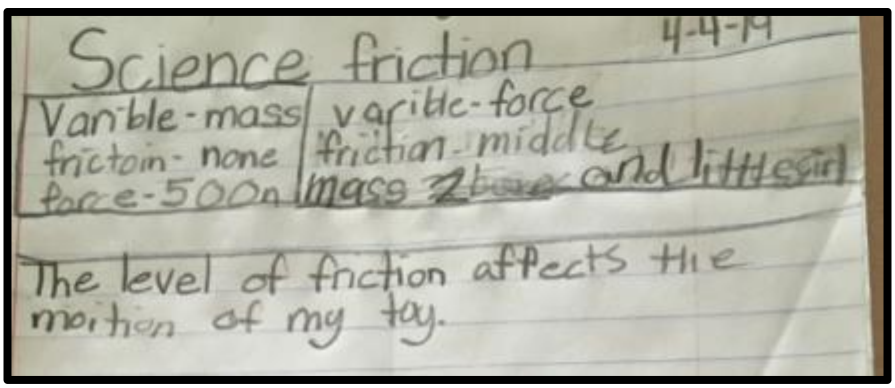


Figure 5.12 Christine's science notebook

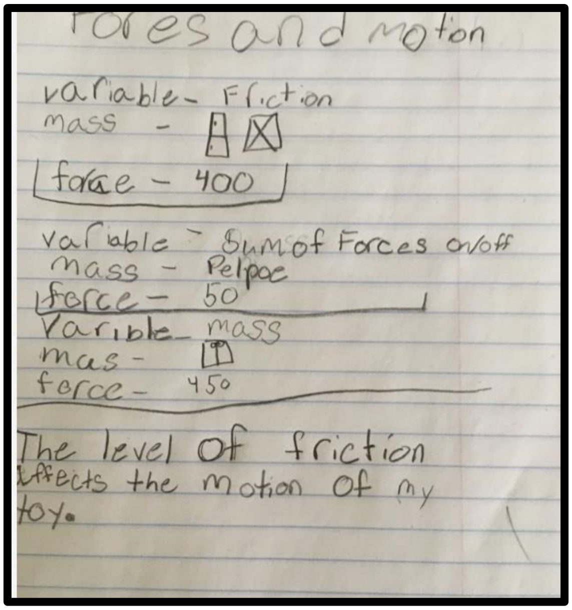


Figure 5.13 Jada's science notebook

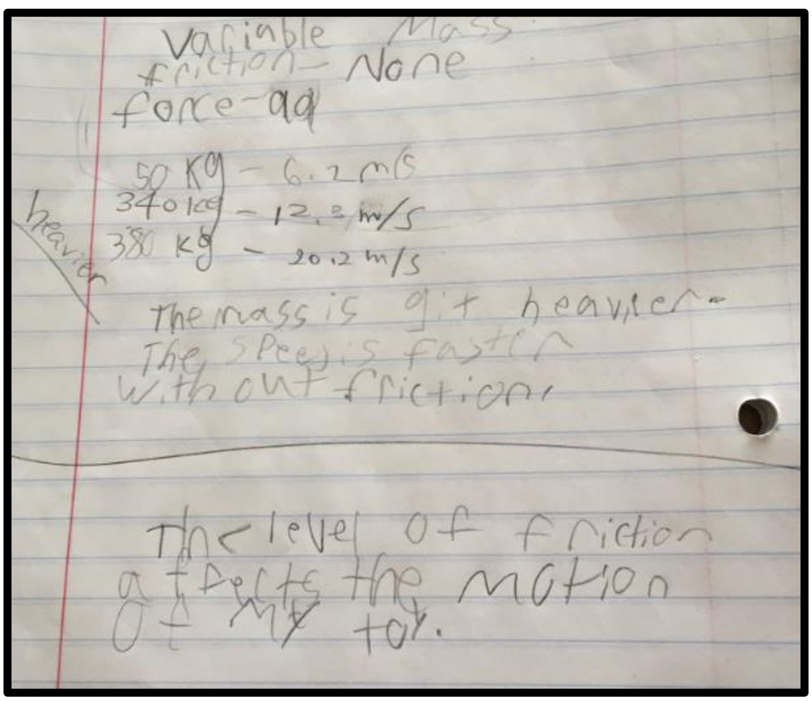


Figure 5.14 Owen's science notebook

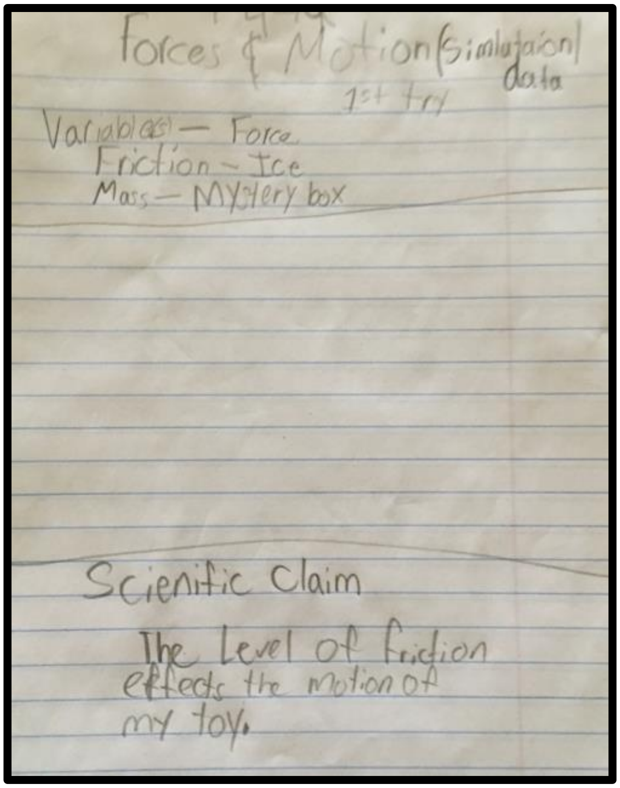


Figure 5.15 Jarius's science notebook

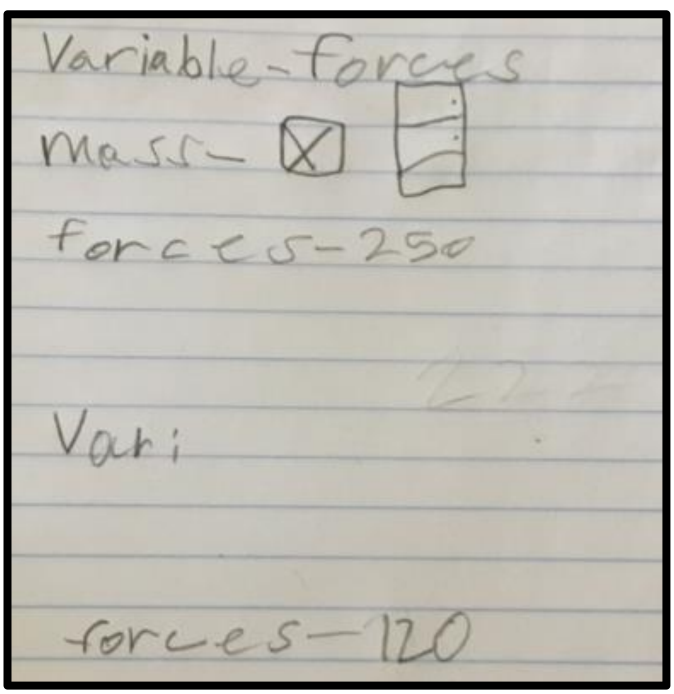


Figure 5.16 David's science notebook

Table 5.8 shows the breakdown of Ms. Lawson's talk during whole-class instruction with the Friction Simulation. Note that the level of conceptual talk in this lesson is lower than in other lessons. This may be related to Ms. Lawson's decision to structure this class with less whole-class conversations and more independent student exploration of the simulation. Ms. Lawson likely asked many conceptual questions to students individually during the independent exploration time: Table 5.8 only represents the talk during whole class conversations.

Table 5.8

Ms. Lawson's Talk during the Friction Simulation Lessons[21]

Talk Type	Frequency
Providing Information	23%
Directive or Discussion Etiquette	18%
Conceptual Question	8%
Revoicing	6%
Inviting	5%
Directing Attention	5%
Procedural Question	5%
Recalling Shared Experiences	4%
Experiential Question	3%
Praise	2%
Repeating	1%
Requesting Information or Clarification	0%

Types of teacher talk that supported student sensemaking. As in the case of Ms. Lane's class, in the sections that follow I will be focusing on types of talk that both solicited and amplified student ideas: directing attention, experiential questions, conceptual questions, inviting, requesting information or clarification, and revoicing.

Directing attention. Like Ms. Lane, Ms. Lawson followed up on her initial plan to open the Friction Simulation lesson by guiding students to observe key simulation features. However,

[21] Does not include one-on-one conversations with individual students

unlike Ms. Lane's class, Ms. Lawson's focal students did not increase their use of simulation features following the teacher-guided observation. On the contrary, four out of five focal students were already fully using the friction-adjustment slider, even before Ms. Lawson explained how to use it. (The sixth focal student arrived late and was not part of the pre/post comparison.) This suggests that not all students will always need to have the simulation features introduced to them. Note that Ms. Lawson's focal students still changed how they *used* the Friction Simulation due to Ms. Lawson's introducing a new recording system that helped students conduct fair tests. They simply did not need Ms. Lawson to show them *how* to work the friction slider – they figured it out independently.

Like Ms. Lane, Ms. Lawson supported student noticing throughout the entire lesson, not only at the lesson's beginning. Sometimes, she gave general prompts designed to support observation ("Is there anything else you noticed up there?"). Other times, she gave specific prompts guiding students to look at a particular feature of the simulation ("So if I go up here and I click masses, do you see how these numbers showed up?" FRD1), or encouraged students to notice whether particular simulation features changed over the course of a scenario ("Okay, with the highest level of friction and the highest level of force, is it going anywhere?" FRD1).

Experiential questions. The types of experiential questions Ms. Lawson asked during the Friction Simulation were consistent with the types of experiential questions that Ms. Lawson had asked during the Net Force Simulation, as well as the kinds of experiential questions that Ms. Lane asked during the Net Force and Friction Simulations. These included questions about general life or out-of-school experience ("Who's ever traveled along ice?" FRD1), experiences from prior science lessons ("What were we saying about it yesterday?" FRD1), and experiences that occurred earlier within the same science lesson ("Did that go faster or slower on that slippery surface than the refrigerator?" FRD1).

Conceptual questions. Ms. Lawson's conceptual questions supported students to engage in scientific practices including: making predictions "If I change the level of friction, what is your prediction?" FRD1), conducting fair tests ("Why do you think it's important that we only change one thing at a time?" FRD1), and developing generalizable claims ("What can you say then about the level of friction, since that's the only thing we changed?" FRD1). In our post lesson conversation, Ms. Lawson reported greatly valuing the opportunity to let students practice conducting fair tests, "The middle school science teacher in me is like, 'yes!', because it's variables…I think fair test is still difficult for them, because they want to always say everything's unfair or whatever. But really, really hammering home that concept that you only change one thing at a time, because you won't know actually what your data reflects or you won't know what your outcome is if you change a bunch of things. .. And I think that simulation did a nice job of introducing …the idea of only changing one thing" (Lawson, SR).

Ms. Lawson also used conceptual questions to assess and support student understanding of key concepts such as: force, friction, mass, and newtons. ("Friction, how are we defining it?" FRD1) and to ask students to critically consider the purpose of the simulation. ("What do you think we're really looking for? With our simulation. What's the purpose of this?" FRD1.)

Inviting, repeating, and revoicing. The combined frequency of these three moves was 12%. After the lesson, Ms. Lawson commented that her lesson had solicited fewer student ideas than she had originally planned, which may have been caused by time-related pressure "So I think I did a little bit more teacher-led than I had planned. Last year I did not do as much teacher-led, I don't know if in the back of my mind I was nervous because we wanted to do it all in one day, but I think that's okay" (Lawson, FRD1).

Nevertheless, Ms. Lawson still consistently made opportunities for students to share their thinking by calling on students whose hands were raised, inviting students to vote with thumbs up/thumbs down, and generally soliciting student thinking ("What are your thoughts?"). As in previous lessons, Ms. Lawson also used repeating and revoicing student ideas to both amplify and expand on student ideas. The following example shows how Ms. Lawson used revoicing to build from a student contribution:

> Megan: Let's say you move your hands together. It makes your hands feel warm.
>
> Ms. Lawson: Okay, so – rubbing my hands together. I'm sliding two surfaces over each other, right? (FRD1).

Considering a student's responses to Ms. Lane's sensemaking support. Again, I conclude the section on Ms. Lawson's enactment by considering a longer stretch of dialogue.

> *Ms. Lawson: Who can tell me what we learned about friction? What does that mean? Friction? What is friction? And you can tell me anything, you can give me a scenario, you can give me part of the definition. Megan?*
>
> *Megan: Let's say you move your hands together it makes your hands feel warm.*
>
> *Ms. Lawson: Okay, so like rubbing my hands together. I'm sliding two surfaces over each other, right? Okay. Adela?*
>
> *Adela: So in art we had a paper and we glued our hand and we rubbed it on the paper.*
>
> *Ms. Lawson: And you felt like that was an example of friction? Two objects in contact? Listening, please. Kenisha? [Pause] I can come back…*
>
> *Kenisha: Friction is like, say you're trying to light - I mean, say it's a bonfire, and like it sparkles. The wood is getting red.*
>
> *Ms. Lawson: Okay, so if you were trying to start a fire or something?*

Kenisha: It gives a spark.

Ms. Lawson: Try to think about ... I put up a slide yesterday ….cause you're giving me great examples of real life things going on. Friction, how are we defining it? What were we saying about it yesterday? (FRD1)

In the above excerpt, Ms. Lawson is asking her students to review what they learned about friction during the previous day's lesson. She makes her question open-ended, giving the students the opportunity to either provide examples or definitions. When Megan provides an example of rubbing hands together, Ms. Lawson re-voices her example to emphasize the fact that rubbing hands together involves sliding surfaces over each other. When Adela provides the example of rubbing a hand over paper, Ms. Lawson again re-voices her contribution, and again she emphasizes the contact between two objects. After a third student provides an example, Ms. Lawson first honors the example by repeating it and then presses the whole class to begin to move from "examples of real life things going on" to a definition. This was typical of Ms. Lawson's practice: she would often open the floor to student contributions, re-voice those contributions to add more scientific detail, and then press students to share more detailed or more specific contributions. This let her students gradually warm up to new ideas, while also raising the level of challenge over time.

Considering the Relationship between Instruction and Curriculum.

As in the case of the Net Force Simulation, both Ms. Lane and Ms. Lawson engaged in a number of practices to support student sensemaking while working with the Friction Simulation. These practices included: directing student attention, helping students make connections to previous experiences, asking students about key science concepts, and asking many different types of conceptual questions (e.g. questions designed to support different scientific practices or questions designed to help students interpret simulation representations.) However, unlike in the case of the Net Force Simulation, *none* of these practices were included in written support materials provided by the MLs curriculum. Recall from Chapter Three that the Friction Simulation was marked as “optional” and supported by a bare-bones description that was only a few lines long. Note that Ms. Lane and Ms. Lawson both chose to support the Friction Simulation in the same way that they had supported the Net Force Simulation, importing sensemaking practices from the Net Force Simulation lesson. Also note that Ms. Lane and Ms. Lawson both seriously extended the amount of time that the MLs curriculum originally allocated for the Friction Simulation.

As in the case of the Net Force Simulation, Ms. Lane and Ms. Lawson both capitalized on advantages provided by the Friction Simulation design. For example, building on a practice introduced in the prior lesson of the MLs curriculum, both teachers used the Friction Simulation to support fair tests because it contained three variables that could be manipulated (applied force, level of friction, and mass of object) and one responding variable that could be measured (speed).

Teachers Assess the Value of the Friction Simulation as a Learning Tool

The perspective of Ms. Lane. Ms. Lane had positive things to say about the Friction Simulation both before and after she taught with it (see Table 5.9 for quotations). Before teaching, she recalled that in previous years the students had both (a) enjoyed using and (b) learned from the Friction Simulation. After teaching, Ms. Lane commented that while some students had been distracted by the “splits feature,” just as Ms. Lane had predicted would happen, she felt that the simulation had helped students understand the relationship between “friction” and “mass.” She also commented that she had been impressed at how quickly students understood and “latched onto” the concept of newtons as a measurement of force. Ms. Lane recommended that the Friction Simulation remain a part of the MLs curriculum.

Table 5.9

Ms. Lane’s Reflections before and after teaching the Friction Simulation

Time	Quotation
Before Teaching	“Well, last year….gosh, like any simulation itself, is neat for them to play around with. And certainly … I really think that they will figure out that you can change the friction of the surface….I think that just solidifies that understanding of friction,” Lane, FR,
After Teaching	“Very supportive. I think especially them being able to go, even though some of them just wanted to make the man do the splits or fall or whatever. I still think I really do think that at some point -I know it's done it for me, since I first started teaching it [the Friction Simulation] - at some point, they're going to make that connection. They're going remember what they did, they're going to go, ‘oh,’ there's going to be even more abilities to make that connection and solidify their understanding of friction and mass. And I was impressed that they knew as much as that they were able to kind of latch on to the newtons. You know, they really kind of sunk into that,” Lane, SR.

The perspective of Ms. Lawson. Like Ms. Lane, Ms. Lawson found the Friction Simulation useful and recommended it remain part of the MLs curriculum. Before teaching with the Friction Simulation, Ms. Lawson expressed concern about its complexity and asked me to review its features with her. After teaching the simulation, Ms. Lawson shared that she felt it synergized well with the physical experiments that students conducted with their toys. In specific, she mentioned that there were clear connections between (a) using a simulation to test how changing friction impacts motion and (b) observing how a physical toy car’s motion changed depending on the kind of surface it was rolling across (See Table 5.10).

Table 5.10

Ms. Lawson’s Reflections before and after teaching the Friction Simulation

Time	Quotation
Before Teaching	“I do need to review with you how things work,” Lawson, FR interview.

After Teaching	But I do think that with the forces simulations, them seeing that really gave them a better understanding … the levels of friction, because you could clearly see ice or like you can clearly see when it became very rough . . . seeing the levels of friction, and testing the levels of friction with their toys, it just went so hand in hand, right? Like, I feel like that is very, very strong. The way that it's set up," Lawson, SR

Summary of Key Points in Relation to Research Questions

This chapter first asks *How do teachers support student sensemaking while working with the Friction Simulation? How do students respond to this support?* Findings in this chapter suggest that Ms. Lawson and Ms. Lane leveraged suggestions from the Net Force Simulation Lesson Plan as they supported student sensemaking by a variety of moves including: directing student attention, asking different types of conceptual questions, and supporting students to make connections with their past experiences. In addition to talk that directly supported sensemaking, the teachers also engaged in talk that helped set conditions that could support sensemaking, for example by setting norms and expectations. Students and teachers engaged in dialogues where both worked together to co-construct ideas, with the teacher supporting students to listen carefully to each other's ideas and to develop ideas more fully. The chapter then asked *What are the teachers' perspectives regarding the use of simulations as sensemaking tools?* Both Ms. Lane and Ms. Lawson felt that the Friction Simulation supported student learning.

CHAPTER 6 The Mystery Plant Simulation

This chapter focuses on the Mystery Plant Simulation. It is organized by the study's two research questions. It begins by considering the first research question: *How do teachers support student sensemaking while working with the Mystery Plant Simulation? How do students respond to this support?* It constructs a case of how each teacher supports student sensemaking in her classroom. Each case contains the following sections (a) how the teacher prepares to support sensemaking prior to beginning teaching, (b) an overview of how the teacher enacted the simulation-based lesson, (c) a closer look at types of teacher talk that specifically supported sensemaking, (d) an illustrative example of how student(s) responded to the teacher's sensemaking support, and (e) the relationship between the teacher's instructional decisions and the support provided by both the simulation and the MLs curriculum. The chapter then moves to consider the second research question: *What are the teachers' perspectives regarding the use of simulations as sensemaking tools?* The chapter concludes with a brief summary of key findings that relate to each of the two research questions.

How does Ms. Lane Support Student Sensemaking while Working with the Mystery Plant Simulation and how do Students Respond to this Support?

The following section considers how Ms. Lane supported student sensemaking both through careful pre-planning and through instructional decisions that she made while teaching.

How Ms. Lane prepared to support student sensemaking prior to teaching. Figure 6.1 shows the overview document that I brought to Ms. Lane, which summarized how students had responded to both the Mystery Plant Simulation pre-test and the items assessing student understanding of fair tests. (Recall that fair tests was a scientific practice that Ms. Lane chose to emphasize while working with the Friction Simulation.) On the first item, most students correctly said that not all seeds from the same parent plant would grow into plants that look exactly the same. On the second item, most students incorrectly said that seeds from the same parent plant would all need *exactly* the same conditions to survive. For the friction fair test item, 16 students correctly identified both the example and non-example of a fair test. In contrast, for the plant fair test item, only eight students correctly identified both the example and the non-example of a fair test. On the last page of the assessment, no students noticed the difference in leaf size between the red and blue offspring, nor did any student predict that the blue plants (which had greater variety of traits among the offspring) would be able to grow in a wider range of environmental conditions, as compared to the red plants.

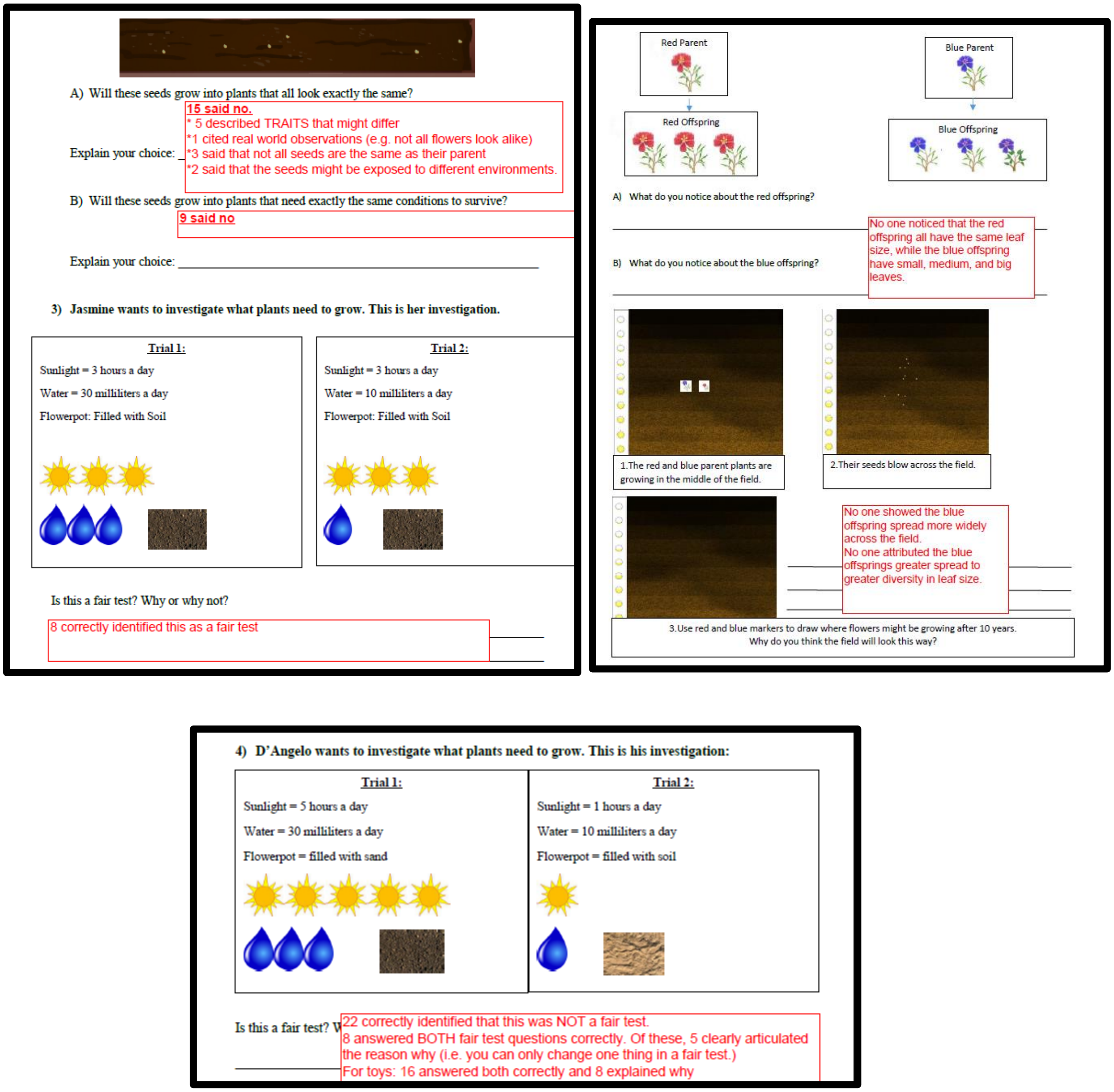


Figure 6.1 Pretest Overview for Ms. Lane's class

When Ms. Lane and I reviewed the pre-test results, Ms. Lane looked for ways to help students learn. When Ms. Lane saw that some students thought that a plant's offspring would (a) look exactly the same and (b) have the exact same needs, she immediately began to brainstorm ways to support student understanding. Her ideas included making connections to students' own families ("we are offspring of our parents…I can tie that in," Lane, PL[22]), making connections to students' experience with pets ("You know, when puppies are born… you have labs that have white labs, yellow labs, chocolate labs," Lane, PL), and making connections to earlier MLs units. Ms. Lane also planned to invite students to focus in on the word "exactly" when considering their answer and to think about what it would mean to look *exactly* the same or need *exactly* the same conditions ("so that's the key word: 'exactly,'" Lane, PL).

Ms. Lane expressed surprise that the students were still struggling to identify fair tests, given how much time her class had spent discussing fair tests while working with the Friction Simulation. She later commented "I think that that's, they get what a fair test is, but then…on the assessments, when they see that word fair, they automatically think - well, that's not fair. There's two different things . . .so trying to remember those that maybe need a little bit more support for understanding what fair' is" (Lane, SR). To give students this support decided to open up the plant simulation lesson with a review discussion focused on fair tests. Ms. Lane also planned to point out the difference between small, medium, and large leaves on the simulation, since no students noticed that difference when completing the pretest.

During the same pre-lesson conversation, Ms. Lane articulated that her main goal for the Mystery Plant Simulation was that students would (a) understand what variations are, and (b) understand that variations help species to adapt and survive (see Table 6.1, below). Unlike in the case of the Net Force and Friction Simulations, Ms. Lane did not share overarching goals related to students improving their ability to engage in science practices, although she did still plan to

[22] Plant interview

have students engage in some science practices (e.g. observation, prediction, reasoning) while working with the simulation. This shift in Ms. Lane's goals may have been related to differences between the PhET simulations and the Mystery Plant Simulation: as discussed at the beginning of this chapter, the Mystery Plant Simulation offered fewer user choices than the other two simulations.

Table 6.1

Ms. Lane's Goals for the Mystery Plant Simulation

Conceptual Goal	Quote
Students will understand what variations are and how they help species to survive over time.	"Variations, you know, what are variations? I do want them to get adaptations… something has to change over time in order to survive" (Lane, PL).

Ms. Lane had two main concerns regarding the Mystery Plant Simulation (see Table 6.2). The first was that the simulation graphics might be difficult for students to understand. Ms. Lane said that she herself did not automatically know how to interpret certain features of the simulation (for example, she did not immediately realize that the small sun icons in the Virtual Greenhouse represented the amount of sunlight that each planter box received.) Ms. Lane's second concern was that the concepts of variation, adaptation, and natural selection might be difficult for the third-grade students to grasp. She shared that she herself found the concepts complicated. Because she found the concepts complicated, she practiced articulating them as she and I spoke together. Her goal in practicing was to make sure she could explain it clearly while teaching.

Table 6.2

Ms. Lane's Concerns about the Mystery Plant Simulation

Potential Challenges/Concerns	Quote
Students may be confused by simulation graphics	"It's very confusing to me. But as I look at it, I can see that that is not as much light, that's a little bit more light, that's full light…So I think that as long as I can point that out to them, as long as I remember to point that out…." (Lane, PL).
The concept of adaptation over time in response to selection pressures may be challenging for students	"'Make a prediction how many different kinds of plants will be growing in the field after many seasons.' Okay, gracious, I really hope they get that one…it's complicated for *me*, as I sit here and try to think of connections…" (Lane, PL).

Ms. Lane's plans to support student sensemaking had the aim of addressing her two main concerns (see Table 6.3). To address the concern of potentially confusing graphics, Ms. Lane made specific plans for ways to support student observations while working with the Virtual Greenhouse and Virtual Field screens. To support students to understand the complex ideas surrounding variation, adaptation, and change over time, Ms. Lane planned to support students to (a) make predictions before working with the Virtual Greenhouse and Virtual Field and (b) make claims after working with the Virtual Greenhouse and Virtual Field. This would give students multiple opportunities to engage with ideas surrounding variation, adaptation, and changes in species over time. Additionally, Ms. Lane made plans to intentionally focus on certain parts of the simulation, while skipping others. She felt this would let her spend more time on the Virtual Greenhouse and the Virtual Field, without overloading the lesson and losing her students in the process. From my perspective, this selectivity of focus seemed appropriate and logical, especially given that the Mystery Plant Simulation was never intended to stand alone, but rather was embedded in a longer series of lessons.

Table 6.3

Ms. Lane's Plans for Supporting Student Sensemaking

Plan for supporting sensemaking	Quote
Supporting students to make predictions and to support these predictions with reasoning.	"'This is the size two plant: will all its offspring plants have the same size leaves?'… We [can] have [a] discussion about this? How many think yes? How many think no? How many don't know? And then why do you think yes? Why do you think no?" (Lane, PL).
Supporting students to observe differences between the offspring plants (including leaf size) in the Virtual Greenhouse.	"They're not exactly the same…that has [leaf] size three . . . this one has [leaf size] two. That one still has [leaf size] one… so they're not all exactly the same. But yet they all came from the same plant" (Lane, PL).
Supporting students to make careful observations as the Virtual Field changes, including directing students' attention to the passage of time and to the data in the bar graph.	"Okay, what does this represent? This represents another season, this represents winter? . . . I may pause it and just say, Okay, look, they're dropping some of their seeds. Did they all have flowers? . . . What do you notice is starting to happen each year? Pay attention to the graph over here. What do you noticing is happening?" (Lane, PL).
Supporting students to make claims based on the Virtual Field.	"I really feel like this [the virtual field screen] one will be a good one to spend time on, and maybe … make some claims…Based on this [the virtual field screen], what do you think about plants and offspring? And do the offspring all need exactly the same thing?" (Lane, PL).
Making connections to previous MLs Units	"Tying in adaptations to survival, I can go back to the birds [MLs unit] or even like the squirrels [MLs unit]" (Lane, PL).
Making intentional choices about which simulation screens to focus on during class and which screens to omit.	"And then are we getting into this [Darwin's' finches]? ... I think it's too much of a jump…I think I would go to this. I think I would skip that one. Yeah, I think it's too much" (Lane, PL).

Overview of Ms. Lane's enactment of the Mystery Plant Simulation lessons. Ms. Lane taught the Mystery Plant Simulation over two days. The first lesson was 37 minutes and the second was 38 minutes. On the first day, Ms. Lane began with a student-led review discussion where students made observations of the mung bean plants from a fair-test investigation they had begun earlier. Students noted that plants that had been denied light were less healthy looking than plants that had received ample light. This discussion provided opportunities to discuss connections between plant environments and plant traits, as well as a review of fair tests, which Ms. Lane had realized that students needed after seeing the assessment results. The opening discussion also included a review of previous learning about the difference between weather and climate.

Ms. Lane then introduced the simulation. On the first screen, Ms. Lane introduced and discussed the concepts of “offspring” and “variation.” As she had planned earlier, Ms. Lane made connections between plant offspring and variation and human offspring and variation, including focusing in on whether anyone is ever “exactly” the same as their parents. On the second screen (The Virtual Greenhouse), Ms. Lane invited students to make observations about the different parts of the simulation (planter box, seeds, etcetera), direct where she placed the different plants and seeds, and interpret the results. As she had planned earlier, Ms. Lane supported students to understand and interpret potentially confusing visuals – with a special emphasis on noting differences in leaf sizes between the plants. On the third screen, Ms. Lane read the conceptual question aloud and invited students to make predictions. Here, Ms. Lane’s plan to have students make predictions was supported by the fact that the simulation itself posed a question that asked students for predictions.

On the second day, Ms. Lane again began with a student-led review discussion focusing on the previous day’s work with the simulation. This included reviewing what they had done with the simulation, what they had learned, and key concepts such as “offspring” and “variation.” Ms. Lane returned to the virtual greenhouse (screen two) and briefly demonstrated what the class had done on the previous day. She then led a brief discussion about how plants are adapted to their environment, based on the information, picture, and question on screen four. Most of the day was spent working with the virtual field (screen five) and answering questions about the virtual field (screen six.) Ms. Lane ended the lesson after discussing the last question on screen six (e.g. "You only planted one type of flowering plant. How did so many types of plants grow?"). This last question set Ms. Lane up to have students make a claim based on the simulation, just as she had planned during our pre-lesson discussion.

The Mystery Plant Simulation did not work on Chromebooks, so Ms. Lane only taught this simulation whole-class. Table 6.4, below, describes Ms. Lane's talk during the Mystery Plant Simulation Lessons.

Table 6.4

Ms. Lane's Talk during the Mystery Plant Simulation Lessons[23]

Talk Type	Frequency
Providing Information	25%
Directive or Discussion Etiquette	14%
Conceptual Question	10%
Directing Attention	10%
Experiential Question	10%
Revoicing	8%
Recalling Shared Experiences	5%
Inviting	4%
Requesting Information or Clarification	4%
Procedural Question	4%
Repeating	3%
Praise	1%

Types of teacher talk that supported student sensemaking. As in the previous chapter, in the sections that follow I will be focusing on types of talk that both solicited and amplified

[23] Does not include one-on-one conversations with individual students

student ideas: directing attention, experiential questions, conceptual questions, inviting, requesting information or clarification, and revoicing.

Directing attention. As she had planned, Ms. Lane spent a considerable amount of time supporting and guiding student observations of the Virtual Greenhouse and Virtual Field, especially regarding the graphics that she considered potentially confusing (i.e. subtle variations in leaf size and variations in amount of sun/shade). As in previous simulations, she opened by asking general prompts designed to support observation ("What are you noticing?" PLD1[24]). Later, she moved to more specific prompts guiding students to look at a particular feature of the simulation ("Do you see over here the field has different amounts of light?"PLD2) or encouraging student to notice how simulation features changed over the course of a scenario ("Watch how the plants in the field change as many seasons go by," PLD2).

Experiential questions. Recall that in her pre-lesson plans, Ms. Lane decided to make connections to students' previous experiences, both from science class experiences and from general life experiences. She followed through on these plans, asking questions about general life or out-of-school experience ("If someone is saying to you 'you look a lot like your dad' or 'you look just like your mom' does that mean you are identical?" PLD1) and questions about experiences from prior science lessons ("What did we do with our mung beans, do you guys remember? What were we wanting to investigate?" PLD1). She also asked questions that helped students connect back to experiences that occurred earlier within the same science lesson ("Okay, there were a ton of seeds that dropped, but did they all turn into flowers? PLD2). As in

[24] Plant Lesson Day 1

previous lessons, Ms. Lane tended to ask a cluster of experiential questions near the beginning of the lesson, to jump start the student-led review discussion of previously covered science content.

Ms. Lane felt that making connections to prior experience was especially important for this particular simulation lesson. In a post-lesson interview, she described that she had been "trying to get them to connect something like in their actual immediate [experience], something they can kind of put their teeth ….trying to get them to have a good base or foundation for understanding" (Lane, SR). In particular, she used students' own experiences to help them gain a more nuanced experience of traits or needs being "exactly" the same. "[I was] trying to emphasize 'exact,' and I think I said that at some point, there are very few things that are exact even when you have identical twins. They're not exactly the same. You can usually tell them apart just by looking at them" (Lane, SR.) Recall that Ms. Lane initially decided students needed support paying more attention to the concept of "exact," after seeing pretests where some students said that plant offspring might look exactly the same or have exactly the same needs. By asking experiential questions about human families' traits and needs, Ms. Lane helped make a bridge between existing knowledge about variation in human siblings' traits/needs and new knowledge about variation in plant offspring traits/needs.

Conceptual questions. Recall that during our pre-lesson conversation, Ms. Lane made plans to support students' prediction, reasoning, and claims. She did this through asking conceptual questions, many of which she took from discussion prompts embedded in the simulation itself. For example, the following two conceptual questions supported predictions and claims, respectively, and both came from embedded simulation prompts: "How many different kinds of plants will be growing in the field after many seasons?" (PLD2); "How did we end up with so many types of plants?" PLD2. However, while some of Ms. Lane's questions came from simulation prompts, she also generated many questions herself, as in the case of previous simulations. For example, when asking that students support their ideas with reasoning, she asked “So you still think ‘no,’ but why? (PLD1).

In addition to supporting students to engage in scientific practices, Ms. Lane also used conceptual questions to assess and support student understanding of vocabulary/concepts including: adaptation, climate, offspring, variation, and weather (“The offspring, they’re kind of like what?” PLD2).

Inviting, requesting clarification, repeating, and revoicing. The combined frequency of these four moves (19%) again speaks to the extent to which Ms. Lane valued student contributions and ideas. When inviting students to share their ideas, Ms. Lane allowed students to talk with students sitting near them, gave students the opportunity to vote thumbs up/thumbs down, called on individual students with their hands raised, and invited students to build off of each other’s response (“Can somebody else add to that?”). Again, Ms. Lane used repeating and revoicing to make student ideas louder or clearer, as in the example of below.

S: I noticed that some of them have different sun,

Ms. Lane: Some of these plants require different amounts of sun, right? (PLD1)

And, again as in previous lessons, Ms. Lane highly valued understanding student sensemaking and would ask for clarification if she was not following a student’s ideas. In the example below, Ms. Lane presses for clarification in order to understand why a student has used the word, “army” to describe a group of plants, and ends up understanding that the student was trying to describe the sudden increase in the number of plants present in the field.

S: Ms. Lane, it’s an army!

Ms. Lane: It’s a what?

S: It’s an army!

Ms. Lane: How is it an army, honey?

S: Because there’s so many. (PLD2)

Considering a student’s responses to Ms. Lane’s sensemaking support. Again, I close the analysis of Ms. Lane's enactment by examining a longer stretch of talk.

Ms. Lane: “This is a leaf size two plant, will all its offspring plants have the same size leaves?” How many people think yes? Give me a thumbs up…Okay, how many people think no.? That's interesting. Does anybody want to give me a reason why they think no?

Ms. Lane: Brittney.

Brittney: Because the plants do not get the same amount of light as the other plant did.

Ms. Lane: Okay, so I'm just asking you about its offspring. We're not talking about the different variables, but its offspring. Do you think its offspring will have the same size leaves?

Multiple Students: No.

Ms. Lane: So you still think no, but why?

Brittney: It won't be the same because it didn't grow in the [inaudible]

Ms. Lane: So when this plant has babies. Are its baby plants, the offspring, going to have the same size leaves?

Multiple Students: No.

Ms. Lane: Okay, so. Can someone else tell us why they think no?

Saul: I think "no" because there not going to be identical, they aren't going to be in the same environment or something.

Ms. Lane: We aren't worried about the environment yet. We're just talking about when the seeds are planted are they going to have the same … but you think "no" because they aren't identical? Okay, quickly Luis.

Luis: I think "no" because not every plant is like, the same, even though they might come from the same exact plant, they're not going to be the same. (PLD1).

In the above conversation, Ms. Lane begins by asking students to predict whether all the offspring plants will have the same size leaves as their parent plant. She reads the prompt directly from the simulation, and then ask students to vote yes or no. Ms. Lane then asks students who voted "no" to share their reasoning.

Brittany's first explanation is based on differences in environmental conditions. Ms. Lane asks Britney not to consider the potential effects of different variables (i.e. changes in the amount of light) but to simply consider the question in the abstract. Ms. Lane then posed the prediction question again. Many students still said no, and again Ms. Lane asked for reasoning. Like Brittany, Saul shared reasoning that was related to extrinsic environmental factors rather than intrinsic genetic variation. Again, Ms. Lane asked students to temporarily disregard environmental factors, and called on a new student to answer. This time, Luis offered new reasoning. He shared that even though offspring might come from the same parent plant, he did not think they would be identical because not every plant is the same. Unlike Britney and Saul's answers, Luis's answer suggests inherent variation among offspring, rather than environmentally induced variations in phenotype.

As in previous examples, we see that Ms. Lane's patience pays off. Recall, from the pretest, that Ms. Lane knew that some students mistakenly believed that all offspring would be identical to their parent. By giving many students a chance to speak, Ms. Lane was able to address this misconception by bringing Luis's idea into the class discussion. Ms. Lane consistently expressed that it was worth it to give students a significant amount of time to explore new ideas out loud. She felt that her students sometimes could learn more effectively by listening to their peers than by listening to their teachers, because students naturally express ideas in kid-friendly language. That certainly seemed to be the case in this particular example: Luis differentiated between environmental and genetic factors far more simply than I could have!

How Does Ms. Lawson Support Student Sensemaking while Working with the Mystery Plant Simulation and How Do Students Respond to this Support?

The following section considers how Ms. Lawson supported student sensemaking both through careful pre-planning and through instructional decisions that she made while teaching.

How Ms. Lawson prepared to support student sensemaking prior to teaching. Figure 6.2 shows the overview document that I brought to Ms. Lawson, which summarized how students had responded to both the Mystery Plant Simulation pre-test and the items assessing student understanding of fair tests. (Recall that, like Ms. Lane, Ms. Lawson also chose to emphasize fair tests while working with the Friction Simulation.) As in Ms. Lane's class, most students correctly said that not all seeds from the same parent plant would grow into plants that look exactly the same. Again, as in Ms. Lane's class, most students incorrectly said that seeds from the same parent plant would all need *exactly* the same conditions to survive. For the friction fair-test item, 11 students correctly identified both the example and the non-example of a fair test. For the plant fair-test item, only seven students correctly identified both the example and the non-example of a fair test. Again, as in Ms. Lane's class, no students noticed the difference in leaf size between the red and blue offspring, nor did any student predict that the blue plants (which had greater variety of traits among the offspring) would be able to grow in a wider range of environmental conditions, as compared to the red plants.

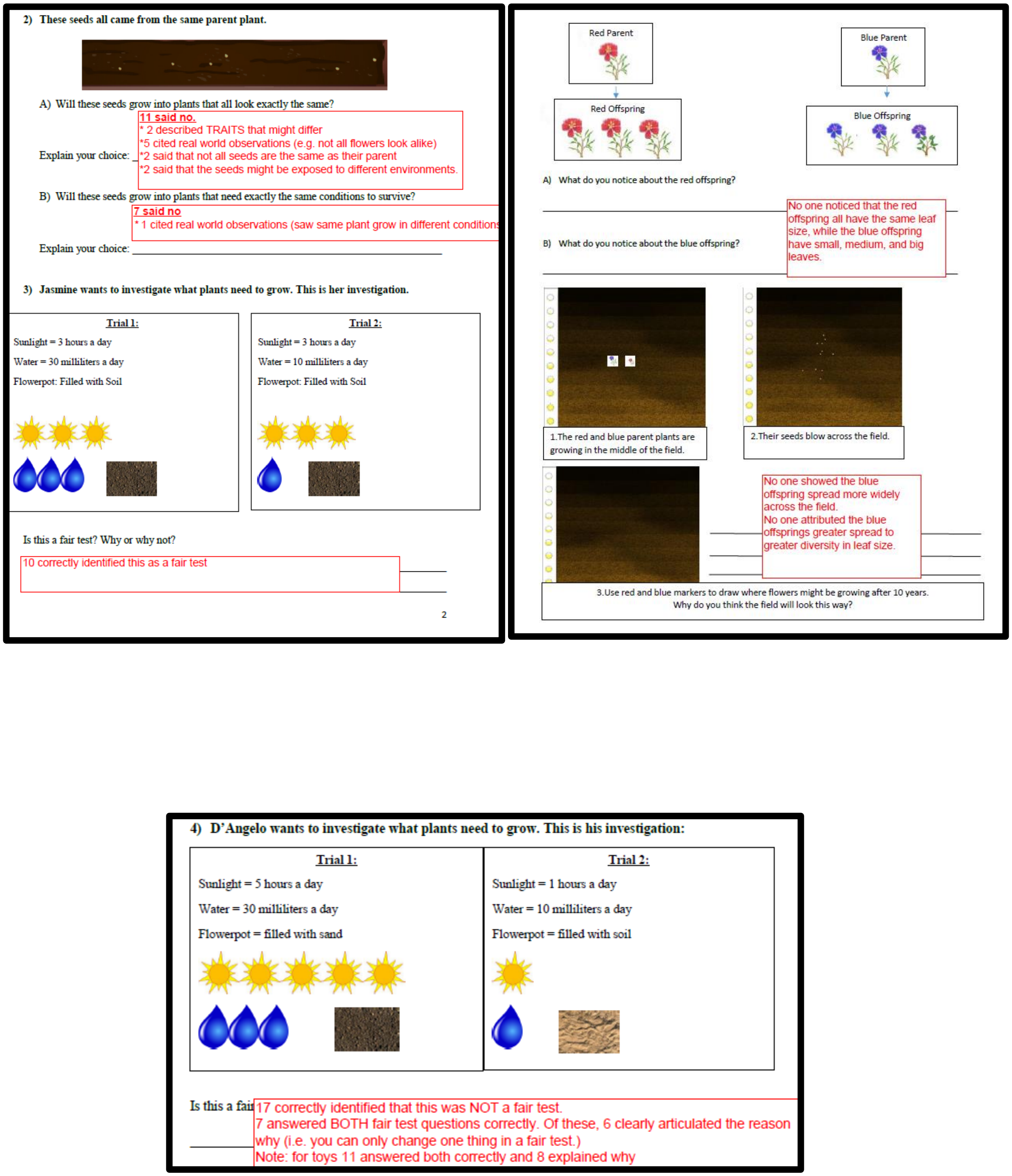


Figure 6.2 Pretest Overview for Ms. Lawson's class

When Ms. Lawson and I went over student pre-test responses, Ms. Lawson noted that she herself would have had difficulty answering some of the pre-test questions. In particular, she was surprised to hear that the blue offspring were different from each other. Looking at the plants, she said, “They’re so close. These are different?” (Lawson, PL.) When I pointed out the differences in leaf thickness, Ms. Lawson replied “Oh. You’re looking at the stem. I only looked at the flowers” (Lawson, PL.) Ms. Lawson also noted that it was hard to interpret the Virtual Field images, although that may, in part, have been related to the poor quality of the black-and-white print out I had shown her (“It’s so dark” Lawson, PL). Later, when Ms. Lawson was deciding how to support student sensemaking while using the simulation, she drew from her own struggles to interpret some of the simulation images in order to determine areas where students might benefit from support.

In the same pre-lesson conversation, Ms. Lawson identified three goals for student learning during the simulation lesson (see Table 6.5). The first goal was that students get practice interpreting features and symbols embedded into text. The second goal was that students understand that different variations of the same species might require different environmental conditions. The third goal was that students understand that plants produce offspring via cross pollination. This last goal stemmed from Ms. Lawson’s concern that the simulation might cause students to think that only one parent plant is needed in order for reproduction to occur.

Table 6.5

Ms. Lawson's Goals for the Mystery Plant Simulation

Conceptual Goal	Quote
Students will get practice interpreting text features such as graphs and symbols embedded in text.	"They're digging into graphs. I love that. They need more graphing" (Lawson, PL). " "This looks very much like their standardized testing. It's good for them to see this again, like where there are symbols within text." (Lawson, PL)
Students will understand that different variations of a species may require different environmental conditions.	"We want them to understand that variation exists and …each variation requires a different [environmental] situation" (Lawson, PL).
Students will understand that plants produce offspring through cross-pollination.	"Offspring - I want them to know what an offspring is. I want them to understand that we're calling them parent plants, but it's not like how they're necessarily going to picture. We're talking about like cross pollination. When we studied midges that crawls inside the flower and pollinates the flower and then seeds would drop [referring to earlier MLs unit]. . .That's major. I think it will need teaching" (Lawson, PL).

Ms. Lawson had more concerns about this simulation than she had about either the Force and Motion simulation or the Friction Simulation. Some of her concerns were related to scientific accuracy. As mentioned above, Ms. Lawson was concerned that the simulation might lead students to believe that only one parent was needed for reproduction to occur. She also thought that it was unreasonable to ask students to predict whether or not the offspring would have the same leaf size as the parent without knowing (a) the leaf size of the second parent and (b) whether the large-leaf allele(s) or small-leaf allele(s) are dominant. As she expressed these concerns, she cited her prior experience teaching genetics as a seventh grade science teacher. ("So, the science teacher in me is like…recessive or dominant?" Lawson, PL). Ms. Lawson was also concerned that the simulation shows large leaf plants always needing less sunlight than plants with smaller leaves, which is an oversimplification that is not always true in real life. Again, she did not want students to pick up misinformation from the simulation.

In addition to having concerns about the scientific accuracy of the simulation, Ms. Lawson also expressed concerns about the clarity of representation within the simulation. In particular, she was concerned that students might not notice the different leaf sizes of the different plants, just as she herself had not noticed differences in plant leaf size, when looking at the pre-test. Ms. Lawson was also concerned that students would be distracted by the differences in flower color and therefore not notice the differences in leaf size. She said that if she had been designing the simulation, she would have made all the flowers the same color.

Table 6.6

Ms. Lawson's Concerns about the Mystery Plant Simulation

Potential Challenges/Concerns	Quote
Simulation may cause students to think that only one parent plant is needed for reproduction to occur.	"So we only know one parent... isn't that misleading? You can't answer that [prediction about offspring]. Because you need both parents… [and you need to know] recessive or dominant….it depends on …what alleles are passed…I worry that they're going to think you only need one parent plant" (Lawson, PL).
In real life, a plants leaf size does not necessarily determine how much sunlight it needs.	"'Mystery plants with thin leaves are adapted to an environment of sunlight. The mystery plants with larger leaves come up in places with less light.' Okay, so that deals with their photosynthesis … [but] that doesn't make any sense! Think about how many things grow [in real life.]" (Lawson, PL).
To understand the simulation, students need to realize that the different offspring have different leaf sizes. However, students may not notice variation in leaf sizes.	"I get why they [they flowers] are different colors. But I wish they weren't [different colors], if they're just looking at leaf size."(Lawson, PL)

Based on both her goals and concerns, Ms. Lawson developed plans for how to support student sensemaking while working with the plant simulation (see Table 6.7). Overall, she felt that she would need to provide more support for the Mystery Plant Simulation than she had for the Net Force or Friction Simulations. ("I think they're going to need more support with this simulation," Lawson, SR). This support would include both making sure that students knew how to use the simulation controls and helping guide students' attention as they watched the simulation. Ms. Lawson planned to alternate between giving students time to explore the different simulation screens and discussing those screens as a class. She also mentioned the importance of reading aloud all information on the simulation, since some students might have trouble reading it on their own. Like Ms. Lane, Ms. Lawson also mentioned the possibility of using prompts within the simulation to support writing a claim as a class.

Table 6.7

Ms. Lawson's Plans for Supporting Student Sensemaking

Plan for supporting sensemaking	Quote
Making sure students know how to use simulation controls.	"I need to show them this feature [how to move plants in the Virtual Greenhouse]" (Lawson, PL).
Alternate working with the simulation as a whole class with students working with the simulation individually.	"What I may do is lead it, but let them have their computers in front of them. Read through this, for my lower readers… And then have them try scenarios, then come back whole group, talking about it. Then go to the next page" (Lawson, PL).
Use the conceptual questions posed within the simulation as the basis for constructing a claim as a class.	"We could even use the question and the answer and type together. I've done that whole group" (Lawson, PL).
Guiding students to watch the simulation carefully and helping them identify what to watch for.	"They're going to need to be told to watch it for a while, because clearly there's stuff changing" (Lawson, PL). "Letting it play. Talking about what we see. Reminding them that because the leaves are hard to see the size, they're color coded," (Lawson, PL)

Overview of Ms. Lawson's enactment of the Mystery Plant Simulation lesson. Ms. Lawson taught the Mystery Plant Simulation over one day. The lesson was 57 minutes long. Before class, I downloaded the Mystery Plant Simulation onto students' laptops. This was a long process (3-5 minutes per computer) that involved installing Java, accepting several security warnings, and restarting the process whenever it timed out. This process only worked on about 75% of student's computers – on the other 25%, I was not able to download the simulation at all. At the beginning of the lesson, Ms. Lawson introduced the simulation. She presented the first screen and introduced the concepts of "variation," "offspring," and "generation." As part of this discussion, she reminded students what they had learned about pollinators (such as midges) in previous MLs lessons. In doing so, she followed through with her pre-lesson plan to discuss pollination, to prevent students from thinking that a single parent plant could produce offspring all by itself.

Ms. Lawson then moved onto the Virtual Greenhouse Screen. She demonstrated how to operate this part of the simulation using the Smartboard, and then gave students time to experiment with it on their own laptops. (Because not all the laptops were working, some students worked in pairs.) As students worked, Ms. Lawson gave procedural tips for how to use the simulation more effectively (e.g. how to use the magnifying glass to determine leaf size). Ms. Lawson then brought students together to discuss what they had discovered while they explored the Virtual Greenhouse.

Next, Ms. Lawson led a class discussion based on the information and prompts on screens three and four (this included making connections to the adaptations of cacti and Venus flytraps as well as discussing variation among offspring). After this discussion, she had students answer the multiple choice prompts on screens three and four at their own computers. She then introduced the Virtual Field using the SmartBoard and gave students time to explore that, as well. As students worked with the simulation at their individual computers, Ms. Lawson provided support (e.g. reminding students to watch and interpret the bar graph as the Virtual Field changed over time.) Ms. Lawson then led a whole-class discussion focused on what students had noticed and learned from the Virtual Field. Finally, Ms. Lawson gave students time to work through the graph interpretation questions on screen six, followed by a class discussion of these questions. Like Ms. Lane, Ms. Lawson ended the simulation after screen six.

The following table summarizes Ms. Lawson’s talk during the Mystery Plant Simulation Lesson.

Table 6.8

Ms. Lawson's Talk during the Mystery Plant Simulation Lesson[25]

Talk Type	Frequency
Providing Information	28%
Directive or Discussion Etiquette	21%
Conceptual Question	15%
Inviting	9%
Experiential Question	9%
Directing Attention	7%
Recalling Shared Experiences	4%
Revoicing	3%
Repeating	2%
Requesting Information or Clarification	1%
Praise	0%
Procedural Question	0%

Types of teacher talk that supported student sensemaking. As in the previous chapter, in the sections that follow I will be focusing on types of talk that both solicited and amplified student ideas: directing attention, experiential questions, conceptual questions, inviting, requesting information or clarification, and revoicing.

Directing attention. Like Ms. Lane, Ms. Lawson directed student attention as students worked with both the Virtual Greenhouse and the Virtual Field. As in the case of earlier simulations, this included general prompts designed to support observation ("What do you see?" PLD1) specific prompts guiding students to look at a particular feature of the simulation ("You need to look . . . is there any difference in color in that field?" PLD1) and prompts encouraging student to notice how simulation features changed over the course of a scenario ("Watch how the plants in the field change as many seasons go by" PLD1). This final example of directing students' attention was drawn from a prompt embedded in the simulation itself, which Ms.

[25] Does not include one-on-one conversations with individual students

Lawson read aloud, just as Ms. Lane had done. Consistent with her earlier plans, Ms. Lawson made sure to direct students' attention to simulation features that Ms. Lawson herself had initially had trouble noticing or interpreting (e.g. representations of variation in the amount of light or variations in the leaf size.)

Experiential questions. As in previous simulations, Ms. Lawson asked experiential questions focusing on connecting to with general life or out-of-school experience ("[Among families] is there variation there in hair color? Or eye color? Or skin color?" PLD1) as well as experiences that occurred earlier within the same science lesson ("Over time, did you see more variation or less?" PLD1). After viewing a video of herself using experiential questions to support students to connect variation in plant offspring with variation in human offspring, Ms. Lawson commented "I think what I'm trying to do with that [question] is adapt it to something that they're more familiar with, right?" (Lawson, SR).

Conceptual questions. As in previous lessons, Ms. Lawson used conceptual questions to support students to make predictions ("Make a prediction. How many different kinds of plants will be growing in the field after many seasons?" PLD1), develop generalizable claims ("What do you think that tells you, about the amount of sunlight?"), and support their ideas with reasoning ("Why did you think, 'after many seasons'?" PLD1). As in Ms. Lane's enactment of the Mystery Plant Simulation, Ms. Lawson often used the conceptual questions that were provided in the simulation itself, as well as conceptual questions that she formulated herself. Given Ms. Lawson's concerns about whether students would be able to easily interpret simulation features, it makes sense that she again asked a number of conceptual questions related to supporting students to interpret simulation features. In these questions, she asked them to explain how they interpreted different simulation features ("Somebody else tell me what is the vertical part of the graph explaining?" PLD1). Other of Ms. Lawson's questions supported student understanding of key concepts including: offspring, season, and variation (e.g. "What do you think offspring are?" PLD1).

Inviting, requesting clarification, repeating, and revoicing. As in previous simulation lessons, the combined frequency of these moves (15%) speaks to the extent to which Ms. Lawson valued student contributions and ideas. Again, as in previous simulation lessons, Ms. Lawson invited student participation not only by calling on students, but also by inviting students to turn and talk with students sitting nearby. Additionally, at several different points she issued invitations to specific students who had not been participating ("Kenisha, Owen, I want you adding to this conversation please," PLD1). Ms. Lawson also prompted students to expand and clarify their thinking ("Keep going. I want to hear more about the science behind this. What's happening?" PLD1). Also as in previous lessons, Ms. Lawson used revoicing to amplify and expand on student ideas. For example, in the exchange below Ms. Lawson takes up a student idea of "babies" and links it to the idea of multiple generations.

S: It means like "babies."

Ms. Lawson: Babies – or the next generation. (PLD1)

Considering students' responses to Ms. Lawson's sensemaking support. Again, I close the analysis of Ms. Lawson's enactment by examining a larger stretch of dialogue.

Ms. Lawson: Okay, so Christine is saying that some of the seeds grew in that middle box. Did you have to move two?

Connor: Yes, one to the very top, one to the very bottom, and then four survived in the middle.

Ms. Lawson: Okay, so what do you think that had to do with? Rob?

Rob: Because the first box, the leaves were-

Ms. Lawson: We're listening to Rob.

Rob: At the size one. In the second box, they were at size two. And the third box they were at size three.

Ms. Lawson: So somebody else, who else found that? That size one was in that upper box, size two leaves were in the middle box for your simulations, and size three leaves were in the bottom box?

[Students raise hands/indicate agreement]

Ms. Lawson: Okay, so hold on. Rob said, "Okay, that's what we found." Who thinks they can build off everything we've heard and tell me what do you think is going on with that? If you have to move some plants around and then you figured out different size leaves grew in the different boxes. Diana?

Diana: Because, the box one there's the most sun and the skinny leaves. In box two there's less sun and they're pointy leaves. And in box three they have the least sun and they have the really big leaves.

Ms. Lawson: Okay, so you're noticing a variation in the leaves, right? A difference in the leaf size and a difference in the amount of sun. Is that what you're saying? And so leaf one needs the most or the least?

Diana: The most. (PLD1)

In the above excerpt, Ms. Lawson supported her students to share what they learned while exploring the simulation individually or in small groups. At the beginning of this excerpt, Ms. Lawson repeated Christine's findings (that most of the seeds were able to thrive in the planter box with medium sunlight, but two seeds needed to be moved into different boxes.) Ms. Lawson asked if other students have the same results as Christine, and Connor shared that he did. Ms. Lawson then asked another student to interpret the results that Christine and Connor shared. After a brief aside, in which Ms. Lawson reminded her students to be respectful listeners, Rob shared the observation that the plants that grew successfully in each different box had different sized leaves. Again, Ms. Lawson checked across the whole class to see if everyone else had results similar to Rob's.

After the whole class agreed that they had the same finding as Rob, Ms. Lawson pressed for someone to interpret Rob's findings. Diana reiterated Rob's findings, adding more detail about the features of the different kinds of plant leaves and the conditions in the different boxes. Ms. Lawson then asked Diana to make a connection between the size of the leaves and the conditions in the box, and Diana successfully made this connection.

Note that in the example above, Ms. Lawson supported students to compare their data with each other, and to identify patterns. She did not support students to make botanical claims based on their findings. This was a deliberate choice on her part, as she did not want to disseminate misinformation to her students. (In real life, leaf size does not determine how much sunlight a plant needs.)

Furthermore, in this excerpt Ms. Lawson balanced (a) giving students time to explore the simulation independently and (b) making sure that everyone in the class had the opportunity to engage in a sensemaking discussion. Her repeated verbal move of asking the class if they saw the same thing in their simulation helped support engagement and participation. It also introduced the scientific practice of replicating investigations in order to ensure validity.

Considering the Relationship between Instruction and Curriculum.

As in the case of the previous two simulations, both Ms. Lane and Ms. Lawson engaged in a number of practices to support student sensemaking while working with the Mystery Plant Simulation. These practices included: directing student attention, helping students make connections to previous experiences, asking students about key science concepts, and asking many different types of conceptual questions (e.g. questions designed to support different scientific practices or questions designed to help students interpret simulation representations.) As in the case of the Friction Simulation, *none* of these practices were included in written support materials provided by the MLs curriculum. (See Chapter Three for more details on written support materials for the Mystery Plant Simulation.) Again, as in the case of the Friction Simulation, Ms. Lane and Ms. Lawson both imported sensemaking practices from the Net Force Simulation lesson.

As in the case of the prior two simulations, Ms. Lane and Ms. Lawson both capitalized on advantages provided by the Mystery Plant Simulation Design. In particular, both teachers made use of the conceptual questions that were interspersed within the Mystery Plant Simulation, discussing each of these questions as it arose. Both teachers also spent extra time supporting the visuals in the Mystery Plant Simulation, given that they felt that not all of the visuals were straightforward or simple to interpret. (E.g. flower color was used as a proxy to represent leaf size.)

Teachers Assess the Value of the Mystery Plant Simulation as a Learning Tool

The perspective of Ms. Lane. Both before, during, and after working with the plant simulation, Ms. Lane had positive things to share (see Table 6.9). Before the simulation, Ms. Lane reported that, last year, she had found the simulation confusing but she understood it better this year and looked forwards to teaching with it. While teaching with the simulation, Ms. Lane shared that the students were loving working with the simulation. After teaching with the simulation, Ms. Lane shared that the plant simulation was the most helpful of all the simulations, because there is no way to show plant populations changing over time without a simulation. (Friction and net force, on the other hand, can be shown through physical experiments.) Nevertheless, after teaching with the simulation, Ms. Lane still had a few concerns about the physical representations in the plant simulation including the fact that the symbols representing full/partial/little light were hard to see and that the leaf sizes were hard to see ("The suns that were on the side, they were hard to see. So maybe make them orange or make them red? . . . the leaf sizes are not as easy because I have to tell you, I probably did not notice those right off the bat," Lane SR). Ms. Lane recommended keeping the Mystery Plant Simulation in the MLs curriculum. She also shared that in future years, she would like to have the students write down observations or claims after working with the plant simulation. ("And again, in a perfect world, I'd probably have them do, like maybe an exit ticket," Lane SR).

Table 6.9

Ms. Lane's Reflections before, during, and after Teaching the Plant Simulation

Time	Quotation
Before Teaching	"I think I'm going to understand it much more this year. Last year, I was still a bit confused just on the connections and what the big idea was just for myself . . . I'm looking forward to doing this" (Lane PL)
While Teaching	"They love it clearly," PLD1
After Teaching	The plant one. Well, that's that that one seems to help me the most - teach it to them. I don't know how else. I mean, I'm sure there's other ways, but I don't know how else I would be able to get them to kind of see what happens over time. That would be fun.

The perspective of Ms. Lawson. Like Ms. Lane, Ms. Lawson had positive things to say about the Mystery Plant Simulation before and after teaching with it (see Table 6.10), and also recommended that it remain part of the MLs curriculum. Although Ms. Lawson had never taught this simulation before, she was confident that her students would do well with it. After teaching, she had some concerns about the simulation design (including visuals that were hard to see and buttons that weren't intuitive to use). She also had concerns about how difficult the simulation was to install, saying that installation difficulties took up time that she didn't have during science class: "you don't have time to get frustrated, you just don't" (Lawson, SR). To alleviate this concern, next year she plans to have students work in groups, two or three students per computer, which would minimize the number of times the simulation needed to be downloaded on different computers. Nevertheless, despite her concerns related to this simulation, Ms. Lawson still felt it was a very important part of the curriculum because it helped students explore concepts that cannot be explored through physical experimentation, because of the time scales involved. Like Ms. Lane, she felt there was no good way for students to experience and experiment with variation, adaptation, and survival of multiple generations of plants except by using a simulation.

Table 6.10

Ms. Lawson's Reflections before and after Teaching the Mystery Plant Simulation

Time	Quotation
Before Teaching	"I think my kids are going to do just fine with this," Lawson, PL Interview
After Teaching	"I find the simulations to be very supportive of student learning. I think with anything, there are some flaws that we found, right? …in the plants, one we know the sunlight really -- larger leaves -- it doesn't correlate, right between the levels of sunlight and having the skinny leaves or the larger leaves, in real life . . .The plant one, I think was a little problematic because of the buttons, right? Like they wanted to drag and click because the other simulations we dragged and clicked the people. … So that the plants one, it's really dark, right? It's hard to tell the soil change - it's just very dark. The seeds are very tiny, which I get, but also like, maybe not so tiny, I don't know. And then the leaves are all very close to the same size. Like all of it is like you need to really, really [pay attention] and so maybe that's good for them. But I don't want it to be misleading, either," Lawson, SR Interview. "And plants, it's not possible to really do all that [test natural selection in real life]. So I do like that one too…. it does reinforce more of what they actually need to know: what they actually need to take with them about the generations, about the offspring, and variations. I think it needs to stay because they get to see that," Lawson SR Interview.

Summary of Key Points in Relation to Research Questions

This chapter first asks *How do teachers support student sensemaking while working with the Mystery Plant Simulation? How do students respond to this support?* Findings in this chapter suggest that Ms. Lawson and Ms. Lane leveraged suggestions provided in the Net Force Lesson

Plan as they supported student sensemaking by a variety of moves including: directing student attention, asking different types of questions, and supporting students to make connections with their past experiences. In addition to talk that directly supported sensemaking, the teachers also engaged in talk that helped set conditions that could support sensemaking, for example by setting norms and expectations. Students and teachers engaged in dialogues where both worked together to co-construct ideas, with the teacher supporting students to both share new ideas and to develop their ideas more fully. The chapter then asked *What are the teachers' perspectives regarding the use of simulations as sensemaking tools?* Both Ms. Lane and Ms. Lawson felt that the Mystery Plant Simulation supported student learning, especially since the concepts covered by the Mystery Plant Simulation could not be covered via a hands-on experiment.

CHAPTER 7 Cross-Case Comparison

In this penultimate chapter of my dissertation, I return to my two research questions, this time looking across the enactments of all three simulations by both of the teachers. This chapter is divided into three sections, focusing on research questions 1A, 1B and 2.

1A) How do teachers support student sensemaking while working with simulations in the context of 3rd grade Project-based science?

In the sections that follow, I identify ways that Ms. Lane and Ms. Lawson worked to support student sensemaking before, during, and after teaching.

Before teaching. For all three simulations, both Ms. Lane and Ms. Lawson conducted careful pre-planning and preparation. Before teaching, both teachers previewed the simulation, identified potential challenges, and set goals for student learning. They used these goals and challenges to brainstorm a series of strategies that they might use while teaching and to consider potential connections to students' prior experiences. They also identified sections or features of the simulation that would be especially important, given their conceptual goals, and other aspects of the simulation that might be less essential. These pre-teaching practices were consistent across both teachers and across all three simulations.

On the one hand, these pre-planning and preparation meetings were highly influenced by my role as a researcher. Part of my data collection included a pre-simulation interview, during which the teachers and I discussed simulation controls, conceptual goals, potential challenges, teaching strategies, and connections to students' experiences. In other words, the data collection processes ensured that detailed pre-planning and preparation would occur.

On the other hand, both Ms. Lane and Ms. Lawson were already engaging in joint planning and collaboration, even prior to Ms. Lawson officially joining the MLs project. Throughout the year of this data collection, they engaged in reflective and collaborative conversations with each other, outside of the scope of my data collection. For example, Ms. Lane and Ms. Lawson routinely ate lunch together and discussed teaching science. They also often spontaneously texted each other (and me) new ideas they had tried during science. [26]And if one of them got stuck while teaching, they were likely to give the other a quick call. In other words, while my role as a researcher scaffolded collaboration pre-planning and preparation specific to the simulation lesson, this built on pre-existing practices of joint planning and collaboration that were already established between Ms. Lane and Ms. Lawson.

While teaching. During all three simulations, both teachers balanced many different teaching practices in order to scaffold their students' sensemaking. First, the teachers used a certain amount of their talk to set procedural expectations and set conversational norms. This helped maintain a respectful and productive climate where sensemaking conversations could occur. This type of talk was not the main focus of the dissertation, but its frequency was captured through the code "directive/discussion etiquette."

Second, teachers used some talk to "prime the pump" by checking in about procedures, directly providing information to students, or by helping students to make connections to their

[26] Note: this practice of lunching together and discussing science teaching pre-dated my dissertation study. Indeed, as discussed in the Methods section, Ms. Lawson and Ms. Lane's discussions about science teaching were what drew Ms. Lawson to ask for access to the MLs curriculum in the first place.

past experiences. These types of teacher talk were not the main focus of this dissertation, but their frequencies were captured through the codes "recalling shared knowledge," and "providing information."

Third, teachers created space for student voices through open-ended prompts inviting students to share their ideas and by repeating student ideas to make sure that they could be heard. This type of teacher talk was captured through the codes "inviting" and "repeating."

Fourth, teachers supported student sensemaking by directing student attention (either to make general observations about the simulation or to watch a particular portion of the simulation) or by asking conceptual and experiential questions. Through experiential questions, teachers helped students to make connections to life experiences, past science lessons, and the current science lesson. Through conceptual questions, the teachers supported students to share their understanding of important concepts, engage in scientific practices, and practice interpreting simulation features. This type of teacher talk was captured through the codes "directing attention," "conceptual question," and "experiential question."

Fifth, teachers expanded on student sensemaking by either revoicing student ideas or by pressing students to add additional detail and clarity. This type of teacher talk was captured through the codes "revoicing" and "requesting information or clarification"

Table 7.1 below shows how teachers balanced the different clusters of practices that I have described above for each of the three simulations.[27] It shows that, while exact proportions differed from lesson to lesson, the broad categories described above were a substantial part all the simulation lessons, regardless of teacher or simulation.

[27] The clusters of codes described above cover all but 2 codes ("praise" and "procedural question") which were omitted due to their relative infrequency.

Table 7.1

Frequency of Overarching Categories of Teacher Talk by Teacher and Simulation[28]

Teacher and Simulation	Setting norms and expectations	"Priming the pump"	Elicit Student Sensemaking	Providing space for student voices and Expanding Student Sensemaking
Lane Net Force	27%	18%	28%	22%
Lane Friction	13%	32%	34%	17%
Lane Mystery Plant	14%	31%	31%	20%
Lawson Net Force	21%	22%	29%	23%
Lawson Friction	31%	33%	16%	12%
Lawson Mystery plant	21%	32%	31%	16%

Looking across this table, the amount of talk devoted to setting expectations and norms range from 13% to 31%. This range could have been related to several factors that varied across the lessons. First, the lessons varied both in (a) total length and (b) how many days the lessons were divided across. For example, the lesson with the most time for norm-setting was taught for an hour straight, which was much longer than a typical science class.[29] Another factor that could have influenced levels of norm-setting talk was the disruption caused by frequent and unpredictable snow days, which affected some lessons more than others.[30]

The amount of talk that supported sensemaking was consistently around 30%, except for Ms. Lawson's enactment of the friction lesson. That lesson included long periods of individual student work time, during which Ms. Lawson circulated to have one-on-one conversations with individual students. Those conversations may have included conceptual talk that was not accounted for in this study (See chapter five for more details).

[28] Does not include one-on-one conversations with individual students

[29] This lesson was extra-long due to several logistical issues related to my schedule and the student teacher's schedule. For more details, see chapter 5.

[30] Note: the teachers were not teaching the exact same lessons at the exact same times as each other, so a given lesson might fall closer to a snow day in one classroom than in the other classroom.

The amount of talk in which teachers provided information to students was significantly lower in the two Net Force Simulations, as compared to the other simulation lessons. This may have been because students had shown strong levels of prior knowledge related to concepts of balanced and unbalanced force, as compared to friction and heredity. Alternatively, teachers may have chosen to alter their teaching practices for the latter two simulations based on their experience in the first simulation, although neither teacher mentioned this in interviews.

The amount of time providing space for student voices and expanding on student contributions was noticeably less in the Lawson Friction Simulation, as compared to the other enacted lessons. As mentioned previously, that simulation involved less whole-class discussion, which likely accounts for less time spent providing space for student voices and expanding on student contributions.

After teaching. After teaching, both teachers talked with me about what changes they might make the following year. Consistently, both teachers had new ideas they wanted to try; they wanted to figure out ways to give students more agency during the lesson. These “next year” conversations occurred both during formal interviews and during informal conversations that the teachers had with each other (e.g. during lunch, during prep, etcetera.)

Table 7.2 summarizes the different ways that the teachers supported student sensemaking before, during, and after enacting the simulation lessons.

Table 7.2

Strategies for Supporting Sensemaking

Strategy to support student sensemaking
Before teaching • Preview simulation: How do the controls work?, What do the graphics represent?, etcetera • Consider connections between simulation content and students prior experience/knowledge • Identify potential challenges students may face when using the simulation • Establish goals for student learning: scientific concepts and practices • Decide how long to use the simulation and what features/sections to foreground • Identify tentative strategies to meet goals while avoiding challenges (see "while teaching") • Compare ideas with colleagues

While teaching
<u>Support a learning context where students sensemaking talk can occur:</u>
• Class culture where there is significant space for student voices during discussions
• Support students communication strategies and respectful listening
• Adapting pre-existing plans and ideas as needed
• Explicitly provide information, context, and guidance when needed
• Open lesson with a student-led discussion reviewing prior learning
• Maintain public record of class's talk/discussions
• Vary participation structures
    o Teacher models using the simulation
    o Teacher invites student(s) to model using the simulation
    o Students work together in small groups
    o Individual exploration time during science
    o Optional exploration time after science

<u>Elicit student sensemaking</u> Support students to… • Consider the purpose of the simulation • Make connections with prior experiences - (science & outside life) – out of school, prior science lessons/ earlier in same lesson • Interpret simulation features • Discuss key concepts/vocabulary • Make observations - general/particular feature/changes in feature • Make predictions • Back predictions with reasoning • Conduct fair tests • Accomplish specific goals • Record investigation results • Interpret results and construct claims
<u>Expand student sensemaking</u> • Re-voice student contributions • Help students to refine/clarify their thinking

After teaching

- Reflect on what worked well and potential changes for next year

1B) Does this support, or student response to this support, shift across the three simulations?

Both teachers were relatively consistent in their use of sensemaking support strategies across all three simulations, despite differences in (a) the support features provided by different simulations, and (b) the level of support provided by the ML curriculum. Student response to teachers' support was similarly consistent. Recall from the previous chapters that all six extended examples that include student responses follow a pattern wherein teachers and students co-construct ideas over a series of exchanges that gradually refine the idea over time. Often, the student had the role of contributing new ideas to the conversation, while the teacher had the role of soliciting ideas, refining ideas, and/or drawing connections between ideas.

In the following section, I discuss ways that differences in both (a) simulation features, and (b) the level of support provided by the MLs curriculum impacted teacher sensemaking support strategies. I also discuss ways that teachers achieved continuity in sensemaking support strategies, despite differing simulation and curricular supports.

Influence of simulation features on teacher sensemaking support strategies. For each of the three simulations, specific types of conceptual prompts were either enabled or constrained by specific simulation features. For example, in the Net Force Simulation, Ms. Lane encouraged students to aim for specific outcomes (e.g.: the simulation isn't moving, but the red and blue pullers aren't identical to each other.) She was able to do this because it was relatively easy to see differences in outcome in the Net Force Simulation. There were only three possible outcomes: red wins, blue wins, or no movement, and each of these outcomes was clearly visible. In contrast, it was harder to see the outcomes of the Friction Simulation, because the pushed object would rapidly reach maximum speed causing the pusher to do the splits and the simulation to end. For this reason, both Ms. Lane and I were not able to come up with specific outcomes for students to aim for when using the Friction Simulation.

On a similar note, it was possible to control variables when using the Friction Simulation, but it was not possible to control variables when using the Net Force Simulation. The three potential independent variables in the Friction Simulation were all unrelated to each other (mass, amount of applied force, and amount of frictional force.) In contrast, two of the independent variables in the Net Force Simulation were interdependent; that is, by increasing the number of people pulling, you also had to give them different positions on the rope, because two people could not pull from the same knot. This meant that it would have been difficult to teach controlling variables using the Net Force Simulation.

Like the Net Force and Friction Simulation, the Mystery Plant Simulation also brought affordances and constraints. Its affordances included embedded conceptual questions, which both Ms. Lane and Ms. Lawson used as focal points for whole-class conceptual discussions. On the other hand, the Mystery Plant Simulation only had one variable that could be changed (amount of sunlight) and one variable that could be measured (whether plants survived to reproduce). This made it hard to use the simulation to support the scientific practice of planning investigations or conducting fair tests, as such practices make more sense in the presence of multiple potential independent variables.

Looking across the three simulations, the features of the Net Force simulation leant themselves to optimizing outcomes, the features of the Friction simulation leant themselves to controlling variables, and the features of the Mystery Plant simulation leant themselves to discussing specific conceptual questions included as part of the simulation. These differences shaped the *types* of conceptual questions that teachers asked in each simulation. However, the *presence* of conceptual questions was consistent across both teachers' enactments of all three simulations, as was discussed in chapters four, five, and six.

On a similar note, across all three simulations, teacher talk fulfilled functions that analogous to functions that could have been fulfilled by simulation features. None of the three simulations possessed attention-directing avatars (Moreno et al., 2010), yet the teachers helped direct student-attention while using the simulation. None of the simulations contained audio voice-overs (Liu & Chuang, 2011), but the teachers shared oral information as students worked with the simulation. The PhET simulations did not contain any type of simulation prompts to provide information (Hulshof & De Jong, 2006), support hypotheses testing (Chang et al., 2008), or support investigation design (Chang et al., 2008) – but the teachers took on the role of providing information, supporting hypotheses testing, and supporting investigation design.

In sum, teachers tailored their conceptual prompts to match simulation affordances, while using teacher-talk to compensate for features that were not present in a given simulation.

Influence of curricular context. Across all three simulations, the types of experiential questions that teacher asked were related to the curricular context provided by the ML unit. In other words, teacher sensemaking support was influenced by how many of the ideas introduced in the simulation had previously been introduced in the curriculum. When teaching the Net Force and Friction lessons, both teachers were supported by the fact that students had already worked with force and friction in the MLs curriculum, before beginning to work with the simulation. For these simulations, teachers were able to support students to make connections to previously shared experiences in science class. In contrast, the ideas of heredity and selection pressure, introduced in the Mystery Plant Simulation, had not been pre-seeded by the MLs curriculum.[31] This meant that teachers were *not* able to make connection to previous science lessons. Instead, both teachers decided to begin the lesson by connecting heredity and variation to students' life experiences.

To my surprise, the sensemaking support provided in the MLs materials often did not correlate with the nature of teachers' sensemaking support during the enacted lesson. This was because teachers often added to and expanded on the written lesson plan. This was particularly notable in the case of the friction lesson, which was only several lines in the written curriculum, but expanded to fill three days in Ms. Lane's class and a nearly-hour-long lesson in Ms. Lawson's class. Both teachers expanded the lesson to include scientific practices (such as designing fair tests and making claims.) Teachers then supported student sensemaking around these newly-added scientific practices, using the same types of sensemaking support as were introduced in the first simulation lesson. As a result, even though the lessons varied widely in length and complexity, the enacted lessons did not show wide variety in the nature and frequency of sensemaking support.

2) What are the teachers' perspectives regarding the use of simulations as sensemaking tools?

As discussed in Chapters 4, 5, and 6, teachers had positive things to say about all three simulations. These positive comments were consistent across all three simulations and were

[31] This was both because (a) these features were not central to the MLs plant unit and (b) the teachers had to skip several MLs Plant Unit lessons due to losing 11 days of science to snow days.

consistent across multiple data sources: teacher pre-interviews, teacher comments during the lesson itself, and teacher post-interviews.

Table 7.3 below provides a summary of teacher comments about the value of the simulations. I initially compiled the table below by reading across all the teacher interviews and making a list that summarized key ideas. I shared this list with the teachers during a member check conversation and both teachers confirmed that the list was consistent with their thinking about the three simulations. Overall, both teachers saw all three simulations as engaging and valuable learning experiences. In particular, they noted that the simulations put students in a position of being able to "make things happen" and they associated the simulation support of student agency with students displaying high levels of engagement while working with all the simulations.

When discussing the relationship between the simulations and the MLs curriculum, the teachers noted two different ways that the simulations supported the rest of the curriculum. First, some of the simulations synergized with hands-on investigations providing multiple opportunities for students to engage with the same ideas in different ways. Second, the simulations allowed students to experience virtual investigations that would not be possible to conduct as physical acts investigations.

However, while the teachers recognized strengths of the simulations, they did not consider the simulations to be perfect. They noted that the simulations were sometimes hard to figure out how to use, contained confusing visuals, or oversimplified in ways that could lead to misconceptions. The teachers did not see these challenges as insurmountable; on the contrary, they felt that some of the shortcomings of simulations could serve as a jumping off point for meaningful class discussions. Furthermore, teachers reported becoming more confident with using the simulation as they gained additional practice from year to year.

The teachers reported that the greatest roadblock to using the simulations was technological issues. Problems that arose from Wi-Fi connectivity issues, difficulty downloading simulations onto laptops, smart boards freezing up, or other issues that were out of the teachers control were frustrating and took time away from sensemaking.

Table 7.3

Participant Feedback

Students and teachers assess the value of simulations as learning tools
Teacher Feedback • Simulations were an engaging and valuable learning experience • Teaching the simulations gets easier with multiple enactments • As teacher comfort level grows, they look for ways to increase both student participation and the conceptual rigor • The simulations consistently engage students - they enjoy “making things happen” (this includes students who are all too often disengaged) • Simulations can help students understand the relationships between different parts of a complex system – including systems that change too slowly to be manipulated/observed in a physical experiment • The simulations synergize well with the hands-on experiments found elsewhere in the curriculum • None of the simulations are perfect: may contain non-intuitive controls, features that distract students, graphics that are not easy to interpret the meaning of, or can even plant misconceptions • However, potentially confusing aspects of the simulation can also be springboards for great discussions • Inconsistent technology poses a challenge when working with simulations

In the final chapter, I consider implications for teaching, teacher preparation, and curriculum design, as well as reflections on limitations of this study and suggestions for future research.

CHAPTER 8 Discussion

This discussion chapter is organized around the implications of the findings presented in chapters 4-7. It is organized occurring to the implications for: teaching, the design of simulations, and the design of curriculum. The implications section is followed by a discussion of limitations and future research.

The first research question asked *How do teachers support student sensemaking while working with simulations in the context of 3rd grade Project-based science? Does this support, or student response to this support, shift across the three simulations?* The findings that address this research question have implications not only for teaching, but also for curriculum design and simulation design. The second research question asked *What are the teachers' perspectives regarding the use of simulations as sensemaking tools?* This question primarily has implications for curriculum design as it does not focus on teacher pedagogical decisions or simulation design decisions, but rather identifies whether or not teachers found the simulations to be a valuable addition to the curriculum.

Implications for Teaching

As described in Chapter 2 of this dissertation, most of the literature on simulations does not consider the role played by the classroom teachers in general, and elementary classroom teachers in particular. One of the goals of this dissertation was to provide support for elementary science teachers who are interested in bringing simulations into their classrooms.

Balancing guidance and open-exploration. We know from the literature that teachers may have concerns about how much guidance to provide when introducing a simulation (Hennessy et al., 2006). Excessive guidance can potentially hamper student initiative, removing potential learning opportunities (Chamberlain, Lancaster, Parson, & Perkins, 2014; González-Cruz, Rodríguez-Sotres, & Rodríguez-Penagos, 2003; Moore, Herzog, & Perkins, 2013). Insufficient guidance may also limit learning opportunities; left to themselves, students may focus on surface level features at the expense of conceptual content (Ardac & Sezen, 2002) (Stephens & Clement, 2015; Wu & Huang, 2007). The existing literature describes several practices intended to balance guidance and open-exploration in middle school, high school, and university classrooms.

1. Collaboratively generate and test ideas using the simulation (Hennessy et al., 2006)
2. Begin with open-exploration and then move towards teacher-guided exploration (Podolefsky et al., 2013)
3. Embed guidance in the simulation itself (Hulshof & De Jong, 2006)

As described in the case studies above, Ms. Lane and Ms. Lawson both used versions of all three practices when supporting students to use the simulations. However, both teachers spent extensive time collaboratively generating and testing ideas with the PhET simulations, but not with the Concord Simulation. This suggests that the practice of "collaboratively generating and testing ideas" may not work equally well with all simulations. This strategy may fit well with simulations that provide users with multiple variables to control, because such simulations allow for multiple hypotheses to be generated and tested. However, this strategy may be less effective with simulations that put more limits on user choice.

At times, both Ms. Lane and Ms. Lawson gave students “time to explore” preceding a formal class discussion, in ways consistent with the second literature-based practice described above. However, Ms. Lane and Ms. Lawson also mixed-and-matched exploration and discussion time in ways not currently described in the literature. This included:

- allowing students to explore on their laptops *during* a class discussion[32]
- allowing students to explore on their laptops during centers time, after science class[33]
- Beginning with a class discussion and then allowing students a full day of open exploration on the following day[34]
- allowing students a full day of open exploration, with class discussion on the following day[35]

All three of these examples from Ms. Lane and Ms. Lawson’s teaching take advantage of a certain flexibility to the daily schedule, which might be more available to elementary teachers, as compared to teachers in middle, high school, or university who may only have their students during science period, as opposed to during the entire day. This suggests that elementary teachers may be able to strike a balance between open-exploration and teacher-guidance in ways that would not necessarily be available to teachers of older students.

The third strategy, which consists of relying on simulation embedded guidance, was used by both Ms. Lane and Ms. Lawson when teaching with the Mystery Plant Simulation (i.e. referencing simulation embedded prompts). However, neither teacher ever exclusively relied on simulation-based guidance: both teachers felt that teacher-guidance would be needed during part

[32] See “Overview of Ms. Lawson’s enactment of the Mystery Plant Simulation” for more details.
[33] See “Overview of Ms. Lane’s enactment of the Friction Simulation” for more details.
[34] See “Overview of Ms. Lane’s enactment of the Net Force Simulation” for more details.
[35] See “Overview of Ms. Lane’s enactment of the Net Force Simulation” for more details.

(though not all) of each simulation-based lesson. It may be that the strategy of exclusively relying on simulation-based guidance is more suited towards older students, for example students in a university-level course. In this case study, both teachers felt they had an important role to play guiding students through the simulation and supporting students to interpret the results. This is consistent with what we know about the important role played by teacher talk in supporting student learning in elementary science classrooms (Manz, 2015).

Drawing from talk practices used to support scientific-inquiry. While the literature on teacher talk in the context of supporting sensemaking with simulations is scant, there is a growing body of literature that considers how teacher talk can support sensemaking across various academic disciplines, including science (Fitzgerald & Palincsar, 2019). This study found many parallels between teacher moves designed to support sensemaking in the context of simulations and teacher moves that have been shown to effectively support sensemaking in science instruction, considered more broadly. This overlap in sensemaking moves includes: using conceptual questions to frame class discussions (Cervetti et al., 2014), making connections across a science unit (Puntambekar et al., 2007), making connections to students' out-of-school experiences (Puntambekar et al., 2007), revoicing student ideas in order to reframe an existing idea in terms of scientific language (O'Connor & Michaels, 1993; Puntambekar et al., 2007), using evidence to evaluate mutually-exclusive predictions (Herrenkohl & Cornelius, 2013; Herrenkohl et al., 2011), supporting students to move from observations to claims (Manz, 2016; Manz & Renga, 2017), pressing students to share their reasoning (Puntambekar et al., 2007), pressing students to expand or clarify their thinking (Hogan et al., 1999), and using dialogue to collaboratively generate and critique claims (Engle & Conant, 2002; McNeill & Pimentel, 2009). This suggests that teachers were able to import research-based strategies for supporting sensemaking during scientific inquiry into simulation-based lessons. By using these strategies, the teachers capitalized on similarities between simulation-based inquiry and hands-on scientific inquiry. However, more research would be required to identify whether other strategies might be available that capitalize on ways that simulations *differ* from hands on inquiry. In particular, future research might consider how teachers might support students to understand the affordances and limitations of simulations as representations.

Interpreting representations and developing meta-representation. Existing research has shown that undergraduate students may deliberately ignore representations in a simulation, if they are not comfortable interpreting those representations (Hsu & Thomas, 2002). This suggests that simulation users may need support interpreting representations in order to fully access all the information provided by the simulation. This study shows multiple ways that the teachers supported students to interpret simulation representations. (For example, by asking students to interpret simulation features or by asking students to note how specific simulation features are changing over time.)

Recall from the literature review that interpreting simulation representation was one of the skills that diSessa (2004) included under the umbrella of meta-representational competence. We see in this study that both teachers supported students to interpret simulation representations across all three simulations. Teacher support of student interpretation of representation tended to focus around interpreting specific aspects of individual simulation representations (e.g. the use of color to represent leaf size), as opposed to more abstracted or generalized discussion of trade-offs inherent in constructing scientific models. In future iterations of this work, it might be valuable to add such prompts for meta-level discussions of simulation representations to the MLs lessons and observe whether (and how) these prompts are taken up by classroom teachers. For example, each simulation lesson might include a portion that discusses how, in general, the act of creating representations of scientific phenomena require making certain simplifications that make the model or simulation easier to interpret, yet also distance it from the real world phenomena.

Creating conditions conducive to sensemaking. Although this dissertation has focused on characterizing teacher talk that directly supported student sensemaking, it also noted that teachers used a substantial amount of their instructional talk in ways that indirectly supported sensemaking. This included both (a) setting expectations and norms and (b) making sure that there was space for students to share their ideas. These practices were consistent with research that suggests the value of both norm-setting and opening the conversational floor in order to "set the stage" for sensemaking talk (Mercer et al., 2004; Michaels et al., 2008; Michaels et al., 2010).

Implications for Simulation Designers

The value of clear visual representations. Existing research has shown that the nature of the representations used in a simulation can impact how effectively the simulation supports learning, with overly complex representations sometimes distracting users from focusing on the simulation's core concepts (Lee et al., 2006; Liu & Chuang, 2011; Moreno et al., 2010; Neulight, Kafai, Kao, Foley, & Galas, 2007; Plass et al., 2009). In this study, one simulation confused even the teachers regarding interpreting its visual representations. This suggests that it might be helpful to prioritize beta-testing the clarity of simulation representations/visuals during the simulation design process.

Trade-offs in simulation design. Much has been written about trade-offs to be considered by simulation designers, including trade-offs between (a) giving the user freedom to explore versus guiding the user, and (b) making connections with larger curriculum versus the ability to stand alone (Clark et al., 2009). This study found trade-offs consistent with those described in the literature. In terms of the freedom/guidance trade off, the PhET simulations prioritized user freedom, while the Concord Simulation provided more user guidance. Each approach had its own advantages, with the PhET simulations allowing teachers to use conceptual questions that supported scientific practices such as designing investigations and controlling variables, while the Concord Simulation provided scaffolding (such as embedded questions) that directly prompted teachers to ask specific conceptual questions relevant to the simulation. In terms of the curricular connection/standalone trade off, the PhET simulations were designed to be curriculum neutral while the Concord simulation was designed to fit into the middle of a specific curriculum. This made the PhET simulations easier to integrate into a new curriculum, as compared to the Concord simulation. However, the Concord simulation was very successful within its intended curricular context (Horwitz, 2013; Horwitz et al., 2013; McIntyre et al., 2012). These trade-offs suggest that (a) simulation makers may make different design decisions depending on their goals for how and where the simulation will be used and (b) since different types of simulations have different affordances and limitations, it may serve students well to work with a “balanced diet” of different types of simulations.

The value of running “in browser.” Much has been written about the impact of the “digital divide” between the amount and quality of technological resources available to high-income school districts as compared to low-income school districts (US Department of Education, 2016). This study suggests ways that both simulation designers and policy makers can mitigate the digital divide. Policy makers would be able to lessen or eliminate many of the technological issues that occurred in this case study by (a) increasing the bandwidth of the internet available in classrooms, and (b) making sure to update, service, and maintain SmartBoards throughout the district. Simulation makers, in turn, could mitigate the digital divide by making simulations that can run within the internet browser, rather than needed to be downloaded. As we saw in these case studies, when a school's computers are outdated and the internet is slow, it can be prohibitively difficult to download simulations – especially if other applications (such as Java) need to be downloaded first. The difference between "simulation runs in the internet browser" and "simulation must be downloaded" can be the difference between "all students will get a chance to interact directly with the simulation" and "the simulation can only be done as a whole class demonstration."

Curating a library of NGSS-aligned Simulations. This study demonstrated that when simulation designers and science teachers choose to use a simulation that is not a perfect fit, there may be some implementation challenges. Nevertheless, teachers may choose to continue using said simulation, even though it is not ideal for their purposes, because they cannot find any other simulations covering the relevant topic. This suggests that it might be useful to develop a more organized and complete library of NGSS-aligned simulations.

The NGSS encourages teachers to provide students with the opportunity to learn science through simulations (NGSS Lead States, 2013). However, as of the writing of this dissertation, there is no comprehensive central repository for NGSS-aligned simulation. It might be useful for simulation designers to decide on a central location where *all* NGSS-aligned simulations will be stored (e.g. the NSTA repository of NGSS-aligned resources, including simulations). It might be further useful for simulation designers to compare existing simulations with NGSS Performance Expectations and determine which performance expectations are amply represented by simulations (e.g. certain force and motion PEs) and which might benefit from the creation of additional simulations (e.g. certain life sciences PEs).

Implication for Curriculum Design

Simulations can be a positive learning experience for both teachers and students. Previous research on simulations has found a range of student attitudes towards simulations. In some cases, students promoted more positive attitudes towards learning (Akpan & Strayer, 2010; Kiboss et al., 2004) to working with physical experiments. In one study, simulations did not impact students' attitudes towards learning (Çığrık & Ergül, 2009). In other cases, students objected to learning through simulations, objections which sometimes centered around the complete lack of hands-on experiences during science instruction (Ardac & Sezen, 2002; Kayumova & Cardello, 2018). This study provided additional evidence that, at least under certain conditions, simulations can be a positive learning experience for students and teachers alike. More research would be needed to determine why teachers in these case studies found the simulations to be both valuable and engaging learning experiences, and to what extent their positive evaluation may have been related to the simulations being positioned within a curriculum that was rich in many different kinds of learning opportunities (Kayumova & Cardello, 2018).

Simulations can serve multiple pedagogical purposes within the curriculum. Literacy scholars have identified multiple ways that written texts can support science inquiry. These include (a) providing context for investigations, (b) modeling scientific processes, (c) supporting first hand-investigations, (d) providing opportunities for second hand investigations, and (e) delivering content (Cervetti & Barber, 2008 313). In a similar vein, this study shows that simulations can play different roles in supporting inquiry including: (a) engaging in multiple different scientific practices, (b) reinforcing content that had already been introduced in hands-on investigations, (c) previewing content that would be later introduced in hands-on investigations, and (d) providing representations of concepts that could not be shown through hands-on investigations[36]. This suggests that, like texts, simulations can support hands-on inquiry in a variety of ways. Also, just as different types of texts offer different pedagogical affordances in inquiry-based curriculums (Palincsar & Magnusson, 2001), different types of simulations may be more suited to providing different types of support.

There are multiple ways for curricular materials to scaffold simulation enactments. As mentioned in Chapter 2, the vast majority of literature on simulations does not consider their curricular context (Rutten et al., 2012). As a result, there is currently little guidance available to curriculum designers regarding the kinds of curricular supports that most effectively support teachers to enact simulation-based lessons. This study provides several different examples of curricular scaffolds.

From my perspective, one of the most important scaffolds was the *Week at a Glance*. This scaffold allowed the teacher to quickly reach (a) the simulation itself and (b) suggestions for how to use the simulation. While it might seem like a simple thing, having all relevant curricular materials and supports in one place was a big time saver. Saving teacher time has many positive impacts including reducing the length of transitions and letting the teacher focus more of their attention on teaching science, as opposed to locating science materials.

Somewhat to my surprise, there was no observable relationship between the level of detail provided in the lesson plan and the length/complexity of the enacted lesson. On the

[36] See Chapter three for more details on how the simulation related to the overall ML curriculum, including connections to previous and subsequent hands-on investigations

contrary, the least detailed lesson plan (the Friction Simulation) ended up generating some of the longest and most complex lessons. Rather than limit themselves to specific suggestions from the lesson plan, teachers drew flexibly from scientific practices introduced in previous lesson plans. This might suggest that having a “rich brew” of different scientific practices across an entire curriculum is more important than the level of detail provided in any individual lesson. However, more research would be required to see whether teachers in general are likely to engage in such cross-pollination between different lessons, or whether these two teachers were unusual in that respect.

Limitations

Generalizability. In general, qualitative case studies can provide detailed information about particular instances of teaching and learning, but it is risky to over-generalize from them (Hesse-Biber & Leavy, 2010). In this particular case study, there are multiple factors that might limit generalizability. First, the sample size is small, with only two teachers and around fifty students. Second, both teachers had many years of teaching experience. Third, both teachers had previous experience with the MLs curriculum. Fourth, both teachers received one-on-one support from me to support learning how to use the simulation and to think through how to teach the simulation. The particular findings of this study might not generalize to cases where teachers have less experience and less support. For example, less experienced teachers might have been less likely to add in practices that were not explicitly recommended by the lesson plans.

Curricular context. We know that student prior knowledge has an impact on what students are able to learn from a given lesson (Cervetti & Hiebert, 2015a, 2015b, 2019). In this case study, all students entered the simulation lesson with prior knowledge of both science content and practices that stemmed from their previous work with the MLs curriculum.

Therefore, the findings from this study relate to the use of these particular simulations in a specific curricular context. If these simulations were to be taught in a standalone fashion, without curricular support, the results might be different.

Student learning outcomes. This study does not make claims about student learning outcomes, only about the types of practices that teachers used to support student sensemaking. The intent of the study is to construct a naturalistic case study (Stake, 1995) that documents practices that teachers use while enacting simulation-based lessons, rather than to make claims about the specific efficacy of each practice for supporting learning outcomes on content or practice measures.

Future Research

In future studies, I would be interested in investigating the following questions. First, *What is the trajectory of teachers' enactments of simulations over multiple years?* Currently, I have three years of data regarding Ms. Lane's instruction with the simulations (2015-2016; 2016-2017; 2017-2018) and two years of data regarding Ms. Lawson's instruction (2015-2016; 2016-2017). I would be interested to see when different practices of teaching with the simulations emerged. It would also be interesting to go back in several years and see what teachers are doing after more than five years of experience.

A second question I would be interested in exploring is *How can novice teachers be supported to use simulations in science teaching?* Ms. Lane and Ms. Lawson both drew on years of accumulated experience when working with the simulation. This experience would not be available to novice teachers, but there might be ways to support them to use simulations effectively. Potential ways might include: watching short videos of experienced teachers working with simulations; viewing and discussing lists of strategies for supporting sensemaking with simulations (e.g. some of the Tables in chapter 7); exploring simulations with the purpose of identifying teaching goals, potential areas where students might need extra support, and potential teaching strategies to support sensemaking; practicing working with simulations in peer-teaching situations or in elementary classroom placements; or working with an individual student to support their use of the simulation. I would be curious to try some of these methods with pre-service teachers in methods courses to gain more understanding as to which (if any) of these methods might be helpful to teacher professional learning.

A third question I would be interested in exploring is *How does teacher talk differ in simulation lessons as compared to hands-on lessons that support the same content?* I have video data of both Ms. Lane and Ms. Lawson enacting both Friction Simulation lessons and lesson that involve hands-on exploration of friction. I am curious how their support of sensemaking differs in these two contexts. For example, based on my field notes and in person observation, I noticed that both the hands-on lessons and the simulation-lessons involved significant support for the practices of controlling variables. However, in the simulation-based lessons, the discussion of controlling variables was more abstract (e.g. by naming the variables and deciding which variable to change.) On the other hand, discussions in the hands-on lessons often centered around how not to introduce additional variables by accident (e.g. how to push a toy car with the exact same amount of force on each trial). I would be curious to explore these differences in a more systematic manner with an eye to identifying ways that simulation-based lessons and hands-on lessons may complement each other, when placed together in a curriculum.

Finally, I would be interested in taking a deeper dive into the student interview, student attitude-surveys, and pre-post assessment data surrounding the simulation lessons in order to do student-facing analysis that complements and extends the work that I have done in this dissertation.

APPENDICES

Appendix A

Classroom Observation Protocol
Multiple Literacies in Project-based Learning
2018-2019

Descriptive Information

Teacher:
Grade:
Date:
Observer:
# of students present:
# of adults assisting with instruction:

Lesson Information

Field notes:

Start time:

End time:

II. Relationship of instruction to the curriculum materials

1. If the instruction did not adhere to the recommended activities or order of activities in the curriculum materials, please describe which parts modified/skipped/postponed and how.

2. What, if anything, did the teacher add that was not called for in the lesson plan?

III. Other notes

3. Focus on the **children** (e.g., their engagement, excitement, struggles, interactions)

4. Focus on the **teacher** (e.g., "eureka" moments, moments where she seemed uncertain, struggles)

5. Focus on the **researcher** (e.g., support provided before, during, and after the lesson)

Appendix B

Net Force Teacher Interview Protocol

Name _____________. Date_____________________- Time_______________________

Conceptual Goal(s) for student sensemaking

- What are you hoping students will ***understand/learn*** by working with this simulation?
    - How do you plan to ***support*** students to reach this understanding?

Pretests

- What jumps out at you when you look at these student pretest responses?
    - What concepts do the students seem to be ***understanding?***
    - What are some areas where students may ***need support?***
    - What do you think ***students might be thinking*** as they wrote [ ] answer?
    - What ***prior knowledge*** or ***experiences*** do you think students might be drawing from?

Last year

- ***What went well*** with the simulation last year?
    - Can you remember ***any specific moments*** from working with the simulation last year?
    - Can you walk me through what happened? What you did? What the results were?

- ***What was challenging*** about this simulation last year?
    - Do any instances come to mind when ***students struggled*** with understanding the simulation or needed additional support?
    - Can you walk me through what happened? What you did? What the results were?

- Last year, you used a model of
    - QUESTION/EXPERIMENT → PREDICTION → REASONING → TEST → DISCUSS
    - Do you have any memories/reflections on how well this worked?
    - What ***went well?***
    - What was a ***challenge***?
    - Do you plan to use ***this model again***?

- Is there ***anything you would change*** based on your experience last year? (Including management concerns?)

Participation Structures

- Given your goals for student learning, how do you plan to have students working ***whole class, small groups, or individually***?

- What is your reasoning for this decision?
- Last year, Ms. Lane mentioned the idea of students ***going back and forth*** between whole class and working individually? Is that something you want to try this year?

Focus on Simulation Features

- Given your goals for student understanding, ***which features*** do you anticipate focusing on?
  - People? Numbers? Arrows? Toggles?

Questions/Concerns

- ***Any questions*** about how the simulation works? Want to look at anything together?
- **Any concerns about using this simulation with students?**

Thank you so much for your time in giving this interview -- and for letting me observe students working with the simulations in your class. It's been a privilege to learn from you and from the children. If you're interested, I'd be happy to share my emerging findings and observations, at any time.

Appendix C

Friction Teacher Interview Protocol

Conceptual Goal(s) for student sensemaking

- What are you hoping students will ***understand/learn*** by working with this simulation?
  - How do you plan to ***support*** students to reach this understanding?

Pretests

- What jumps out at you when you look at these student pretest responses?
  - What concepts do the students seem to be ***understanding?***
  - What are some areas where students may ***need support?***
  - What do you think ***students might be thinking*** as they wrote [ ] answer?
  - What ***prior knowledge*** or ***experiences*** do you think students might be drawing from?

Last year

- ***What went well*** with the simulation last year?
  - Can you remember ***any specific moments*** from working with the simulation last year?
  - Can you walk me through what happened? What you did? What the results were?

- ***What was challenging*** about this simulation last year?
  - Do any instances come to mind when ***students struggled*** with understanding the simulation or needed additional support?
  - Can you walk me through what happened? What you did? What the results were?

- Last year, you used a model of
  - QUESTION/EXPERIMENT → PREDICTION → REASONING → TEST → DISCUSS
  - Do you have any memories/reflections on how well this worked?

- What ***went well?***
- What was a ***challenge***?
- Do you plan to use ***this model again***?

- Is there ***anything you would change*** based on your experience last year? (Including management concerns?)

Participation Structures

- Given your goals for student learning, how do you plan to have students working ***whole class, small groups, or individually***?
    - What is your reasoning for this decision?
- Last year, Ms. Lane mentioned the idea of students ***going back and forth*** between whole class and working individually? Is that something you want to try this year?

Focus on Simulation Features

- Given your goals for student understanding, ***which features*** do you anticipate focusing on?
    - Arrows? (Applied force/net force/ friction force)? Friction slider? Fore slider? Numerical values? Changing ground cover?

Questions/Concerns

- ***Any questions*** about how the simulation works? Want to look at anything together?
- **Any concerns about using this simulation with students?**

Thank you so much for your time in giving this interview -- and for letting me observe students working with the simulations in your class. It's been a privilege to learn from you and from the children. If you're interested, I'd be happy to share my emerging findings and observations, at any time.

Appendix D

Plant Teacher Interview Protocol

Co-exploration

- As we walk through this simulation together…..
    - Anything that's confusing/unclear?
    - Any parts students might need extra support to support their learning?
    - Parts you might want to spend more/less time on.

Conceptual Goal(s) for student sensemaking

- What are you hoping students will ***understand/learn*** by working with this simulation?
    - How do you plan to ***support*** students to reach this understanding?

Pretests

- What jumps out at you when you look at these student pretest responses?
    - What concepts do the students seem to be ***understanding?***
    - What do these pretest results suggest about what support students might ***need?***
    - What do you think ***students might be thinking*** as they wrote [ ] answer?
    - What ***prior knowledge*** or ***experiences*** do you think students might be drawing from?

Last year

- ***What went well*** with the simulation last year?
    - Can you remember ***any specific moments*** from working with the simulation last year?
    - Can you walk me through what happened? What you did? What the results were?

- ***What was challenging*** about this simulation last year?

- Do any instances come to mind when ***students struggled*** with understanding the simulation or needed additional support?
- Can you walk me through what happened? What you did? What the results were?

- Is there ***anything you would change*** based on your experience last year? (Including management concerns?)

Participation Structures

- Given your goals for student learning, and the fact that this won't play on Chromebooks only laptops, how do you plan to have students working ***whole class, small groups, or individually***?
  - What is your reasoning for this decision?

Text Features

- The Mystery Plant Simulation (flower box screen) has many features, including images and animation. (For example: flowers have different numbers of leaves, flowers wilt and "un-wilt," planter boxes have different amounts of sunlight.)
  - What features do you think might be most challenging for your students to interpret?
  - How will you support students to understand these features?

Questions/Concerns

- **Any concerns about using this simulation with students?**

Thank you so much for your time in giving this interview -- and for letting me observe students working with the simulations in your class. It's been a privilege to learn from you and from the children. If you're interested, I'd be happy to share my emerging findings and observations, at any time.

Appendix E

Stimulated Recall Teacher Interview Protocol

For Stimulated Recall
What are you noticing about the sensemaking students are engaged in?
What decisions are you making in this moment?

Perspective/Attitude/Evaluation

Overall, did you find this simulation to be supportive of student learning?

Were there any challenges you or your students experienced while working with this simulation? (How did you respond?)

Did you enjoy teaching with this simulation?

Do you think your students enjoyed learning from this simulation?

Do you recommend that this simulation remain part of the MLs curriculum next year? Why would you make this recommendation?

What advice do you have for the designers of the simulation?

If you recommend that it remain, are there any changes to the lesson plans or supports that you think would be helpful?

If you teach with this simulation next year, is there anything you would do differently?

Specific Decision Making
Can you comment about decisions you made with respect to:

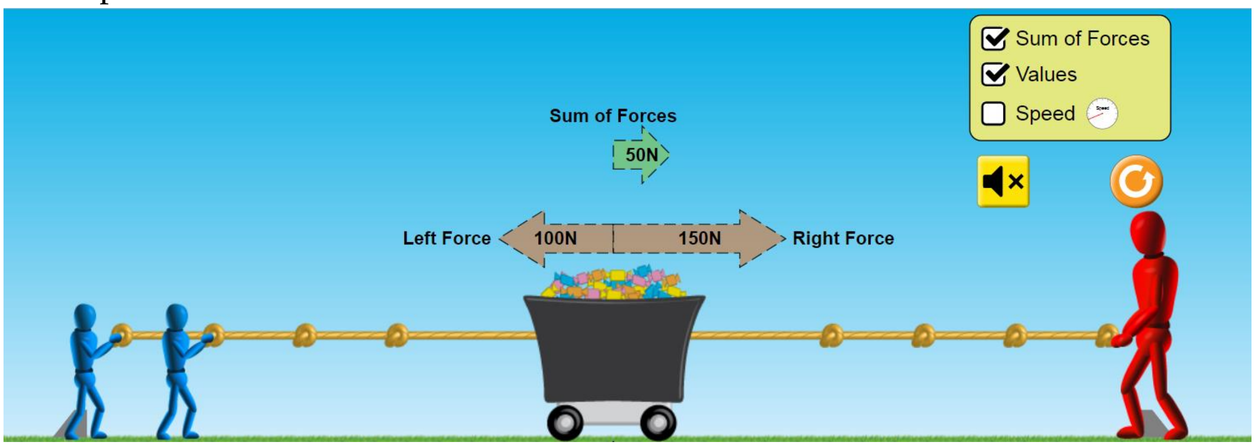
- Providing more individual work time
- Changing lesson order from BR/Car/Sim; BR/Sim/Car
    - Why change?
    - Two transitions this year
    - Next year?
- Teaching the simulation in one day vs multiple days; what they'd do next year

Is there anything further you'd like to add? About these simulations? About this unit?

Appendix F

Net Force Assessment

1. These people are pulling on opposite sides of a cart. Which way do you predict the cart will move?



A) Left  B) Right  C) It will not move

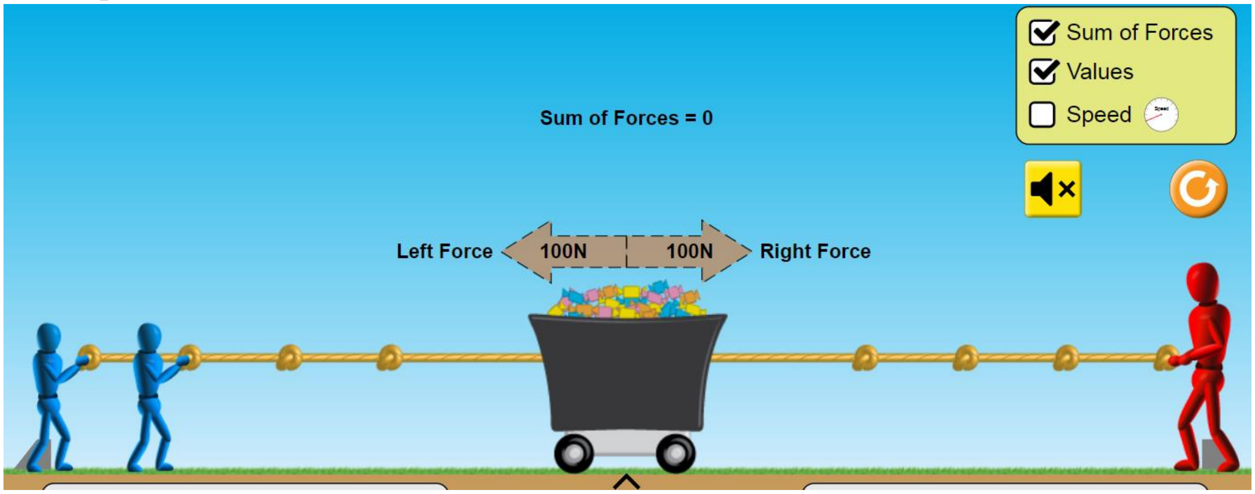
Explain why you think this will happen. Give as many reasons as you can.

____

____

____

2. These people are pulling on opposite sides of a cart. Which way do you predict the cart will move?



A) Left  B) Right  C) It will not move

Explain why you think this will happen. Give as many reasons as you can.

____

____

____

____

____

Rubric for Scoring Net Forces Pre/Post Assessment

CRITERIA	EXAMPLES	Question 1	Question 2
Is student prediction correct?			
Does student reasoning mention differences in length between the left and right force arrow	e.g. “one arrow is longer” “the arrows are the same length” “the arrow on the left is shorter” “the arrow on the blue side is shorter”		
Does student reasoning mention differences in the VALUE of left and right forces?	e.g. “It is pulling left 100, but it is pulling right 150”		
Does student reasoning mention the sum of forces arrow or value?	e.g. “the sum arrow pointed left” “Because the green arrow pointed that way.” The sum of forces is zero.		
Does student reasoning mention whether forces are balanced or unbalanced?	e.g. “the same amount of force on each side.” “more force on one side” “pulling harder on one side” “pulling the same amount” “unbalanced forces”		

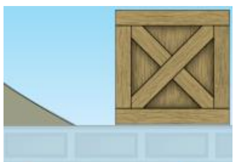
Scoring: One point for each check mark

Highest Possible Score: 10

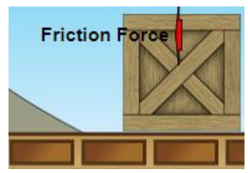
Appendix G

Friction Assessment

1. Which box will be easiest to push?



B) The box on smooth ice



B) The box on slightly rough dirt

C) The box on very rough grass

D) All the boxes will be the same

Explain why you think your answer is true. Use as much detail as you can.

____

____

2. DeAndre is pushing a box over very rough grass. When he stops pushing, what will do you think will happen to the box?

A) It will stop moving.

B) It will keep moving.

Explain why you think your answer is true. Use as much detail as you can.

____

____

3. Mariana is pushing a box over very slippery ice. When she stops pushing, what will happen to the box?

A) It will stop moving B) It will keep moving

Explain why you think your answer is true. Use as much detail as you can.

____

____

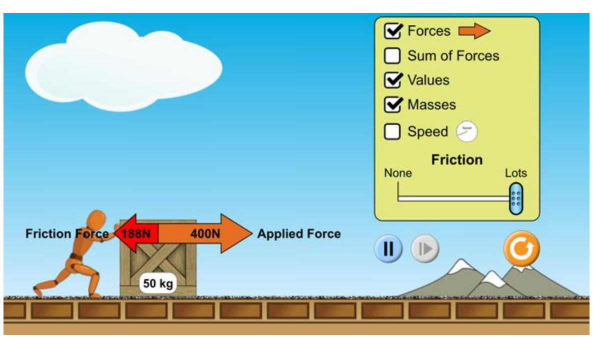
4. Isabelle wants to investigate friction. This is her investigation.

Trial 1:

Friction = Lots

Mass = wooden box (50 kg)

Applied force = 400 newtons

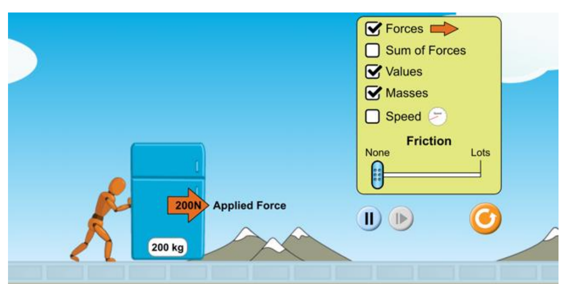


Trial 2:

Friction = None

Mass = refrigerator (200 kg)

Applied Force = 200 newtons

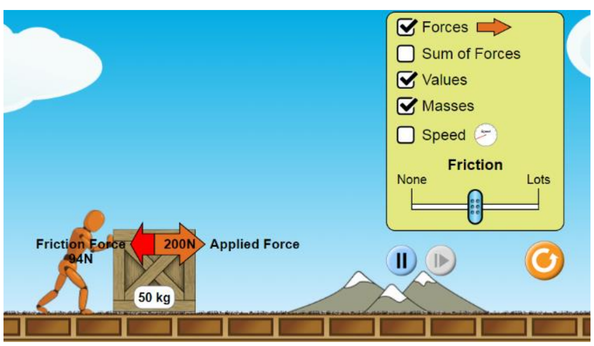


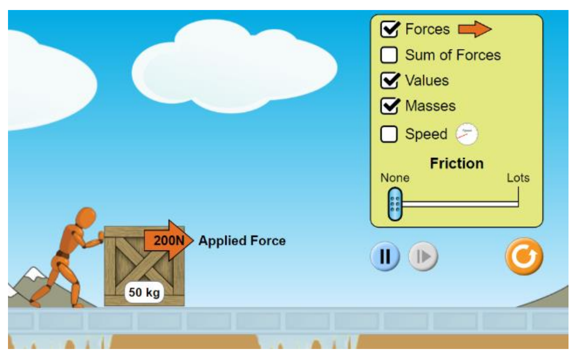
Is this a fair test? Why or why not?

____

____

5. Akihiro wants to investigate friction. This is his investigation.

<table>
<tr><th><u>Trial 1:</u></th><th><u>Trial 2:</u></th></tr>
<tr><td>Friction = Medium
Mass = wooden box (50 kg)
Applied force = 200 newtons</td><td>Friction = None
Mass = wooden box (50 kg)
Applied Force = 200 newtons</td></tr>
<tr><td>


</td><td>


</td></tr>
</table>

Is this a fair test? Why or why not?

____

____

Rubric for Scoring Friction Pre/Post Assessment

CRITERIA	EXAMPLES	Question 1	Question 2	Question 3
Is student prediction correct?				
Does student reasoning mention differences in how rough/smooth the surface is?	e.g. because ice is slippery			
Does student reasoning use the word "friction"	e.g. "C because it has the most friction"			

Scoring: One point for each check mark

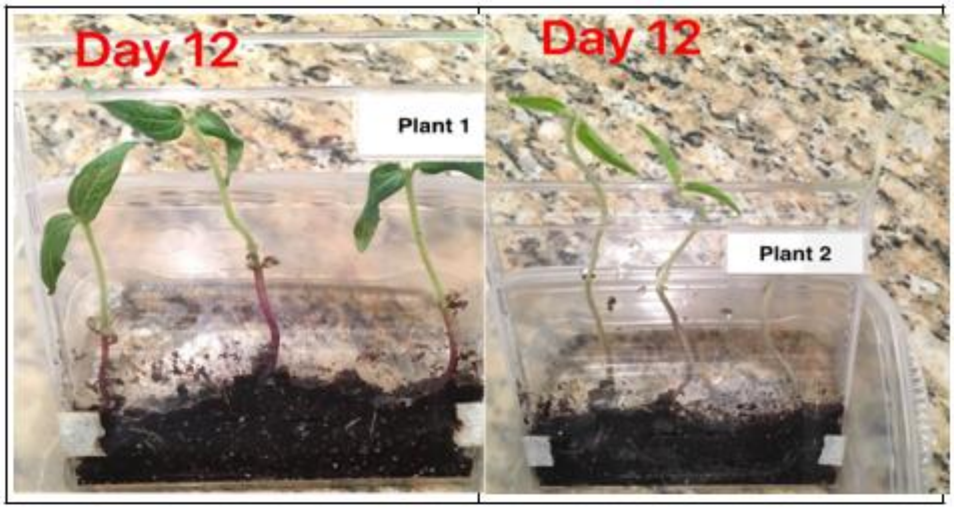
Highest Possible Score: 9

Appendix H

Plant Assessment

Name: ____________________

1) **Plant 1 and Plant 2 are the same kind of plant, growing in different environments.**



A) What similarities do you notice between Plant 1 and Plant 2?

____

____

B) What differences do you notice between Plant 1 and Plant 2?

____

____

C) What do you think caused the differences between Plant 1 and Plant 2?

____

____

2) These seeds all came from the same parent plant.

A) Will these seeds grow into plants that all look exactly the same?

Yes No

Explain your choice: ____

B) Will these seeds grow into plants that need exactly the same conditions to survive?

Yes No

Explain your choice: ____

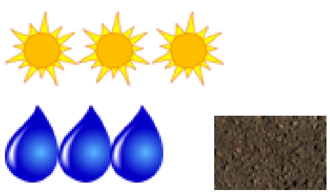
3) Jasmine wants to investigate what plants need to grow. This is her investigation.

<u>Trial 1:</u>

Sunlight = 3 hours a day

Water = 30 milliliters a day

Flowerpot: Filled with Soil

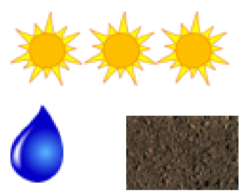


<u>Trial 2:</u>

Sunlight = 3 hours a day

Water = 10 milliliters a day

Flowerpot: Filled with Soil

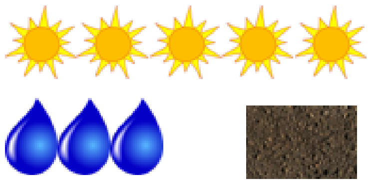
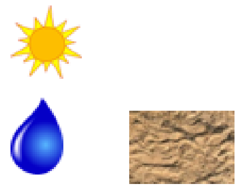


Is this a fair test? Why or why not?

____

____

4) D'Angelo wants to investigate what plants need to grow. This is his investigation:

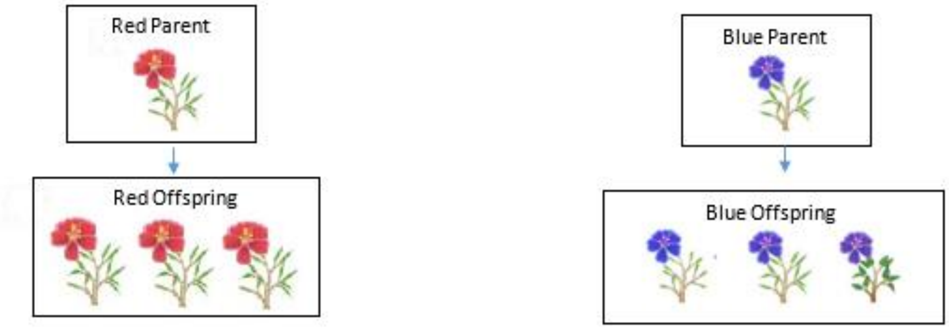
<u>Trial 1:</u>	**<u>Trial 2:</u>**
Sunlight = 5 hours a day	Sunlight = 1 hours a day
Water = 30 milliliters a day	Water = 10 milliliters a day
Flowerpot = filled with sand	Flowerpot = filled with soil
	

Is this a fair test? Why or why not?

____

____

5) Draw and label a design for a garden. Include everything your plants will need to survive.

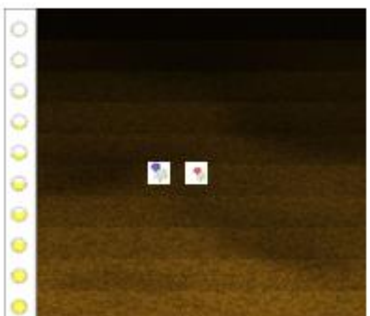


A) What do you notice about the red offspring?

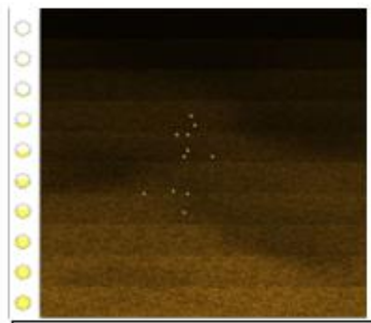
____

B) What do you notice about the blue offspring?

____



1.The red and blue parent plants are growing in the middle of the field.



2.Their seeds blow across the field.

____

____

____

3.Use red and blue markers to draw where flowers might be growing after 10 years.
Why do you think the field will look this way?

Rubric for Scoring Simulation Related Portion of Unit IV Pre/Post Assessment

CRITERIA	SCORE
Does student understand that not all seeds will grow into plants that look EXACTLY the same?	
Does student understand that not all seeds will grow into plants that need EXACTLY the same conditions to survive?	
Did student note that the blue plant has variations in leaf size while the red plant did not?	
Did student observe that the blue plant grew in more different kinds of conditions than the red plant?	
Did student make a connection between the greater variety in the blue plant and the	

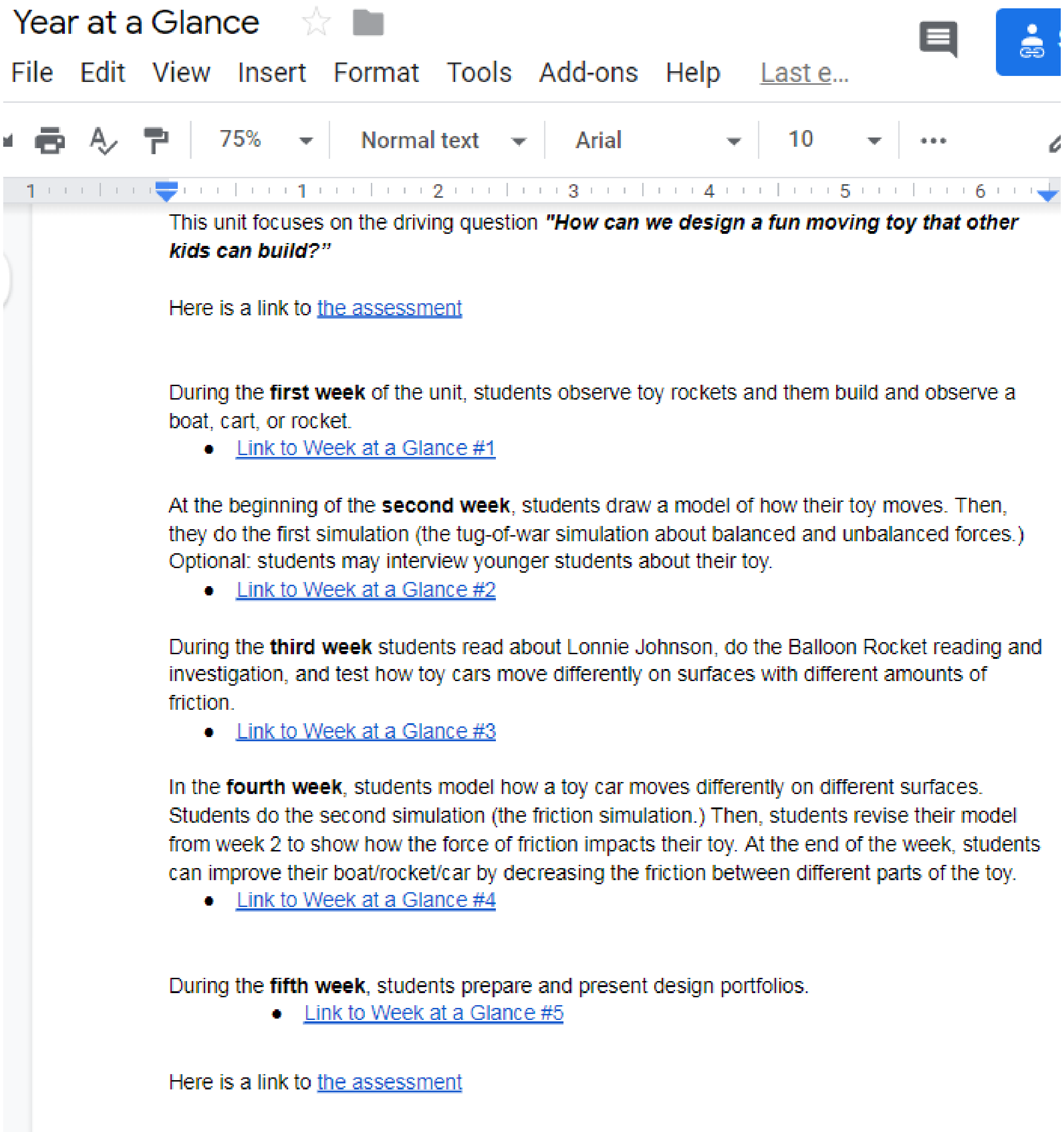
fact that the blue plant could grow in more conditions?	

Scoring: One point for each check mark

Highest Possible Score: 5

Appendix I

Curricular Supports for the Net Force, Friction, and Mystery Plant Simulations



This unit focuses on the driving question ***"How can we design a fun moving toy that other kids can build?"***

Here is a link to the assessment

During the **first week** of the unit, students observe toy rockets and them build and observe a boat, cart, or rocket.

- Link to Week at a Glance #1

At the beginning of the **second week**, students draw a model of how their toy moves. Then, they do the first simulation (the tug-of-war simulation about balanced and unbalanced forces.) Optional: students may interview younger students about their toy.

- Link to Week at a Glance #2

During the **third week** students read about Lonnie Johnson, do the Balloon Rocket reading and investigation, and test how toy cars move differently on surfaces with different amounts of friction.

- Link to Week at a Glance #3

In the **fourth week**, students model how a toy car moves differently on different surfaces. Students do the second simulation (the friction simulation.) Then, students revise their model from week 2 to show how the force of friction impacts their toy. At the end of the week, students can improve their boat/rocket/car by decreasing the friction between different parts of the toy.

- Link to Week at a Glance #4

During the **fifth week**, students prepare and present design portfolios.

- Link to Week at a Glance #5

Here is a link to the assessment

TOYS Week at a Glance #2 **Unit Driving Question: How can we make a fun moving toy that other kids can build?**

Lesson 1.4	Lesson 1.5	Lesson 2.1 (optional)	Lesson 2.2 (optional)
How can I show others what causes a toy to start moving? Lesson 1.4 Introduction Discuss how forces cause toys to start moving. Use the video of dominoes in the Lesson 1.4 Slides to define and discuss "cause" Lesson 1.4 Activities With support from the teacher, students work in pairs or individually to draw models that show how unbalanced forces cause objects to start moving. (Students may also construct models using collabrify flipbook) Students share their models with each other, then revise based on feedback. Discuss ways to represent force and motion in the models. *If you are using flipbook, then after students have finished making pencil-and-paper models they can make flipbook models*	**How can I use a model to predict how different forces can change the motion of my toy?** Lesson 1.5 Introduction Ask students if a contact force always causes an object to move? Push equally hard on both sides of one of the toy carts made by students. Ask students how they would need to change the contact force to get the toy to move. (See lesson 1.5 slides). Students discuss picture on slide 5. Click the picture to open the Net Force Simulation [Click here for a teacher guide to using the simulation] 1.5 Activities Demonstrate to students that you can manipulate the model in the simulation by changing the people pulling on each side. Put the same size and number of people on each side. Ask students to predict how the cart will move and describe how the representations in the model (arrows and people) helped them make the prediction. Click on "GO" to animate the model to test their prediction. Ask students to explain why the cart did not move. Demonstrate pushing on the real cart with the same amount of force on each side. Redo simulation. Click "Values buttons" so students can see force measured in Newtons. Redo simulation. Click "Sum of forces." Discuss *balanced forces*. Ask students to predict how they could make the cart in the simulation go right. Test their suggestion. Discuss *unbalanced forces*.	**How can other kids help us design moving toys?** Lesson 2.1 Introduction The teacher brings out the air rockets and discusses the price of the toys and the difficulties in getting them for all students. Introduce lesson 2.1 slide show. Show embedded video clip (slide 3) of a kid who invents things and discuss his process of getting ideas and planning inventions Lesson 2.1 Activities Students generate and record questions that they could ask other kids in order to help them design the toys. Students practice asking their interview questions and demonstrating their toy Students share and critique interview questions with another group that is designing the same toy. Lesson 2.1 Wrap Some groups share interview questions with class. Discuss behavior expectations for the upcoming interviews.	**How can other kids' ideas help us design moving toys?** Lesson 2.2 Introduction The teacher will remind students of the purpose of their interviews. Student groups will prepare for their interviews. (See slideshow, slides 1-3) Lesson 2.2 Activities Each group demonstrates their toy and interviews younger students about potential design improvements. (See slideshow, slide 4) Teacher facilitates a class discussion identifying the criteria and constraints for toy designs. (See slideshow, slide 5) Make a class chart identifying examples of "testable solutions" (*ideas we can try* as opposed to *ideas we cannot try.*) Lesson 2.2 Wrap Up Student groups will pick one testable design solution that they would like to plan for their toy

TOYS Week at a Glance #2 **Unit Driving Question: How can we make a fun moving toy that other kids can build?**

	Continue to have students try different combinations of forces. For each combination, have students: predict the motion, explain their prediction, and test their prediction. Ask students to describe the *net force* (strength and direction) and identify if it is *balanced* or *unbalanced*. 1.5 Wrap Up Revisit demonstration from beginning of lesson. Then, have students label balanced and unbalanced forces in their models from the previous lesson.		

How can we design fun moving toys that other kids can build?

Learning Set 1: What makes toys move?

Lesson 1.5: How can I use a model to predict how different forces can change the motion of my toy?

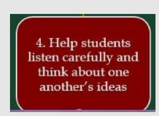
<table>
<tr>
<td>Lesson Overview (40-50 min or 1 class period)</td>
<td>
Lesson DQ: How can I use a model to predict how different forces can change the motion of my toy?

Lesson Snapshot
1. <u>Introduction:</u> Discussion of Driving Question Board and previous lesson regarding modeling forces that cause toys to start moving.
2. <u>Modeling:</u> Students use an interactive computer model of balanced and unbalanced contact forces to predict how an object will move.
3. <u>Wrap Up:</u> Students will identify balanced and unbalanced forces in their models from the previous lesson.

Learning Performance
Students use models to identify the sum of forces acting on objects and predict the motion of objects caused by these balanced and unbalanced contact forces.

Building toward Performance Expectation (PE)
3-PS2-1 Plan and conduct an investigation to provide evidence of the effects of balanced and unbalanced forces on the motion of an object.
</td>
</tr>
<tr>
<td>Materials and Prep</td>
<td>
Preparation
• Practice using the simulation to become familiar with the tool and make sure that it works in your classroom.
• 2- Sentence strips to put on the DQB or interactive word wall.
  ○ “Balanced forces-when the forces on each side of the object are the same strength but in opposite directions and the sum of the forces is zero.
  ○ Unbalanced forces-when the forces on the object are greater in one direction and the sum of the forces is not zero.”

Materials
• Force and Motion Simulation linked in L1.5 PowerPoint or if you want students to work with the simulation independently: https://phet.colorado.edu/sims/html/forces-and-motion-basics/latest/forces-and-motion-basics_en.html or lef.imlc.io (WeRead)
• Student models from L1.4
</td>
</tr>
</table>

Lesson Component	How to Implement
What are kids figuring out?	**Students are figuring out that** unbalanced forces occur when forces are greater in one direction so that the sum is greater than zero and causes a change in the pattern of motion of an object. When objects are not moving, multiple forces act on them, but the forces are balanced because the sum of the forces is zero. **Look Fors** 1. Look for students describing connections between their experiences with the toys and the representations in the simulation models. 2. Look for students predicting the motion of the object and describing the cause of the motion as forces being balanced or unbalanced. Connection to prior experiences
1 Introduction (10 mins)	**Engaging with DQ** 1. Remind students of the Driving Question. Remind students that in the last lesson they learned that it takes a contact force to start a Ask students if a contact force always causes an object to mo students the following phenomena: Push equally hard on bot one of the toy carts made by students. Connection to prior experiences/physical investigation/conceptual question 2. Ask students to describe what they see: (The following questions are also found on the L1.5 PowerPoint) • ***Does the toy car move?*** *(no)* • ***Am I applying a contact force?*** *(yes, 2 forces)* • ***Why do you think the toy doesn't move?*** ***(****accept* *for now****)*** • **How would we have to change the contact force toy to move?** *(add more force to one side)* Conceptual question/predictions/reasoning 3. Ask students to describe the direction you are pushing with each finger. The toy doesn't move even though you are applying a force because the forces are in opposite directions. Describe to students that you are pushing on both sides with the same amount of force. As you go through the next set of demonstrations allow students to just share their thinking. At this point in the lesson it is only important that they are able to identify that a contact force is being applied and the object is not moving. (Students may discuss balanced forces from Lesson 1.3 however this will be reinforced through the models in the simulation.) You will revisit these demonstrations lat ill help students Figure out **why** the object is no 4. Tell students that they re out why the toy is not moving. Supporting students to listen attentively and build off of each other's ideas
	Help students build on each oth n when a student makes a response, ask how their response relates to the previous comment. To do so students will need to listen carefully to each other. **Suggested Prompt**: "*How does your idea relate to what _______ said?*" 

2
Description of Lesson

(20-30 mins)

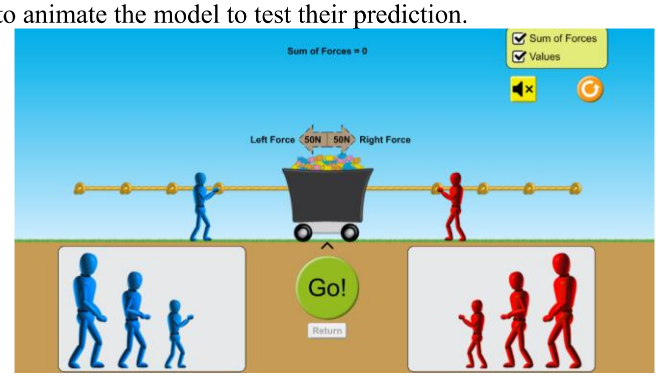
Modeling Balanced and Unbalanced Forces

Comparing representations, predictions, reviewing definition of model

1. Ask students to look at the picture labeled net forc PowerPoint. Ask students to turn-and-talk to their
   - **How is this picture similar to our class model of our toys?**
   - **What can you explain from the picture?**
   - **How do you think the cart will move? Why do you think so?**
   - **Is this picture a model?**

2. Open the simulation by clicking on the picture in slide 5 of the L1.5 PowerPoint. Remind students that in the last lesson they learned that a model shows the relationship between the parts that cause something to happen. Models can allow others to explain what happened. How can we use this model to explain why the car did not move when we pushed on both sides?

3. Demonstrate to students that you can manipulate the model in the simulation by changing the people pulling on each side. Make sure to put the same size and number of people on each side. Ask students to predict how the cart will move and describe how the representations in the model (arrows and people) helped them to make the prediction. Click on "GO" to animate the model to test their prediction.

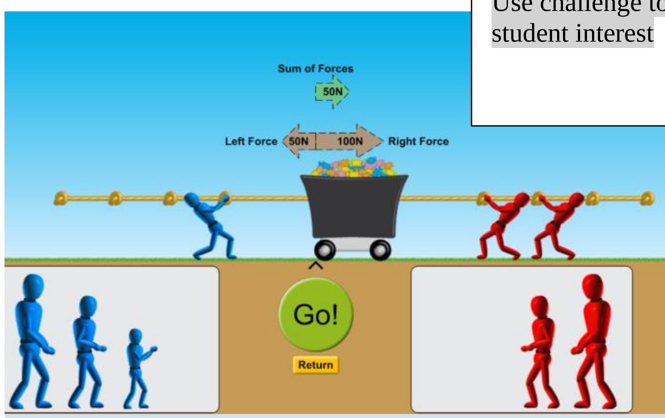


prediction

4. Ask students to explain why the cart did not move. Demonstrate pushing on the real toy cart from both sides with the same amount of force and ask students how this is similar to the model in the simulation? (*does not move, same amou*nt force on both sides *forces are in the opposite direction*) How is it different? (*real toy c force, simulation model-pulling contact force*)

Focus on illuminating case; reasoning/interpreting results; connection to physical experiences

5. Redo the simulation but click on the values button to shov forces. Explain to students that the N stands for newtons which is t measure forces. Explain to students that these forces are called bal in developing a class description of balanced forces and write it on Example: when the forces on each side of the object are the same s directions they are called "**balanced.**" Post the sentence strip for b DQB.

	6. Click on the sum of forces and then click on “GO” to animate the model. Ask students why they think the sum of the forces is zero even though there are 2 contact forces applied to the object. (*The forces are the same strength in opposite directions so the object cannot move. When an object is not moving the net or total value of the force applied to the object is zero*.) Conceptual question. 7. Ask students what they could do to make the cart in the simulation go to the right? (*Either add more people or a larger person to add more force on the right.*) Use challenge to engage student interest  8. Try their suggestion and click GO to animate the model and test their idea. Ask students if the forces on the cart are balanced now? (*No, the net force on the cart is 50N to the right.)* Remind students that forces have a strength and a direction. When the net force they need to describe both. Support students in developing a cla of unbalanced forces and write it on a sentence strip. Example: When the for of the object have different strengths and are greater in one direction they are “**unbalanced.**” Post the sentence strip for unbalanced forces on the DQB. Conceptual question. Prediction/reasoning/conceptual questions 9. Have students try different combinations of forces, predict the and then explain why they think so. Each time test their predictions and describe the **net force -- both the strength and direction -- and identi unbalanced**.
4 **Wrap Up** (10 mins)	1. Revisit the demonstration from the beginning of the lesson by asking a stu both sides of the toy car. Ask students to turn-and-talk to their partner and are balanced or unbalanced? How do you know? (*Balanced, because the c so the net force must be zero*) Let students share ideas. Participation opportunity

<table>
<tr>
<td></td>
<td>2. Have students take out the models of their toy. Have them label the 2 models: balanced before the toy moves and unbalanced as the toy begins to move. Ask them to write a sentence describing the (net) sum of the forces for each model. Example:

Before it moved, the sum of the forces on my skimmer is zero because it is not moving and the forces are balanced.
As the toy begins to move, the sum of the forces or than zero because my skimmer starts moving in the force of the air, and the forces are unbalanced. (If s acting on the bottle rocket or any other toy before i them what is the force pushing up to balance gravit down. If students do not mention this then do not address it as it will come up later in the unit.)

Updating representation to match model

3. Refer back to the DQB. Ask students to turn and talk to their partners and discuss how figuring out what forces are acting on their toys can help them answer the Driving Question. Share out a few student ideas and ask if there are any new questions that they need to add to the DQB.</td>
</tr>
<tr>
<td>Formative Assessment</td>
<td>Assessment Description
Look For

Look for students describing connections between their experiences with the toys and the representations in the simulation models.
Look for students predicting the motion of the object and describing the forces as balanced or unbalanced.

Evidence Statement
Students’ descriptions of forces represented in the simulated models and students’ own models correctly identify forces as balanced or unbalanced. Students’ descriptions of the forces also include the sum of the forces as being zero when forces are balanced and greater than zero when forces are unbalanced. Students’ predictions of the motion of objects are accurate and based on information from the model.</td>
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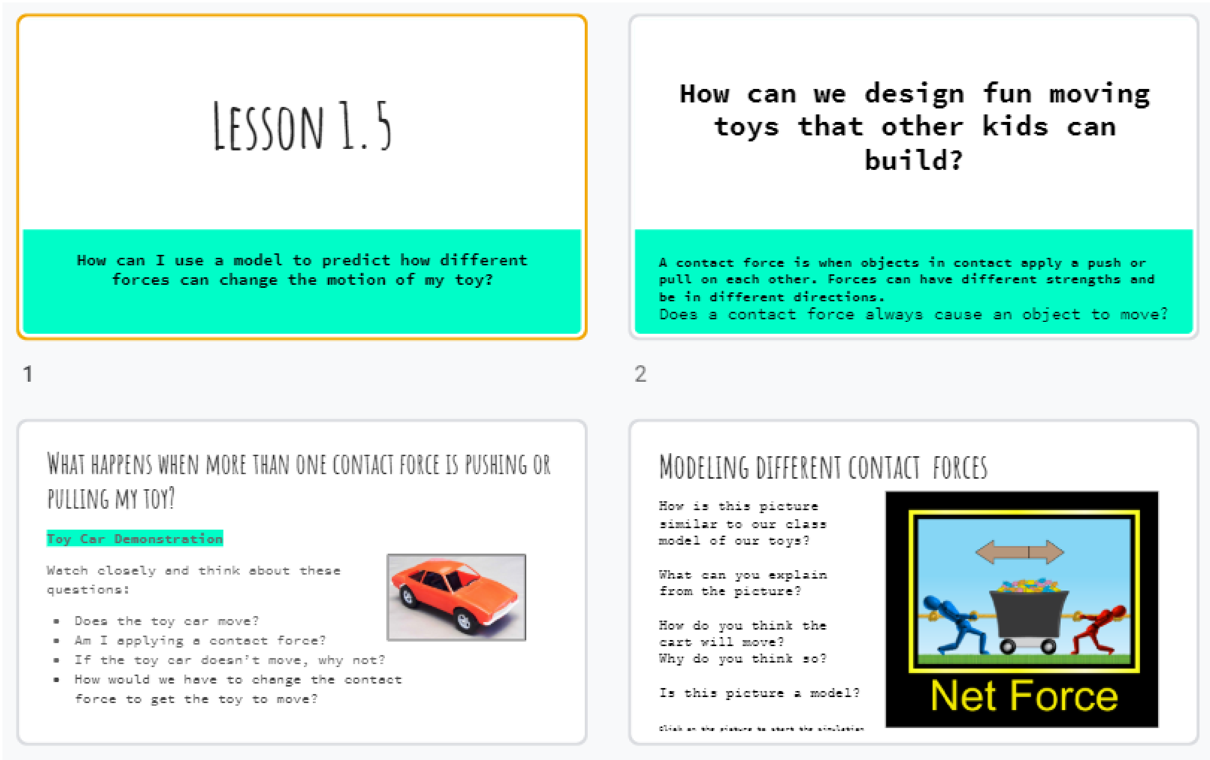
</table>



Lesson 1.5
How can I use a model to predict how different forces can change the motion of my toy?
1
How can we design fun moving toys that other kids can build?
A contact force is when objects in contact apply a push or pull on each other. Forces can have different strengths and be in different directions.
Does a contact force always cause an object to move?
2
What happens when more than one contact force is pushing or pulling my toy?
Toy Car Demonstration
Watch closely and think about these questions:
Does the toy car move?
Am I applying a contact force?
If the toy car doesn't move, why not?
How would we have to change the contact force to get the toy to move?
Modeling different contact forces
How is this picture similar to our class model of our toys?
What can you explain from the picture?
How do you think the cart will move?
Why do you think so?
Is this picture a model?
Net Force

Tips for Using PhET simulations in classrooms

Retrieved from https://www.physport.org/recommendations/Entry.cfm?ID=93340

1. **Demonstrate** one experiment or scenario in the simulation. It may help to highlight the variables and settings that you've chosen, to give students ideas about what controls are available.
2. **Ask students questions** based on this demonstration. For example, what will happen if I turn on friction? What affects the period of a pendulum? Then use the simulation to leverage the features of the simulation to guide the discussion.
3. Encourage **students to propose new questions** and experiments. If it's still the first few times students have been asked to suggest ideas, give them starter prompts to help, like "*What if…?*" or "*Will it be higher (or lower) if we…*" or "*What should we change in order to….?*" The more often you use the simulations, the more students will become comfortable asking spontaneous questions.
4. Ask for other **students' predictions** in response to these suggestions and questions.
5. Discuss and **evaluate the reasoning** behind any predictions. Even when students agree on the predicted outcome, they may have differing reasons that should be compared, and perhaps followed-up with further tests to see if these reasons always hold.
6. **Test** the students' proposal(s) with the simulation to see if the outcome matches their predictions.

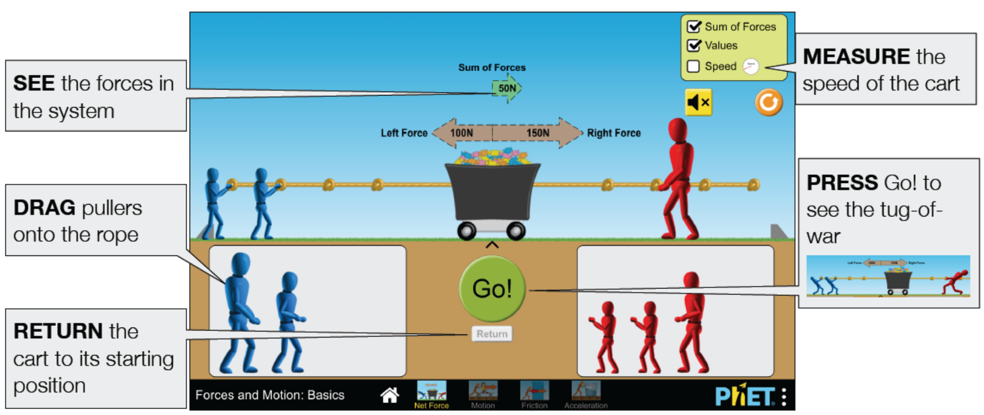
Force and Motion Simulation Controls

Retrieved from https://phet.colorado.edu/en/simulation/forces-and-motion-basics#for-teachers-header

PhET Tips for Teachers Forces and Motion: Basics

Net Force Screen

Investigate the difference between balanced and unbalanced forces as pullers compete in a tug-of-war for a cart of candy.



TOYS Week at a Glance #4 **Unit Driving Question: How can we make a fun moving toy that other kids can build?**

Lesson 3.4	Lesson 3.4 (Part II)	Lesson 3.5 (Part I)	Lesson 3.5 (Part II)
How can I explain what happens when more than one force is pushing or pulling on my toy? Lesson 3.4 Part I Introduction: Students review their results from the toy car investigation. Use slide show to support class discussion. Lesson 3.4 Part I Activities: Students develop models based on the question: ***How do different materials change the motion of my toy?*** Sample model for teacher After developing their initial models on paper and/or in Collabrify Flipbook, students share and compare their models and give each other feedback. Then, students revise as needed. (E.g. by identifying motion, and balanced and unbalanced forces.) Lesson 3.4 Part I Wrap up Students have the opportunity to share their models with the class.	**How can I explain what happens when more than one force is pushing or pulling on my toy?** Lesson 3.4 Part II Introduction Tell students that they will be using a simulation to investigate the effects of friction on motion. (Teacher tip sheet for the simulation) Lesson 3.4 part II Activities Before beginning, click on both the **sum of the forces** and **values** box. While using the simulation 1) **Demonstrate** one experiment or scenario. 2) **Ask students questions** about the demonstration. 3) Encourage **students to propose new questions/experiments** 4) Invite students to **make predictions** about these questions/experiments. 5) **Discuss the reasoning** behind students predictions. 6) Test student predictions by running the question/experiment/scenario proposed in step 2. Lesson 3.4 part II Wrap up Make sure that students notice that once the figure stops pushing the only horizontal force acting on the object is friction in the opposite direction of the motion. When the object stops moving the sum of the (horizontal) forces is zero. Ask if they have any new questions about friction and toys to add to the DQ Board.	**How can I change the forces of friction on my toy?** Introduction Introduce driving question. Push a cart on a towel where students can see and ask students what force caused the cart to stop rolling? (friction) Discuss where friction forces are affecting the motion of EACH of the toys (i.e. along the straw of the rocket, the bottom of the skimmer, & the wheels of the cart) Revising Models Have students **revise their model (from week 2)** by **adding arrows** to show where they think **friction** might affect the motion of their toy. Wrap up Students share their models and give each other feedback.	**How can I change the forces of friction on my toy***?* L 3.5 Part II - Introduction Discuss whether having more friction or less friction will help the toys move faster. **Brainstorm ideas for increasing and decreasing friction** in each toy such as: · Adding rubber bands to the wheels of the car to add friction · Adding powder to the inside of the straw for the bottle rocket or the axle straws on the car to decrease friction. · Adding a smoother surface to the bottom of the skimmer to decrease friction. · Changing the shape of the top of the straw rocket to reduce the friction from the air pushing against the rocket as it flies. · Changing the shape of the cart so it has less air pushing against it to decrease friction. L 3.5 Part II – testing idea Students record their ideas for **one change to the design of their toy** to reduce friction. Students **test the motion of their toy before and after the design change** and record the results on their design sheet. L 3.5 Part II -Wrap Up Discuss results as a class..

Tips for Using PhET simulations in classrooms

Retrieved from https://www.physport.org/recommendations/Entry.cfm?ID=93340

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3. Encourage **students to propose new questions** and experiments. If it's still the first few times students have been asked to suggest ideas, give them starter prompts to help, like "*What if…?*" or "*Will it be higher (or lower) if we…*" or "*What should we change in order to….?*" The more often you use the simulations, the more students will become comfortable asking spontaneous questions.
4. Ask for other **students' predictions** in response to these suggestions and questions.
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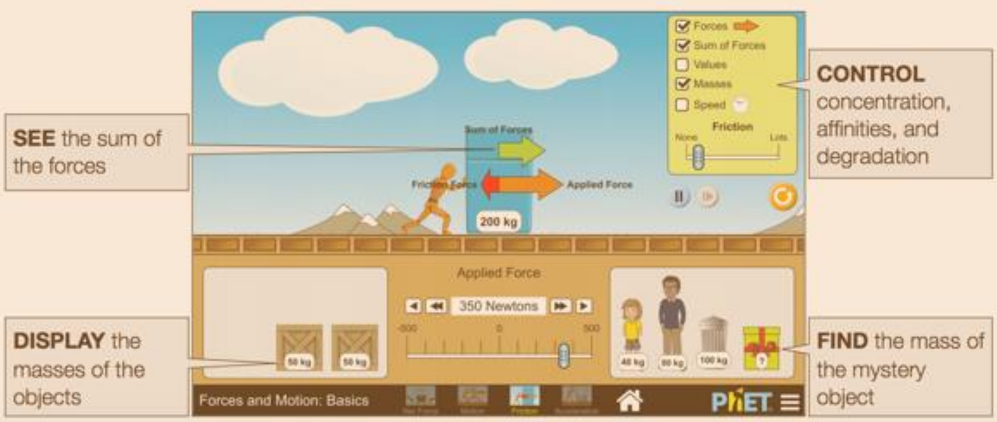
6. **Test** the students' proposal(s) with the simulation to see if the outcome matches their predictions.

Force and Motion Simulation Controls

Retrieved from https://phet.colorado.edu/en/simulation/forces-and-motion-basics#for-teachers-header

Friction Screen

Create an applied force to push various objects, and adjust the amount of the amount of friction and see how it affects their motion.



PLANTS Week at a Glance #4

Plant Unit Driving Question: How can we grow plants for food in our community?

Lesson Plan 3.4	Lesson Plan 4.1	Lesson Plan 4.2	Lesson Plan 4.3
How do variation in traits affect plants' survival and reproduction? Introduction: Ask students to think back to the previous lesson and turn and talk about the following prompt: *Why did a particular variety of winter wheat survive better in Texas than other kinds of wheat?* Pose question to the class: *Do all plants of the same species have the same traits?* After students share their ideas, ask students *Will all plants of the same species survive equally well in the same environment? Why or why not?* Lesson: Project the Mystery Plant Adaptation simulation. Work through simulation as a class. Wrap Up: Discuss what has been learned by using the simulation.	**What can happen to plants when they are exposed to hazardous weather as they grow?** Introduction: Remind students about what they have learned about how weather and climate affect how plants grow for food in their community. Introduce the lesson DQ. Lesson: Engage students in asking question and making observations in the context of a visual inquiry presentation displaying images of the effects of different types of hazardous weather on plants grown for food. Discuss with students the different types of hazardous weather they've experienced in their own community, and how they think this weather could impact the plants they are growing once they move them outside. Next, students work in small groups to sequence the life cycle of an apple. After discussing, students view a table that provides information about conditions that are good and bad for apple growth. Students record these conditions. Wrap Up	**How can engineering solutions protect plants from hazardous weather?** Introduction: Introduce the lesson driving question Lesson: Engage students in reading about a design solution proposed by a scientist to help fruit farmers protect their crops from extreme cold temperatures. (Click here for interactive reading guide). As they read about the design solution, support students to make claims about the merit of the solutions, citing evidence about the criteria for success and constraints. Use slide show to connect the reading to a local newsletter from the Wasem Fruit Farm. Wrap Up: Wrap-up the lesson by supporting students to begin brainstorming how they could protect their own plants from frost or extreme cold. Optional Extension: Students may write to a local orchard to describe what they have learned and propose one of the solutions for protecting local fruit trees.	**If the environment around here changes, how can we keep our garden alive?** Introduction: Introduce the lesson DQ and remind students of their exploration of design solutions for problems related to weather hazards. Lesson: Use slides to introduce a farmer in Africa who developed a solution that would allow him to grow plants for food in his community despite the effects of desertification on the environment. As students watch the video (Slide 5) , they will describe and evaluate the different features of his design solution, and make a claim about how well his solution addressed the problems caused by desertification. Wrap Up: Support students to make connections between how the farmer changed the environment in his community to combat the effects of desertification to how they are working to create the ideal environment for their plants to grow.

Unit 4: How can we grow plants for food in our community?

Learning Set 3 How does the climate affect how plants grow in our community, in other parts of the United States, and around the world?

Lesson 3.4 How do variation in traits affect plants' survival and reproduction?

Lesson Overview (50-60 min)	**L3.4** How do variation in traits affect plants' survival and reproduction? **Lesson Snapshot** 1. Introduction: Introduce lesson level DQ (*How do variation in traits impact plants' survival and reproduction?)* Students discuss DQ and add questions, predictions, or observations to DQ Board. 2. Lesson: Introduce simulation and students observe its different features. Work through the simulation as a class. 3. Wrap Up: Discuss what has been learned by using the simulation. Class constructs a claim about how variation in

	traits impacts plants' survival and reproduction. Add claim to DQ Board, together with any additional noticings and wonderings. **Learning Performance** Students construct an argument using evidence from a simulation to describe patterns in how a group of similar plants can survive differently in the same environment because of differences in their traits. **Building toward PE(s)** **3-LS3-1** Analyze and interpret data to provide evidence that plants and animals have traits inherited from parents and that variation of these traits exists in a group of similar organisms. **3-LS4-3 Construct** an argument with evidence that in a particular habitat some organisms can survive well, some survive less well, and some cannot survive at all.
Materials and Prep	Materials • Concord Simulation: Mystery Plant Adaptation • Post-it notes (optional for the DQ Board) Preparation • Download and preview simulation to ensure that the simulation will load and run on your computer. • Note: This simulation requires Java. Most computers have this program, but if not, it can be downloaded for free at www.java.com. This simulation will not run on Chromebooks.
What are students figuring out?	**Students are figuring out** that differences in plants traits impact whether they will survive and reproduce. **Look for** 1. Students are using evidence from the simulation to support claims about how plants' traits influence their survival. 2. Students are making connection to previously discussed ideas about how squirrel, bird, and winter wheat traits influence their survival.
<u>Lesson Component</u>	**<u>How to Implement</u>**
1 Introduction	1. Ask students to think back to the previous lesson and turn and talk about the following prompt: *Why did a particular*

(5 min)	*variety of winter wheat survive better in Texas than other kinds of wheat?* 2. Invite students to share their ideas and emphasize ideas involving the importance of certain traits that help survival. 3. Pose question to the class: *Do all plants of the same kind have the same traits?* Encourage students to share different ideas regarding this prompt. ○ If students need additional support, remind them to think about their mung bean plants and how different plants growing in the same cup look similar and different. 4. After students share their ideas, ask students if they think that all plants of the same species are able to survive equally well in the same environment? In other words, do some plants survive while others die, or do all plants survive? Encourage students to draw on their own observations and prior knowledge when answering this question. 5. Tell students that they will be exploring this more today. Introduce the lesson DQ: *How do variation in traits impact plants' survival and reproduction?*
3 **Mystery Plant Adaptation Simulation** (15-20 min)	1. Tell students that they are going to be using a simulation to gather data to answer the lesson DQ. You may remind them about the two simulations they used in the toy unit and the data that they collected regarding balanced/unbalanced forces and friction. 2. Project the Mystery Plant Adaptation simulation. Work through the simulation together as a class. This simulation introduces students to the ideas that the traits of offspring can vary from their parents (i.e., leave size) and these variations influence which offspring survive (and reproduce) and which offspring die in the same environment.
4 **Wrap Up** (10 min)	1. Ask students what they learned from the simulation. Invite students to turn and talk about their ideas. Select several students to share. As each child shares his or her ideas, support students to: ○ Identify data from the simulation that supports their idea

	○ Share their own reactions to other students' ideas (agree/disagree and why) 2. Invite students to add additional questions or ideas to the DQ Board.
Formative Assessment	**Assessment Descriptions** **Look for** 1. Students are using evidence from the simulation to support claims about how plants' traits influence their survival. 2. Students are making connection to previously discussed ideas about how squirrel, bird, and winter wheat traits influence their survival. **Evidence Statement** Students make predictions, support their predictions with reasoning, and observe whether or not their predictions occur. Student's spoken observations use evidence from the simulation to support a claim that plant traits impact their survival and reproduction.

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