“Model-Based Reasoning is Not a Simple Thing”: Investigating Enactment of Modeling in Five High School Biology Classrooms

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Dissertation Abstract

Modeling is an important scientific practice through which scientists generate, evaluate, and revise scientific knowledge, and it can be translated into science classrooms as a means for engaging students in authentic scientific practice. Much of the research investigating modeling in classrooms focuses on student learning, leaving a gap in understanding how teachers enact this important practice. This dissertation draws on data collected through a model-based curricular project to uncover instructional moves teachers made to enact modeling, to describe factors influencing enactment, and to discuss a framework for designing and enacting modeling lessons.

I framed my analysis and interpretation of data within the varying perceptions of modeling found in the science studies and science education literature. Largely, modeling is described to varying degrees as a means to engage students in sense-making or as a means to deliver content to students. This frame revealed how the instructional moves teachers used to enact modeling may have influenced its portrayal as a reasoning practice. I found that teachers' responses to their students' ideas or questions may have important consequences for students' engagement in modeling, and thus, sense-making.

To investigate factors influencing the portrayal of modeling, I analyzed teacher interviews and writings for what they perceived affected instruction. My findings illustrate alignments and misalignments between what teachers perceive modeling to be and what they do through instruction. In particular, teachers valued providing their students with time to collaborate and to share their ideas, but when time was perceived as a constraint, instruction shifted towards delivering content. Additionally, teachers' perceptions of students' capacity to engage in modeling is also related to if and how they provided opportunities for students to make sense of phenomena.

The dissertation closes with a discussion of a framework for designing and enacting lessons for engaging students in modeling. I draw on examples from this study to provide context for how the framework can support teachers in engaging students in modeling. Altogether, this dissertation describes how teachers facilitate modeling and why varying enactments may be observed, filling a gap in researchers' understanding of how teachers enact modeling in science classrooms.

“The literalist science curriculum for the nonscientist communicates, in spite of itself, a perversion of the meaning of science and, in the end, creates a climate of opinion inimical to science. By failing to distinguish the physically seen from the inferred, and the conceptual embodiment from what is embodied, the literalist curriculum leads the students to confuse the one with the other or to analogize all of them to the status of things of common sense. Force, gene, kinetic energy, or superego are indiscriminately assigned the same existential status as breakfast food and the automobile. From this failure of discrimination, the students learn to expect certain behaviors of commonsense objects, which, of course, do not occur. The end effect is confusion, uncertainty, and cynicism about the validity of science, and its social value (p. 377).”

--Joseph Schwab, 1958

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Chapter 1 Introduction to the Dissertation

This dissertation consists of three separate papers that provide a descriptive account of how teachers enacted modeling in high school biology. The work grew out of an interest in understanding the coordination of science content knowledge and scientific practice in classrooms. I first began to wonder about best practices for this kind of integration while working on my Master's degree at Purdue University. At that time, my Master's advisor, Clark Gedney, encouraged me to become involved in his education outreach programs. Up to that time, I had made every attempt to avoid teaching; however, with Clark's encouragement, I began visiting schools and working with elementary and high school science teachers throughout northern Indiana. Those first experiences have led me down a path that I never expected and have never regretted.

The lessons I created through those programs gave students opportunities to observe what I perceived to be an engaging phenomenon: a small, marine invertebrate smashing a large, hard snail shell with its hammer-like appendage. This entry into the fascinating world of science education allowed me to see the ways in which educators might leverage student interest and curiosity about the natural world. From there I started working on a project entitled *Go with the Flow.* For this project, I worked with local K-12 teachers to create inquiry-based lessons using a concept-centered design approach. We focused on giving students opportunities to develop ideas concerning broad concepts, such as ecosystem interactions, and afterwards would have students develop a testable model using an easily learned visual programming language (STELLA). This was my first exposure to model-based reasoning in science classrooms, although I did not realize it at the time. However, these foundational experiences were instrumental in providing me with opportunities to observe problems of practice and to develop innovative means for making science instruction akin to the research I conducted in the laboratory.

Following my time at Purdue University, I left academia to gain a better perspective by teaching elementary school science. For five years, I was a K-8 science specialist at a small school in San Francisco. Although it was a private school, I taught a culturally and linguistically diverse set of students. A majority of the students spoke a language other than English at home, and many were first-generation citizens, yet the curriculum I was asked to teach was reading and writing intensive, and incorporated little experimentation. I knew from my previous experiences in science and education that this would not work for my students; therefore, in my second year, I introduced a new science curriculum using an existing, research-supported resource that I would scaffold to fit my students' needs. Since English was a second language for many of my students, I wanted to focus on developing proficiency, not only in reading and writing science text, but also in evaluating and communicating scientific information. Therefore, I took a broad view of scientific discourse that included various ways for students to articulate and represent their ideas. In addition, my students and I developed driving questions that served to focus our lessons and investigations. Upon starting the doctoral program at the University of California, Davis, I recognized that my teaching style was similar to model-based reasoning and that my experience as a scientist heavily shaped my instructional approach. My pedagogical style was similar to the ways in which I had conducted science: an observation leads to a question, and through investigation and analysis and interpretation of data, sets of ideas, based on evidence, emerge that help to answer the question.

Although teaching was fulfilling due to the success and engagement I saw in my students, I wanted to pursue a PhD to enact change beyond my classroom. I wanted to bridge my science expertise with my work in education, which led me to the University of California, Davis. I applied to the Science and Agricultural Education program with interests in Curriculum and Instruction because I wanted to improve teacher quality in science through collaborative approaches targeting diverse learners. It is then that I explicitly learned of model-based reasoning; as an approach to teaching, it struck me as intuitive. It was similar to the ways in which I taught my own students, and I could immediately envision its potential in providing students with opportunities to engage in authentic science experiences; however, enacting model-based reasoning is inherently complex. This dissertation is my attempt at characterizing some of the complexity of this kind of instruction.

Dissertation Context: Modeling Scientific Practice in High School Biology

The year I am writing this dissertation is the first year that teachers in sixteen states are expected to teach to the *Next Generation Science Standards* [NGSS] (NGSS Lead States, 2013). NGSS calls for what has come to be called "three-dimensional learning", due to its characterization of what students should be able to know and do by the time they complete high school. Dimension One of NGSS outlines a set of scientific and engineering practices, which represent an epistemological view of what should count as science and as engineering in the classroom. Dimension Two describes cross-cutting concepts, which are major themes that transcend each of the science disciplines, such as the concepts of energy and matter or scale and proportion. Dimension Three delineates the disciplinary core ideas of the life sciences, earth sciences, and physical sciences. If all three dimensions are implemented in the classroom in a coherent manner, then students should gain a rich epistemological view of the sciences and of engineering, that is integrally tied to the appropriate disciplinary content (NGSS Lead States, 2013).

Although there have long been calls for shifting science instruction towards methods similar to "three-dimensional learning", the traditional approach to school science, i.e. teaching "the scientific method", continues to dominate (Rudolph, 2005), despite research, professional development, and teacher educators' efforts to further innovation. This brings to bear an important, yet complex question: what is needed to facilitate instructional change consistent with educational reform? Although our research community may never arrive at a satisfying answer, we can draw on an emerging body of literature to concentrate our focus.

Within the last decade, research in science education has focused on the ways in which scientific practice, such as that outlined in the science and engineering practices of NGSS, can be productively utilized in the classroom as a means for students to learn disciplinary content. Broadly, this research tells us two things: teachers must transform their views concerning who is capable of generating knowledge (Ford, 2008); and teachers need support in productively implementing scientific practices (e.g., Ford, 2008; Halloun, 2007; McNeill, Katsh-Singer, González-Howard, & Loper, 2016; Passmore, Stewart, & Cartier, 2009). This dissertation is embedded in a project that addresses the need for the curricular and pedagogical supports, particularly those necessary for teachers to provide students with opportunities to generate knowledge through engagement in the practice of "developing and using models".

This dissertation research was conducted within the context of a larger project entitled *Modeling Scientific Practice in High School Biology* (MBER Biology; National Science Foundation DRL Award No. 1348990; IRB ID: 648673-1). It was a collaborative project between teachers, education researchers, and scientists. Over four years, we co-designed a yearlong high school biology sequence that included the curricular materials and pedagogical supports for teachers to utilize models and modeling as a means for enhancing student learning.

In year one, we focused on developing the curricular sequence and the day-to-day lessons that would be included. To assist in this effort, two teachers, Clair and Helen[1], were major contributors to the design of MBER due to their prior experience in model-based reasoning professional development and in the design of modeling lessons. In year two, Clair and Helen piloted the materials, and in observing them, I became interested in the different ways they enacted modeling. For example, there were times when modeling instruction was student-centered and others when it appeared to be more teacher-centered. Upon reflection, the teachers discussed how to redesign their MBER lessons to become more student-driven and focused on student sense-making. This change seemed to provide preliminary evidence of teachers' evolving knowledge of the purpose and use of models in the classroom. It also implied the mediating role of curricular materials in this type of learning. To capitalize on these initial observations, I chose to focus my dissertation broadly on the use of models in the classroom. I began collecting data towards the end of our pilot year, when ten new teachers were brought onto the project in order to "scale up" and implement the curriculum (year 3). I am writing and submitting this dissertation in year four of the project.

The new teachers that started the project in year three, or T10 as we called them, were introduced to the MBER curriculum through an initial meet-and-greet, and through two summer professional development institutes totaling six days. After completing the institutes, they were given access to a website that housed all of the curricular materials and pedagogical supports. It also included a "social networking" like function that allowed for peer feedback and questions[2].

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[1] Names of individuals and places throughout this dissertation have been changed to protect the confidentiality of participants.
[2] www.modelbasedbiology.com

Study Participants

Teachers were solicited for participation in this project through the Sacramento Area Science Project listserv. The Sacramento Area Science Project focuses on both science education research and K-12 science teacher professional development and has cultivated partnerships with many Northern California districts and teachers. School districts and individuals who have participated in SASP related projects or professional development sessions were contacted about the MBER project, its goals, and its requirements for participation. Eighteen applications were received and ten were chosen to participate. Overall, we wanted to include teachers who taught in diverse contexts, primarily taught biology, had a range of teaching experience, and who had a range of NGSS and modeling understanding; therefore, we were purposive in our sampling methods (Miles & Huberman, 2013). Table 1 provides an overview of the participating teachers for Year 3.

Table 1-1. *Demographics of MBER Teacher Participants in Year 3.*

Name	**Years Teaching**	**School**	**Teaching Credential in Biology**	**Bachelor's Degree in Biology**	**Advanced Degree (MA or PhD)**
Connie	30	Spring H.S.	Yes	(unknown)	unknown
Lori*	20	Wildwood H.S.†	Yes	Yes	No
Steve	13	Wildwood H.S. †	Yes	No	No
Amanda	14	Wildwood H.S. †	Yes	No	No
Eric*	14	Wildwood H.S. †	Yes	No	No
Catherine*	20	James K. Polk H.S.	Yes	Yes	No
Margo	7	Davidson Charter	Yes	No	Yes (MA)
Frances*	12	James K. Polk H.S.	Yes	No	Yes (MA)
Leslie	16	Navy H.S.	Yes	No	Yes (MS)
Fred*	1	Valley H.S. †	Yes	Yes	Yes (MA)

Note: Teaching experience is the number of years prior to participation in MBER.
*Teachers that I will focus on in this dissertation.
†Same district.

Although we collected data across all 10 teachers, I have chosen to focus on five due to their proximity in locations, their range of experience in teaching and with NGSS, and their collaborative nature. Lori, Eric, and Fred taught within the same district, and Catherine and Frances taught within the same school. These five teachers also had easy access to individuals who had previous modeling experience, as Eric was a previous participant in extensive model-based reasoning professional development, and a co-worker of Frances and Catherine was a co-designer of the MBER curriculum (Clair). In chapters 2 and 3, I further explicate the reasoning behind our sampling methods.

Curriculum Overview

The MBER Biology curriculum is designed as means for providing students opportunities to engage in modeling to generate scientific understanding. In creating the curriculum, we had *a priori* design commitments in addition to the focus on modeling. First, we wanted to create a curriculum that had a clear storyline with explicit connections between biological ideas. This naturally led to positioning evolutionary models as the core family of models that students would be generating and reasoning with throughout the academic year. Within the biology community, evolutionary models are regarded as central to explaining a variety of phenomena in the natural world as well as connecting a range of other biological ideas (Passmore, Gouvea, Guy, & Griesemer, 2016). Second, we wanted to provide teachers with pedagogical supports that outlined "model moves" for implementing the curricular materials. Ultimately, we instantiated these model moves in "reasoning triangles" which incorporated the three main components of any modeling lesson: the phenomenon, the question about the phenomenon, and the model that explains the phenomenon. The reasoning triangles also communicated the connections between all three components: the model serves as a framework for answering the question about the phenomenon (Gouvea & Passmore, 2017; Passmore, Gouvea, & Giere, 2014). Third, we wanted to create a curriculum that was not prescribed; rather we wanted a curriculum that would give teachers agency to determine what is useful for both themselves and for their students, and to be able to modify the sequence to accommodate their needs. What emerged from these commitments was a yearlong, model-based sequence that is intended to give teachers the support needed to coordinate modeling and content in a student-centered approach. In the following sections, I will briefly describe what models and modeling are, the MBER curricular sequence, and its corresponding reasoning triangles. A more thorough treatment of each is included in subsequent chapters.

Models and Modeling. Scientific models are dynamic entities, consisting of sets of ideas, based on evidence, that serve as abstracted frameworks for answering questions about phenomena (Giere, 1988; S. W. Gilbert, 1991; Nersessian, 2002; Passmore et al., 2014). Models are dynamic because science is an ever-changing field, proving or disproving current understandings, and models change as new evidence arises, or as the criteria, the phenomenon, and the question about the phenomenon change. In order to generate models, scientists engage in the act of *modeling*, which includes questioning, investigating, and analyzing and interpreting the natural world. In the classroom, if students are engaged in modeling and developing models as a means for making sense of phenomena, then they are participating in model-based reasoning (Passmore et al., 2014). Thus, the focus of MBER is to have students engaged in model-based reasoning as a primary means for learning and understanding high school biology.

MBER Sequence and Reasoning Triangles. We focused on developing supports that guide teachers in considering instructional moves, or "model moves", that facilitate model-based reasoning. The moves outlined for each lesson consisted of one or two of the following components: (1) the phenomenon to be investigated (P); (2) the driving question ("how" or "why") about the phenomenon that serves to narrow the focus of investigations (Q); and (3) the model that serves as a framework for generating an explanation that answers the question about the phenomenon (M). Figure 1-1 illustrates a kind of model move outlined in the curriculum. In this lesson segment, teachers are facilitating the development of a question about a phenomenon. Thus, reasoning triangles are designed to support teachers in their lesson planning, so that they can be intentional about using productive "model moves" that facilitate model-based reasoning. These model moves are broken down based on what the focus should be for a given learning segment. In organizing the curriculum, the reasoning triangles helped to illustrate the sequence in a coherent way, especially when viewed through the lens of a question. Appendix A has a map of the sequence used by T10 during the year of this study.

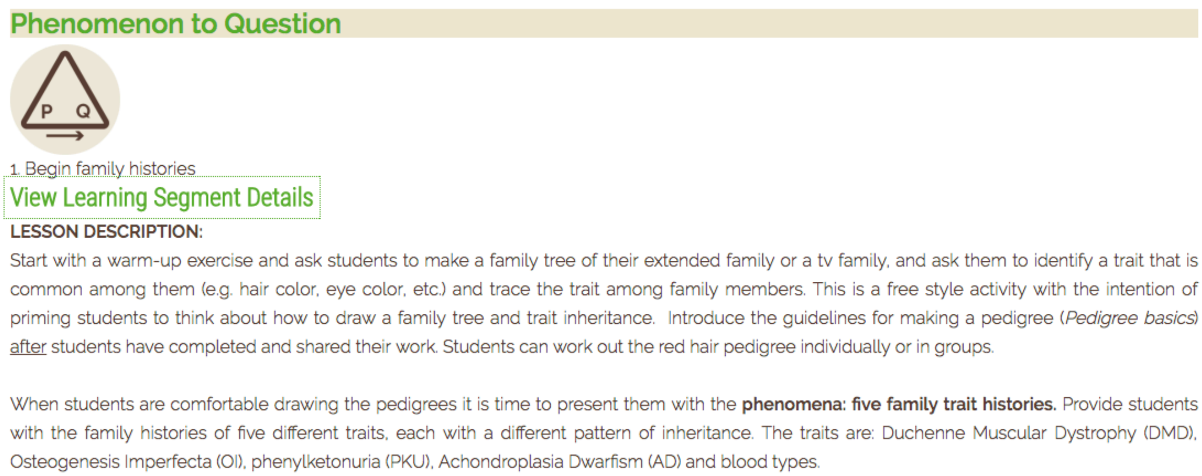


Figure 1-1. *A screenshot of a model move for Mendelian Genetics (triangle 19).*

Positionality and Role of the Researcher

Although this dissertation is part of a larger project, I have been an integral part of the research team, assisting in the development of the curriculum, the research questions, and our data collection scheme. I was supported by the entire MBER Biology team in the data collection and in portions of the analysis; however, the ideas for this dissertation and the development of the framework are my own. I also want to acknowledge that in addition to being as a member of the MBER design team, I was a regular participant-observer (Merriam, 2009) in the classroom. Additionally, as the teachers worked to enact the curriculum, I was an instructional coach, assisting them in their understanding of science content and model-based reasoning. I have taught in K-12 classrooms and have designed and implemented lessons for facilitating model-based reasoning. I also have conducted scientific research and understand what it means to engage in the practice of scientific modeling. I have a thorough theoretical and empirical grounding of what it means to engage students in this important scientific practice and what that could possibly look like in the classroom; therefore, I have the knowledge and capacity to understand what teachers should be doing to facilitate model-based reasoning and what the students should be learning. Furthermore, as a member of the MBER curricular design team, I recognize that I had a vested interest in how the curricular materials were utilized by the teachers in the classroom; however, I made every effort not to step in during the classes I observed, unless the teacher asked me to do so.

Finally, I would like to acknowledge that for the remainder of this dissertation, I will continue to use the collective "we" and "our" in addition to the singular "I". This was a huge collaborative effort and I would be remiss not to acknowledge the MBER team's intellectual contributions to this work.

Dissertation Organization

This dissertation is organized as three independent, but theoretically connected papers, all focused around the scientific practice of modeling. The papers are connected by a commitment to better understanding the ways in which this important scientific practice is enacted, and what might lead to varying enactments. Combined, the three papers seek to answer three questions:

1. In what ways do teachers facilitate modeling when enacting a model-based curriculum?
2. What factors impact modeling instruction in high school biology classrooms?

3. How can teachers design lessons for supporting students' engagement in modeling, and thus, sense-making?

Chapter two focuses on the instructional moves teachers made as they enacted modeling. Chapter three focuses on factors, perceived by us and by teachers that may have influenced modeling instruction. Chapter four is practitioner-oriented chapter focused on how to design lessons for engaging students in sense-making. The abstracts of each chapter follow.

Chapter 2: Teachers' Instructional Moves for Facilitating Modeling

Modeling is a powerful means by which to engage students in authentic scientific practice. As such, there is extensive research describing what students can do when given opportunities to develop and use models to make sense of phenomena. Additionally, a widening body of research describes what teachers know about models and what they should attend to in order to engage students in this important reasoning practice. However, little is known about the ways in which teachers take up and implement this ambitious pedagogy in the classroom. In order to address this gap in the research, I examined how teachers enacted modeling in high school biology classrooms. During the year in which our research group collected data, the teachers implemented a yearlong curricular sequence that centralized modeling as a core practice through which students would generate biological knowledge. The findings suggest that teachers tended to use four categories of instructional moves for mediating modeling, and that the ways in which these moves were used may have fostered or constrained students' sense-making. The findings have implications for understanding what the consequences of these varying enactments might have on student learning and for understanding how the science education research community might improve the design of learning environments, not only for students but also for teachers.

Chapter 3: Factors Influencing Enactment of Modeling in High School Biology Classrooms

In this yearlong study, I examined the factors affecting implementation of modeling in high school biology classrooms. Data were collected within the context of a National Science Foundation curriculum development project that centralized modeling as a means for engaging students in authentic scientific practice. Video-recordings of instruction, stimulated-recall interviews, semi-structured interviews, and teacher reflections were used as means to understand why enactments of modeling varied. Analysis focused on affordances and barriers to implementation perceived by the teachers and by the research team as we observed teachers utilizing modeling in their classrooms. Overall, I found four broad categories of factors that may have affected how modeling was enacted and how modeling may have been portrayed: teachers' intentions, beliefs, and values; teachers' real-time instructional considerations; teachers' views and understanding of science; and teachers' perceptions of the role of the curricular materials. The results of this study have implications not only for better understanding the complexity of practices-based instruction, but also for providing teachers with support in enacting practices-based instruction.

Chapter 4: Modeling Phenomena in High School Biology: A Focus on Sense-Making

In this practitioner-oriented chapter, I discuss how the coordination between phenomena, questions, and models can serve as a framework for designing and enacting lessons with a focus on student-sense-making. Drawing on examples and findings from research into teachers' implementation of a model-based curriculum, I present the framework with respect to the instructional moves and strategies teachers can use for facilitating instruction that positions students as the disciplinary authorities in the classroom. I situate the examples and strategies within the context of a model-based lesson that promotes students' sense-making about classical genetics.

Why does understanding teachers' facilitation of modeling matter?

At the beginning of this dissertation, I include a quote from Joseph Schwab, an influential scientist and philosopher, whose extensive work emerged from an interest in how science was portrayed to students. He was concerned that science textbooks and curriculum provided to teachers miscommunicated science as a static body of knowledge. In his own words, he stated that this incorrect translation of science creates "confusion, uncertainty, and cynicism about the validity of science, and its social value (1958, p. 377). Additionally, he implies the danger in non-scientists perceiving science as infallible; on the contrary, it is a human endeavor that is not without limitations.

Given our current political climate, the defunding of science research, and the recent withdrawal from the Paris Climate Agreement, a clear understanding of what science is and what it can be is more important than ever, and the development and implementation of effective learning environments could be a useful means for directly providing students with the agency to critically reason with and about science. As one research participant, Lori, noted in an interview with us,

> "My idea is that when this [student] is an adult and they see science in the news or they have to make real decisions for society, whether it's global climate change or something, they have the wherewithal to look at the data. To look at data, to look at a diagram and truly assess intelligently what it means. Because that's how I see what–we're talking about our future, who's going to make decisions. And it's worrisome if they look at a graph and they go, 'oh yeah, well it's pretty and it goes up so that must be good.'" (Lori, Interview, 9/24/15)

In order to effectively design learning environments that support students in developing the reasoning skills described by Lori, we must first understand what teachers do as they endeavor to engage students in the practices of scientists. Therefore, this dissertation, that is situated within a novel curricular context, emerges from an interest in how we might best support students and teachers in understanding what the scientific enterprise does, and how the ways in which scientists generate knowledge might be productively leveraged in the classroom.

Chapter 2 Teachers' instructional moves for facilitating modeling

Abstract

Modeling is a powerful means by which to engage students in authentic scientific practice. As such, there is extensive research describing what students can do when given opportunities to develop and use models to make sense of phenomena. Additionally, a widening body of research describes what teachers know about models and what they should attend to in order to engage students in this important reasoning practice. However, little is known about the ways in which teachers take up and implement this ambitious pedagogy in the classroom. In order to address this gap in the research, I examined how teachers enacted modeling in high school biology classrooms. During the year in which our research group collected data, the teachers implemented a yearlong curricular sequence that centralized modeling as a core practice through which students would generate biological knowledge. The findings suggest that teachers tended to use four categories of instructional moves for mediating modeling, and that the ways in which these moves were used may have fostered or constrained students' sense-making. The findings have implications for understanding what the consequences of these varying enactments might have on student learning and for understanding how the science education research community might improve the design of learning environments, not only for students but also for teachers.

Introduction

The new vision for science education set forth in the *Next Generation Science Standards* (NGSS Lead States, 2013) will require a shift from traditional forms of school learning towards a more practice-oriented approach (National Research Council, 2012). The intention behind NGSS is to coordinate scientific content with scientific practice, and as such, the authors of both *A Framework for K-12 Science Education* (National Research Council, 2012) and NGSS (NGSS Lead States, 2013) identify eight scientific practices that describe the cognitive work that scientists do to construct, examine, and evaluate scientific knowledge. Within that set is “developing and using models”, a much-studied practice that has garnered attention as a way for introducing authentic scientific practice in the classroom (J. K. Gilbert, 2004; S. W. Gilbert, 1991; Windschitl, Thompson, & Braaten, 2008) and for anchoring practices-based instruction (Gouvea & Passmore, 2017; Passmore, Coleman, Horton, & Parker, 2013; Passmore, Schwarz, & Mankowski, 2016; Passmore et al., 2009).

Research on models and modeling highlights the powerful reasoning that students can do when engaged in the scientific practice (e.g., Louca & Zacharia, 2014; Passmore & Stewart, 2002; Schwarz & White, 2005; Wilkerson-Jerde, Gravel, & Macrander, 2015). It also highlights teachers varying understanding of what models are and what constitutes modeling in the classroom (e.g., Justi & Gilbert, 2002a; Justi & van Driel, 2005; Van Driel & Verloop, 1999; Williams & Clement, 2015). However, there is a need for research describing how teachers enact and support students in this important scientific practice (Louca & Zacharia, 2012; Oh & Oh, 2011). To extend this line of research, in this chapter, I report on the findings of a descriptive study conducted to map the ways in which teachers facilitate modeling.

To make sense of modeling instruction, I present a framework that synthesizes the varying perceptions of what modeling can be in science classrooms. I then use this framework to investigate teachers' enactment of modeling instruction. The teachers in this study were participants in a National Science Foundation funded curriculum project, and implemented a yearlong sequence designed by a team of researchers, scientists, and teachers. The resources provided to the participants included the curricular and pedagogical supports for facilitating the generation and revision of biological models. The purpose of this paper is to describe the varying ways in which teachers implemented modeling, as depicted in these materials, and what effects it may have had for how modeling is portrayed in science classrooms. This work is important because it provides new and needed insights into the role of models in science classrooms. To investigate this space, specifically, I ask: in what ways do teachers facilitate modeling when enacting model-based curriculum?

The Act of Modeling in Science Classrooms

Modeling is a practice that is central to the generation and evaluation of scientific knowledge (Giere, 1988; S. W. Gilbert, 1991; Nersessian, 2002). As an act, it encompasses the development of a *model* that serves as a framework for predicting the behavior of or explaining an aspect of a phenomenon under study (Passmore et al., 2014). Nersessian (1989) describes the model development process as one that is based on axiomatic understandings of science and that involves constructing representations, analogizing, and thought experimentation (p. 136). As a whole, this iterative process involves the development of a model that provides an explanatory account of a phenomenon under study. Thus, when scientists develop a *model*, they are engaging in *modeling*, and developing sets of ideas, based on evidence, that answer a question about a phenomenon (Passmore et al., 2014). Describing the model generation process as an act emphasizes the importance of the cognitive agents who are doing the reasoning, which in this case are scientists (e.g., Giere, 2010; Gouvea & Passmore, 2017; Passmore et al., 2014).

Some have argued that the act of modeling can be translated into science classrooms so that students' work can parallel that of scientists (e.g., Passmore et al., 2014; Schwarz & White, 2005; Windschitl et al., 2008). Namely, researchers suggest that the epistemic aim of science–to explain natural phenomena–can be productively used as a means to more genuinely represent the scientific process, than does the scientific method (S. W. Gilbert, 1991; Passmore et al., 2014; Windschitl et al., 2008). Consequently, if students are generating and evaluating scientific knowledge through modeling, then the students are the cognitive agents doing model-based reasoning (Gouvea & Passmore, 2017; Passmore et al., 2014). This difference between *modeling* and the *model* and their relationship to student reasoning is important because within the current reform context of NGSS (NGSS Lead States, 2013) educators are being asked to foster in students "a level of facility in constructing and applying appropriate models" (National Research Council, 2012, p. 59). To promote this sort of understanding, teachers will, at a minimum, need to understand how models operate in science and recognize the utility of models both in science and in science classrooms (for what are they being used), that more than one model can be used to explain a phenomenon (depending upon what aspect of the phenomenon is being investigated), and that models can be revised in light of new evidence (Oh & Oh, 2011).

In addition to understanding the nature of models and their purposes and uses, guiding students in proposing, testing, and evaluating models necessitates teachers' attention to student ideas because their conceptions provide leverage points for generating models of phenomena they observe in the classroom. Therefore, educators wanting to support students as the cognitive agents in modeling will need an orientation towards a student-centered classroom. As students share their ideas, teachers will need to push for students to explicate their reasoning and will need to assist students in building on ideas that they share (Hammer & Schifter, 2001). This attention to ideas also requires mediation by the teacher in order to drive instruction forward. Halloun (2007) analogizes the teachers' role in modeling classrooms to that of a *moderator* and an *arbitrator* (p. 681). The teacher is a moderator as they assist students in negotiating ideas, both their own and that of others in the classroom. The teacher is an arbitrator as they assist students in deciding what ideas to build on and what ideas to set aside. Most importantly, through this act of modeling, teachers should afford students opportunities to generate their own understanding, transitioning classrooms away from the "traditional school science" approach of knowledge transmission towards a conceptual understanding orientation to learning.

Research, however, indicates that teachers' understanding of and implementation of this scientific practice is variable, which could be problematic for modeling enactment. For example, Van Driel and Verloop (1999) found that teachers generally provide superficial accounts of models. Similarly, Justi and Gilbert (2002b) found that their survey respondents focused more on the content of models rather than viewing them as tools for teaching how scientific knowledge is constructed. However, Van Driel and Verloop (1999) also found that some teachers could identify the explanatory power of a model. Williams and Clement (2015) investigated "exemplary, model-based science educators" (p. 5) and found that, although their teachers struggled to reconcile student-generated models with current or historical models, their participants positioned students as cognitive agents.

In addition to finding that teachers' understandings of models are varied, research indicates that teachers' use of models is variable. For example, in a study examining how teachers use models in their classrooms, the authors found that even if teachers understood that modeling is a means for generating knowledge and made attempts at engaging their students in modeling, the focus turned towards delivering content, rather than using the model as a means for reasoning (Justi & Gilbert, 2002a). In another study, Dass, Head, and Rushton (2015) provided their teacher-participants with professional development focused on utilizing modeling as a means for construct explanatory accounts of phenomena; however, in observing teachers enact modeling in their classrooms, they noticed a focus on content rather than model generation and evaluation by students. They noted, though, that over time and with practice, the teachers began to see their students' capacity to engage in the practice and thus began shifting their instruction towards providing students with opportunities to develop models themselves. These findings, in coordination with the literature on what constitutes models and modeling, illustrate that there are variable perceptions of modeling, by both teachers and researchers, that can influence how models and modeling are enacted. In the next section, I illustrate how these varying enactments can be used to investigate how models and modeling are portrayed in science classrooms.

Model-Based Instruction Can Affect the Portrayal of Modeling

In my review of the models and modeling literature, I illustrated that different perspectives of modeling have emerged: one that views modeling as a means for engaging students in generating their own understanding of science, and another that views modeling as a means for communicating to students the body of scientific knowledge (Justi & Gilbert, 2002a, 2002b, 2003; Justi & van Driel, 2005; Van Driel & Verloop, 1999, 2002). Research also indicates that these perceptions are not either/or, and that they can vary as teachers move forward in enacting modeling (Dass et al., 2015; Justi & Gilbert, 2002a; Williams & Clement, 2015). Moreover, because the purpose and utility of models are only apparent when used in context

(Morgan & Morrison, 1999), it stands to reason that how model-based instruction is enacted can have an impact on the ways in which the act of modeling is portrayed. I suggest then that the instructional actions teachers take to move modeling forward may largely vary along a continuum, and can be described as falling anywhere between providing students opportunities to engage in sense-making to delivering content to students. Instruction that actualizes modeling as a means for generating knowledge about the natural world has the potential to encompass opportunities for engaging students in sense-making. Instruction that tends to use models to represent static content knowledge may portray modeling as a means for knowledge transmission (Brewe, 2008). Figure 2-1 illustrates these perceptions on a continuum that represents what modeling could look like in science classrooms.

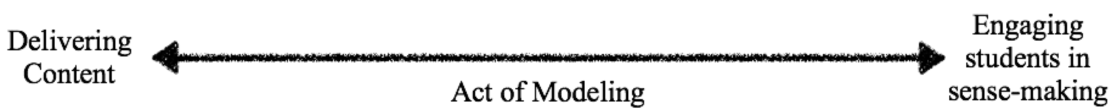


Figure 2-1. *The act of modeling continuum illustrates what modeling could be used for in the classroom.*

This framework thus offers a lens through which teachers' instructional actions can be examined and described to better understand how they enact modeling in high school biology classrooms. It also helps to make sense of how their instruction influences the portrayal of modeling.

Methodology

Study Context

This study took place within a National Science Foundation funded curriculum development project that grew out of a need for high quality, research-supported curricular materials designed for and aligned to NGSS. Our goals in designing the curriculum were to foreground the practice of developing and using scientific models and to provide teachers with the curricular and pedagogical supports needed to enact a yearlong curriculum. The curriculum was designed by a team of science education researchers, scientists, and two teachers, who also piloted and revised the curriculum before it was made available to the teacher-participants in this study. The curricular materials and supports were designed based on a framework that depicts the relationships between three components: a biological phenomenon for students to observe (P); a driving question students could ask about the phenomenon (Q); and the set of ideas that answer the question about the phenomenon (the model, M). With these elements combined, we identified twenty-four interconnected biological models that form the basis of the MBER curricular sequence. Figure 2-2 illustrates the curricular sequence.

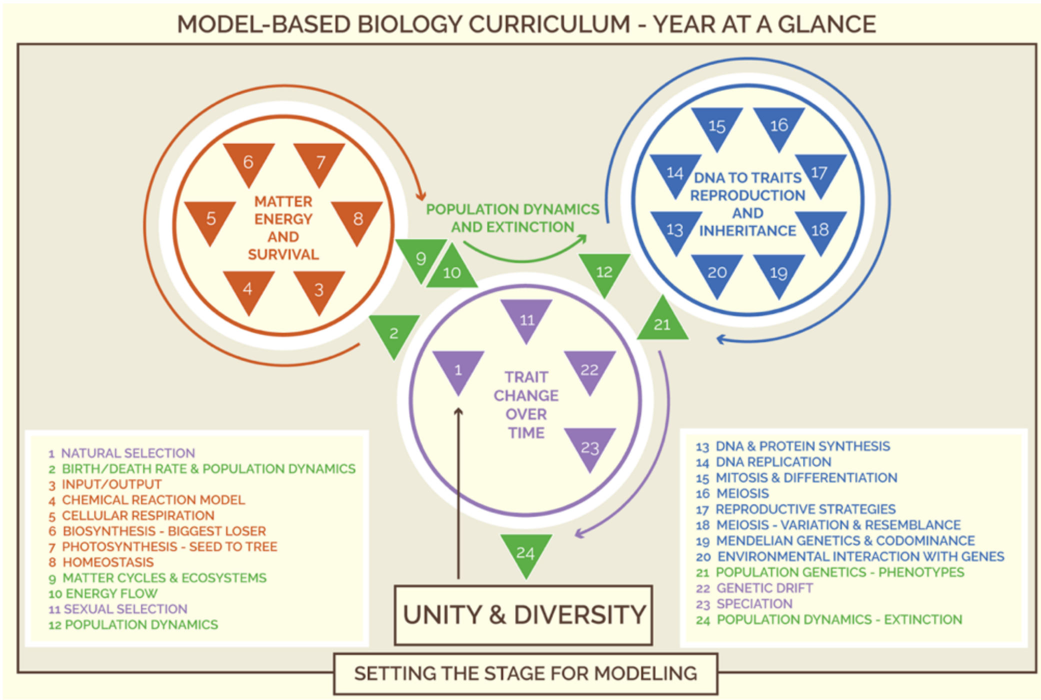


Figure 2-2. *The MBER Biology curriculum sequence is organized around mechanisms for evolution and how traits change over time.*

The curricular sequence displayed in figure 2-2 is illustrated through numbered triangles. The numerical sequence indicates the order in which the models are generated throughout the academic year, and their color represents their relationship to core ideas in biology: purple indicates models related mechanisms for evolution, matter and energy or bioenergetics related models are red, and blue indicates models of heredity and inheritance. Triangles were used because the models and their relevant components were communicated to teachers through what we called "PQM reasoning triangles". These triangles served two purposes in the curriculum: (1) they served as a high-level overview of the phenomenon, question and model for a given unit (what is displayed in figure 2-3); and they provided an overview of what the focus would be for a given lesson or series of lessons–what we called a "model move". Figure 2-3 illustrates a reasoning triangle that served as a high-level overview for natural selection (triangle 1), and the smaller triangle to the right illustrates the focus of a lesson to be enacted during natural selection.

In that lesson, the teachers would be guiding students through development of a question about a phenomenon; therefore, they would be enacting a "phenomenon to question" model move.

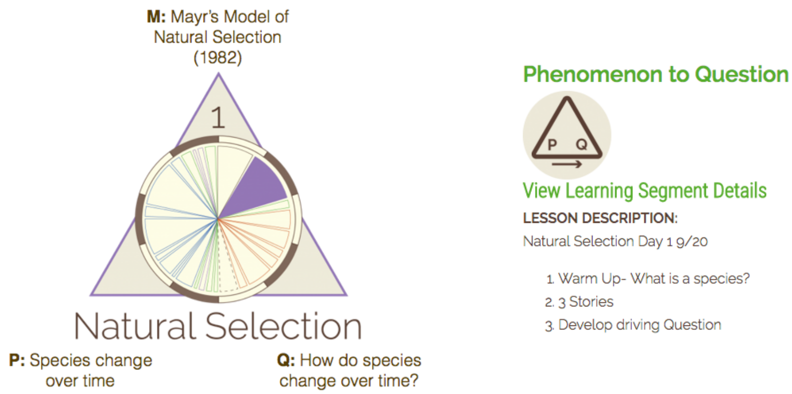


Figure 2-3. *Illustration of a high-level modeling triangle and a triangle illustration a "modeling move".*

Embedded within the descriptions of particular model moves were the presentations, student handouts, and worksheets designed to guide students' generation of the model. All of the curricular and pedagogical supports could be accessed via a website where teachers were able to copy and edit reasoning triangles for use in their classrooms. Also included in the website was a place where teachers could reflect on their day-to-day instruction, and a forum where they could ask questions of other teachers implementing the curriculum. Therefore, teachers had multiple pathways for accessing the supports embedded in the curriculum.

Study Participants

Teachers were solicited for participation in this project through a professional development-related listserv associated with the researchers of this study. The solicitation included information about the MBER project, its goals, and the requirements of participation. To apply, teachers completed a questionnaire that asked about their teaching experience, subjects taught, credentialed discipline, their academic background, and their professional development experiences. In addition, teachers had to complete two short essay questions, one describing their use of technology in the classroom, and the second explaining why they wanted to be involved in the project. Letters of support from their principals were also required. Eighteen applications were received and ten teachers were chosen to participate; we wanted to include teachers who taught a diverse population of students, primarily taught biology, had a range of teaching experience, and who had a range of NGSS and modeling understanding. Table 2-1 provides an overview of the final participating teachers for Year 3.

Table 2-1. *Demographics of MBER Teacher Participants in Year 3*

Name	**Years Teaching**	**School**	**Teaching Credential in Biology**	**Bachelor's Degree in Biology**	**Advanced Degree (MA or PhD)**
Connie	30	Spring H.S.	Yes	(unknown)	unknown
Lori*	20	Wildwood H.S.†	Yes	Yes	No
Steve	13	Wildwood H.S. †	Yes	No	No
Amanda	14	Wildwood H.S. †	Yes	No	No
Eric*	14	Wildwood H.S. †	Yes	No	No
Catherine*	20	James K. Polk H.S.	Yes	Yes	No
Margo	7	Davidson Charter	Yes	No	Yes (MA)
Frances*	12	James K. Polk H.S.	Yes	No	Yes (MA)
Leslie	16	Navy H.S.	Yes	No	Yes (MS)
Fred*	1	Valley H.S. †	Yes	Yes	Yes (MA)

Note: Teaching experience is the number of years prior to participation in MBER.
*Teachers that I will focus on in this dissertation.
†Same district.

Each of the ten teachers taught at least two sections of biology per day and agreed to utilize only the MBER materials for the 2015-16 academic year. Prior to implementing the curriculum, they participated in six days of professional development spread over two summer sessions. The purposes of these meetings were to orient teachers to (1) our perspective on model-based reasoning, (2) the reasoning behind our curriculum design; and (3) the website where they would access the materials. Furthermore, teachers were provided with support as requested by them throughout the year they implemented the curriculum. Additionally, we met with the all of the teachers five times over the course of the year to answer questions and to provide them with an open forum for communicating concerns or ideas they had regarding improvements to the design of the curricular and pedagogical supports.

Although ten teachers were chosen to participate in the implementation of MBER, for this study I focus on only five of the ten, as indicated by asterisks in Table 2-1. These five teachers taught in similar contexts: three of the teachers were in the same district but talked often and shared resources and worked collaboratively with one another via Google Classroom (Eric, Fred, and Lori). Eric and Lori also taught in the same school. Catherine and Frances taught in a nearby district, but in the same school. Additionally, the subset of participants had a range of experience in model-based reasoning. Fred had recently completed a credential program where methods instruction included a focus on modeling. Eric had previously participated in a modeling-focused research project, and a co-worker of Frances and Catherine was a co-designer of the MBER curriculum. Moreover, Catherine and Frances had implemented some of the MBER lessons in the year prior to participating in this project. Lori had no known modeling experience. Thus, these five teachers represent a convenient, yet stratified sample (Miles & Huberman, 2013). Their geographic locations and proximity to one another allowed for intensive data collection that could span multiple days, and their range of both modeling and teaching experience provided interesting contexts to observe MBER implementation.

Data Collection

Seven researchers including the author of this dissertation collected data during the 2015-16 academic school year. We were co-creators of the curriculum and designed the professional development the MBER teachers experienced in the summer before enacting the curriculum. During the year in which this study took place, each of us were also instructional coaches, assisting teachers in their understanding of the curriculum and model-based reasoning; however, we tried to maintain an objective stance when observing and only stepped in to assist when the teachers asked us to do so. Therefore, we were regular participant-observers in the MBER classrooms (Merriam, 2009).

Our primary source of data for this study included observations of instruction that were video and audio recorded. We purposefully chose to observe teachers during specific time points throughout the academic year. First, we observed all teachers enacting the first triangle, natural selection and triangle 19, Mendelian genetics. In four of the five classrooms, triangle 19 was the last one implemented. Catherine proceeded further into the curriculum; however, that was not observed. Between these two triangles, we were purposive in targeting the teachers' facilitation of model generation and model application across biological content areas, and each teacher was observed enacting these components of the curriculum at least twice. These additional observations took place during lessons related to bioenergetics and ecosystems, the red and green triangles, respectively, illustrated in figure 3.

During observations, we tried to maintain a consistent protocol for what to observe and record: we looked for the ways in which teachers explained the purpose for engaging in the MBER activities and what motivated the questions about phenomena; we focused on what the teachers and students were attending to as they engaged in the activities, and we looked for any evidence related to teachers' uptake of the MBER PQM framework, the curricular materials, or in how they developed and responded to classroom norms. In conjunction with the video and audio recordings, field notes were written in order to provide a context for what was occurring in the classroom and to provide detailed notes corresponding to our observation protocol.

In addition to the observations, we also conducted teacher interviews and collected reflections the teachers wrote about their enactment of MBER. The teachers were interviewed at a minimum following both Natural Selection and Mendelian Genetics, but Eric was interviewed a total of four times and Fred three times. The interviews were semi-structured (Seidman, 2013) and at least one interview per teacher included a stimulated recall component (Calderhead, 1981). Teacher reflections from both the website and from the five group meetings were also collected as a means to better understand teachers' intentions behind particular components of enactment. Table 2-2 provides an overview of the models each teacher was observed enacting and the types of data collected for each teacher throughout the year. Although we collected a large data corpus, the primary data sources for this study are the video recordings of teachers' instruction and the associated field notes. Because the purpose of this study is to examine the ways in which teachers implemented modeling in high school biology classrooms, these sources provided us with the richest context for what was happening in the classroom. Bold text in table 2-2 indicates the data sources utilized for this study.

Table 2-2. *Data collected for each teacher for the 2015-16 academic year.*

Cases	T1	T2	T4	T5	T6	T7	T9	T10	T11	T14	T16	T19	M1	M2	M3	M4	M5
Catherine	**V,** I, C	**V**, C	—	**V**, C	**V**, C	**V**, C	**V**, C	**V**, C	—	—	—	**V,** I	R	—	R	R	—
Eric	**V,** I, C	—	—	I[†]	**V**	**V,** I	—	—	**V**	—	**V**	**V,** I	R	R	R	R	R
Frances	**V,** I, C	—	**V**	—	—	—	—	—	—	—	—	**V, I,** C	R	R	—	R	R
Fred	**V,** I, C	—	—	**V**, C	—	**V,** I	—	—	—	**V**	—	**V**, I, C	R	R	R	R	R
Lori*	**V,** I, C	—	—	**V**, C	—	—	—	—	—	—	—	**V,** I	R	R	R	R	—

Table Key: Curricular reflections collected for the corresponding triangle (C); Interview conducted about instruction within the corresponding triangle (I); Reflection prompts collected during group meetings (R); Triangle for which the data was collected (T, see Figure 3); Instruction video-recorded for the corresponding triangle (V)
Bold text indicates data sources that were used for this paper.
Group Meetings (M) took place on 10/20/15 (1), 12/14/15 (2); 2/10/16 (3); 4/26/16 (4); 6/7/16 (5) [Due to the differences in teachers' schedules, there is no triangle that directly corresponds to each meeting date.
*Lori also provided a copy of a notebook she kept for the entire year that include her ideas for instruction and notes about the curricular materials.
[†]This interview was conducted while Eric was implementing triangle 5, but the focus of the interview was to better understand his lesson planning process and how he utilized the resources on the MBER website.

Data Analysis

To examine the ways in which teachers enacted modeling, I began with videos from Triangle 1 so that I could gain a foundational understanding of what was happening in the MBER classrooms. Videos were analyzed using StudioCode software, and in my first coding pass I binned the data based on our research team's observation protocol. Therefore, I was intentional in looking for moments where teachers were instructing and/or engaging in dialogue with the students. I tagged these instances as: "setting up the task", "taking stock", "referring to norms" and "modeling talk". "Setting up the task" refers to moments in which teachers described the modeling tasks to the students; "taking stock" occurred when teachers interacted with students as a means to uncover their ideas and/or make their reasoning public; "referring to norms" occurred when teachers referenced classroom rules and guidelines for interactions that had been co-constructed earlier in the academic year; and "modeling talk" refers to instances of teachers explicitly calling something a phenomenon, a question, or a model.

When watching the instances described above, I viewed them through the lens of what it means to engage students in the act of modeling, and focused on trying to understand how teachers would afford or constrain student sense-making. In doing so, I began to notice patterns in what teachers did and in their discursive interactions with the students:

- The teachers provided students with opportunities to share their ideas with one another or to work in groups on data analysis and model generation tasks.
- The teachers provided students with opportunities for engaging in dialogue with one another through whole class conversations[3].
- Teachers were sometimes evaluative when responding to their students.
- Instances of "setting up tasks" and "taking stock" were the key moments when teachers were discussing phenomena, questions, and models.

Based on these initial findings, my second pass through the data focused exclusively on the instances where teachers set up the modeling tasks and when they took stock of student

[3] Although we observed teachers interacting with students while they worked in small groups, our video and audio recordings were not clear enough to substantively analyze these moments.

thinking in the whole class setting. Utilizing StudioCode, I exported these moments and created a movie for each teacher that provided a chronological account of the teachers' modeling instruction for natural selection. I watched these instances and created typed narratives that described the ways in which the teachers enacted the lessons. Through creating these narratives, I recognized that instruction could be delineated into a series of instructional moves, similar to those described by Harris, Phillips, and Penuel (2011). In this case, the teachers' moves were particularly centered on actions they took to engage students in dialogue, to let students share ideas, and to give students time to process tasks. Using Excel, I then distilled the teachers' instruction, as observed in the movies I created, into instructional moves, organized chronologically.

In my third pass through the data, I categorized the instructional moves based on what the teachers were focusing on through their actions: a phenomenon, a question about the phenomenon, about the model, or combinations thereof. I call these high-level actions, "modeling moves", based on what had been communicated to teachers through the curricular supports embedded in the curriculum. Actions where teachers would switch to focusing on classroom management (organizing students into groups, checking and/or collecting homework, passing out worksheets, admonishing behavior, etc.), were not included in the analysis because it was not directly related to facilitating learning through modeling. Table 2-3 illustrates sections of transcript from Fred's classroom that represent each of the categories of modeling moves.

Table 2-3. *Sections of transcript extracted from video recordings of Fred instructing (9/17/2015, 9/18/2015 and 9/22/15).*

Modeling Moves	**Description of Instructional Moves**
Introducing Phenomena (P)	Fred presents three stories: one about peppered moth variation, another about antibacterial resistance, and a final story about an increase in average beak depth in Galapagos ground finches.
Identifying the Phenomenon (P)	Fred asks the students, "what do these three stories have in common. Is there a common thread that connects these three stories together?"
	Fred gives students three minutes to individually consider his question and another 45 seconds to share with their nearby peers.
	Fred says to the students, "Ok, let's try to collect some of these thoughts. Someone tell me something that you came up with."
	A student responds, "We were saying like they were all living organisms."
	[Eight minutes of dialogue between the students and Fred that leads to the identification of the phenomenon they will explore]
Generating the question about the phenomenon (P and Q)	Fred tells the students, "We're asking questions, this is the phenomenon. There's a phenomenon, organisms are doing what?
	Students chorally respond, "Changing."
	Fred then says, "Our question, we want to ask a question that if we came up with the answer to that question we should then explain what is going on. Like detailed explain. So, just kind of think for a minute and try to build that question, a good question, that just looks at a part of that big questions we looked at yesterday. What question could you ask about these three stories? Just think about the question. We're doing to come up with a question to drive our discussion.
	Fred gives students 30 seconds to discuss their questions in groups.
	Fred asks the students, "what's our question that we can ask?"
	A student responds, "I don't know. How are they all the same?"
	Fred asks, "how is what the same?"
	[This dialogue lasts for approximate six and one-half minutes before the class arrives to a driving question.]
	[The next section picks up during the next class period, after Fred has given students a dataset about the Galapagos ground finches and a worksheet for organizing their ideas.]

Table 2-3 *(continued)*

Modeling Moves	**Description of Instructional Moves**
Investigating the phenomenon (P and M)	Fred tells the students, "What you are doing is using this to see if you can try to find a pattern and to make connections." He then tells them “the final task is to explain a story answering the question using the data."
	[Students are given 15 minutes to work together in groups to analyze the dataset and generate explanations.]
Generating the model that questions the question about the phenomenon (P, Q, and M)	[The next section picks up two days later, when Fred begins to collect the ideas students have generated.
	Fred tells the class, “So, what I'm going to go is I'm going to go around by table and if you have an idea, you can throw it out there, and I might ask you to refine it a little bit. If it's not general enough I might ask you to try to think about what would be more general [begins telling student to pay attention]. We're going to come up with a list and you guys can write this list down in your second doodle.”
	[Classroom Management]
	Fred tells the class, “Ok, so we're going to go around and you guys can help me know what your general idea was that causes change and answers our question. I'm going to start with table 8 and we'll go around. Table 8, what do you think? What was one of your key ideas?”
	[Model generation conversations continues for 17 and ½ minutes]

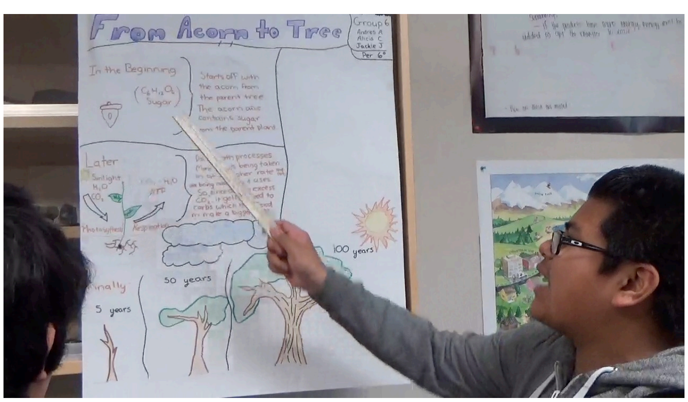
Table 2-3 contains sections of transcript extracted from video recordings of instruction that spanned four days (three days included in the table, a fourth day was also dedicated to both investigating the phenomenon and generating the model). When Fred introduced the phenomenon to his students, he presented to them three stories that had a common unifying theme that traits changed over time. Once he was finished presenting the stories, his instructional moves focused on helping students identify the pattern or theme, which was categorized as identifying phenomena. Once students had identified the phenomenon, he moved to help them generate a question about the phenomenon: how and why do traits change over time? Following development of a question about the phenomenon, Fred presented the students with a data analysis task whereby students would interpret data that would facilitate development of a model of natural selection. The task and the time Fred provided them to analyze the data was categorized as "investigating the phenomenon" because students were examining an aspect of traits changing over time. A caveat, however, is that even though students were investigating the phenomenon, they were doing so as a means to generate a model, which answers the question they developed. In regard to generating a model, the same is true with respect to the phenomenon, question, and model: as Fred goes table-by-table to let students share ideas, he is helping students come to a consensus about the model that answers the question about the phenomenon. Thus, the phenomenon, the question, and the model are not necessarily mutually exclusive components within a particular model move; however, it was helpful to distinguish between these moves as a means of understanding characteristics of enactment. As I will describe later, categorizing the moves in this way allowed me to examine whether or not instructional actions related to particular modeling moves were the same or different across all kinds of modeling moves I categorized.

Upon completing high-level categorization of model-moves, I looked across teachers to see how they mediated the modeling moves. These "mediating moves" refer to the actions teachers took while enacting the modeling moves. In categorizing these, I was interested in what Halloun (2007) described as the moderation and arbitration of ideas: how teachers assisted students in negotiating identification of the phenomenon, development of a question about the phenomenon, and generation of the model. Through analysis of the mediating moves, I found four broad categories of actions used by our participants in triangle one: giving students process time, letting students share ideas, responding to students, and focusing students' attention.

Giving Students Process Time. For each of the modeling lessons, teachers provided opportunities for students to engage in dialogue with one another or to consider a particular task, question, or idea individually. Usually this would start with a teacher introducing a task to the students. For example, at the beginning of the natural selection lessons (Triangle 1), teachers presented three stories to their students that illustrated a theme of trait change over time. After the presentation, the teachers posed the question, "is there a common theme that links these three stories together?" The students were then given time to consider the question in groups, and to write down their ideas before sharing them with the class. Pictured on the right is an example of students working together (taken on 5/10/2016). In this case, two students from Lori's class are trying to determine if their model of simple dominance helps to explain the pattern in a pedigree they have been given.

Opportunities for group or individual processing also arose during implementation of other modeling moves, such as when teachers provided openings for students to consider what questions they have about phenomena, when teachers gave students time to investigate phenomena, and when teachers asked students to consider ideas that may help to explain phenomena.

Letting Students Share Ideas. After teachers provided students with opportunities to talk with one another, they would let students share their ideas with the class. In all classes, for all models observed, teachers allowed their students to share their ideas in some way. This move was used when enacting all model moves, except for the introduction of the phenomenon. An example of sharing ideas occurred when Eric asked his students to share ideas they had about the relationship between biosynthesis and what happens to the matter when an individual experiences drastic weight loss. He first gave students time to process the question in groups and to write their ideas on a dry erase board. Once all the groups had finished, he asked them share their ideas by orally presenting to the class what they had written. In MBER classrooms, group presentations such as the one described in Eric's classroom were one common way of letting students share their ideas.



Another common method of providing space for students to share their ideas was through "gallery walks" (pictured on the left, taken on 3/01/2016 in Eric's classroom). Instead of orally presenting ideas to the entire class, groups of students would display their ideas on portable dry erase boards or poster paper that were arranged around the edges of the classroom, similar to art hung on the walls of a gallery. The class would then be given time to walk through the "gallery" and read the displays and/or ask questions of the groups whose work was being presented. In this picture, a student is explaining to another how an acorn grows into a tree. As he does so, he is invoking cellular respiration, photosynthesis, and biosynthesis models to explain where the matter comes from for the growth process to happen.

A third strategy used by teachers was to individually call on students or groups to share an idea, rather than make a presentation. In all strategies used, I noticed that the teachers would begin the sharing by encouraging students to participate and by reminding students to be respectful of one another, often by telling the students that "there are no right or wrong answers."

Responding to Students' Ideas. This mediating move occurred following opportunities for letting students share their ideas. This move appeared to be mostly dyadic in nature and mostly took place between the teacher and the student or group who had shared their ideas. Teachers' responses to students' ideas took one of four forms: they would summarize or repeat a student's or group's idea, they would ask students or groups to clarify or expand on an idea, they would identify flaws in a student's or group's reasoning, or they would respond with the "correct' answer.

In looking across cases to further examine these kinds of responses, I noticed that they were sometimes used as a means to evaluate the students' answers in ways similar to traditional patterns of initiate-respond-evaluate (Mehan, 1979) or triadic dialogue structures (Lemke, 1990). Although these evaluative patterns may seem intuitive for responses that identified flaws in student reasoning or that provided the correct answer, it was interesting that teachers were sometimes evaluative when asking for clarification or summarizing and repeating. Each of the five teachers used all four kinds of responses, including whether or not they were evaluative. These responses occurred after teachers provided students opportunities to share their ideas. A summary of the types of responses to students can be found in table 2-4.

Table 2-4. *Summary table of the different ways in which teachers enacted the mediating move of focusing students' attention.*

Mediating Move	Subcategory of Mediating Move	Description of Subcategory	Examples from Instruction
Responding to students	• Asking for Clarification	• Questioning a student or a group of students to further explain or expand on their ideas. Was either evaluative or not evaluative.	*Catherine:* Ok, cool [calls on another student]. Is there anything up here not on your list or anything you don't particularly agree with? *Student H:* The population. *[letting student share ideas]* Catherine: And you'll have to expand upon what that means? (not evaluative, 10/02/2015) *Catherine:* Ok, so this is what I was asking you, [Student name] because what this group is talking about was that among the finch population there were different beak sizes. Is that what you guys meant? (evaluative, 10/02/2015)
	• Identifying flaws in reasoning	• Pinpointing inconsistencies in or problems concerning a student's or a group's ideas or explanations. Always evaluative.	*Fred:* What are we making those from? *Student:* ATP. *[letting student share ideas]* *Fred:* That may be involved, but that isn't something we've talked about. (1/21/2016)

Table 2-4 *(continued)*

Mediating Move	Subcategory of Mediating Move	Description of Subcategory	Examples from Instruction
	• Providing answers	• Explicitly providing a student or a group with a correct answer. Always evaluative.	*Eric:* They're exact copies right? So if I'm only taking half as many chromosomes as the parent has, could the gametes be formed through mitosis? *[asking for clarification]* *Students:* No. *[letting students share ideas]* *Eric:* No. Exactly it wouldn't be a full copy. It would be half as many chromosomes. Does everybody see that? *[4/19/2016]*
Responding to students	• Summarizing or Repeating	• Recapping or restating a student's or a group's idea. Either evaluative or not evaluative.	*Student:* Sometimes parents have it and sometimes they don't. *[letting student share ideas]* *Lori:* Ok. Sometimes the parents have it and sometimes they don't. And sometimes the offspring have it and sometimes they don't. [not evaluative, 4/20/2016] *Student:* The same elements don't come out of it (explaining an incorrect chemical equation) *[letting students share ideas]* *Leslie:* Ok, the same elements do not come outcome out and, if we go back to here [referring to a slide] we see that we have the law of conversation of matter, and you can't create new matter [evaluative, 1/18/2015]

Focusing Students' Attention. When teachers were engaging in dyadic interactions with students or groups, I recognized that they would sometimes emphasize something a student or group had shared to the entire class by asking the class to consider it. This opened up the exchange to include all member of the class, rather than just a student or subset of students. This focusing happened in all conversations that occurred in the classroom. Sometimes, this move would be used to focus students' attention on a particular pattern in data that they wanted students to explain, or on the pattern that would serve as the phenomenon. At other times, they would use it to focus students' attention on the goals or purposes of the task, on a particular question, on vocabulary, on a model or on its relevant ideas. However, this mediating move did not solely happen following teacher-student or teacher-group interactions. It also was utilized as an opening move for a particular task. If we look back to the question that teachers used in natural selection to initiate identification of the phenomenon ("Is there a common theme that links these three stories together?"), we can see that they could immediately focus a particular task by specifying what the students should attend to.

In addition, the focusing moves were not necessarily used in mutually exclusive ways. For instance, sometimes when teachers would introduce a modeling task to the students, they would not only focus students' attention on the task and how they would accomplish it, but they would also remind students of the question about the phenomenon, or the model they were trying to generate. For example, during triangle 5, when Lori was enacting the generation of the model, she began the class by focusing the students' attention on what they had accomplished prior to the class:

> "Now we have this phenomenon of weight loss…so we specifically looked at this question [points to question written on the board in the front of the room]…Where did his 200 pounds go? Remember that was before break and that was yesterday's conversation. This is what we need to revisit today. We know we have to take in food and another

> input is that you also take in oxygen. We left off with, what about this water thing?" (Lori, 1/07/15)

In this quote, Lori is communicating to the students their task for the day: they have determined that oxygen and food are important components of the model that will help them to answer the question about weight loss. And, in this lesson, they will focus on figuring out whether or not water might be important. She also is bringing their attention to the phenomenon (weight loss) and the question (where did the weight go). Table 2-5 provides a breakdown of the kinds of focusing teachers would do and representative examples from the classrooms.

Further analysis of the modeling and mediating moves involved examining other instances of teachers "setting up tasks" and "taking stock" that followed in other triangles throughout the academic year. My goal in these final analyses was to ensure that the categorization of modeling and mediating moves continued to encompass the actions teachers took throughout the academic year. See Table 2-2 for a summary of coded video.

Table 2-5. *Summary table of the different ways in which teachers enacted the mediating move of focusing students' attention.*

Mediating Move	Subcategory of Mediating Move	Description of Subcategory	Examples from Instruction
Focusing Students' Attention	• On the goals and/or purposes of the task	• Used to bring students' attention to a task. This would sometimes take the form of reminding students what they were doing	*Catherine:* So, now what you are going to do is look at the graph. What I'm going to ask you to do on this graph is a couple of things. First, what general patterns or patterns do you see, and what you think might cause the general pattern. And, think about what kind of information you would want to help you think about the wolf graph. (1/20/2016)
	• On a model or model idea	• Used to draw students' attention to a model or model idea, or to emphasize a model idea shared by a student or student group	*Student A*: There's a couple of different things that say change and adapt [*letting students share ideas]*. *Frances:* Ok, that's the first bullet, right? That environmental change means that species need to adapt. Would that also be the second bullet? Living things change to adapt? Ok, between the first and second bullet, which one do we want to keep? They are both equally good, but one you might have like more affinity for. So, guys, look at the first one that environmental change means species have to adapt. Living things change to adapt. (10/08/15)
	• On a question	• Used to emphasize a question that a student or student group generated about a phenomenon, or would use this to remind students of a driving question for a particular triangle (model)	*Frances:* Our question is going to be: how do we actually get matter and energy from this rearranging? So you know there's this rearrangement, so how does this actually take place? (11/18/15)

Table 2-5 *(continued)*

Mediating Move	Subcategory of Mediating Move	Description of Subcategory	Examples from Instruction
Focusing Students' Attention	• On a phenomenon	• Used to remind students of the phenomenon they were investigating, or it was used to draw students' attention to a phenomenon a student or group identified	*Fred:* Ok, and again, this is what he observed. Every organism had a set of these traits, these physical or behavior traits that made them unique. so that's what he's observing. so he's walking around in his garden observing the flowers. He's looking at the peas, he's noticing that each one of them he looks at has a group of traits, or some particular traits that make that unique. (5/12/2016)
	• On a pattern in data	• Used to focus students' attention on a pattern in a graph or across a dataset.	*Lori:* Excellent observations. Did you guys hear that? [Student] said nothing was guaranteed. There was no one certain set pattern in any one when you compare one to another. Using his own data from their family tree. He gave an excellent example and he said "like even when the parents have it, sometimes the offspring did and sometimes they didn't. What else? Thank you Josh. (5/20/2016)
	• On vocabulary and/or definitions	• Used to draw students' attention to a vocabulary word associated with a concept they have discussed or will discuss	*Lori:* When you see just pea generation to F1 and I don't see green, what does that mean about yellow? [*Lets students share some ideas*]. Oh, it's dominant. It's stronger. It's showing. But the green's not going away right? And some of you already know that term. What's that term when it's hidden? (4/20/16)

In order to further illustrate how these four kinds of mediating moves were used by teachers throughout the academic year, in the findings, I present cases of model development, where a case consists of the teacher and the students involved in the modeling tasks. I describe examples from Eric's and Fred's classrooms that illustrate two different ways in which the same kinds of mediating moves were used to develop a model explaining trait change over time. I end with an example from Catherine's classroom that illustrates the development of a model that took place later in the academic year, and that demonstrates a third way to utilize the mediating moves. Thus, in the findings, I present two main claims. First, teachers' instruction converged in that the teachers utilized the same kinds of moves to facilitate instruction. Second, the teachers use of the mediating moves diverged with respect to one another–teachers in this study sometimes used the moves in ways that reflected different paths towards model development. In addition, I highlight how the ways in which teachers respond to their students may have implications for how modeling is portrayed in high school biology classrooms.

Findings

Although each of the five teachers utilized the same curricular materials throughout the year in which our research team collected data, the teachers' implementation varied in interesting ways. In this section, I begin with a description of how the modeling and mediating moves were related to one another in the high school biology classrooms we observed. Their relationships illustrate how the teachers' instruction converged on the same moves. I then present representative contrasting vignettes of mediating moves that highlight the divergent means through which the moves were used during the academic year.

Instruction Converged on the Same Modeling and Mediating Moves

In my analysis process, I categorized the teachers' instructional moves based on their relationship to the modeling moves described in the curricular supports (see table 2-3). Although I categorized the teachers' moves in this way, what emerged was a pattern illustrating that the teachers' instruction, in general, paralleled the modeling moves articulated in the curricular supports. I call the moves teachers used to enact the modeling moves, mediating moves, because these moves are the actions teachers took to moderate and to arbitrate students' ideas (Halloun, 2007). The modeling moves and their related mediating moves are displayed in figure 2-4, and represent the way in which the teachers' instruction converged on the same kinds of modeling and mediating moves. The modeling moves typically used by all teachers in this study to facilitate the MBER lessons are displayed on the left and include: the identification of the phenomenon; development of questions about the phenomenon; investigation of the phenomenon, and generation of the model that explains the question about the phenomenon. The modeling moves are displayed linearly to illustrate the typical flow of the MBER modeling lessons enacted by the teachers in this study. On the right side of the figure are the ways in which the teachers mediated the modeling moves: by giving students processing time, by letting students share ideas, by responding to students, and by focusing students' attention on particular aspects of modeling or particular ideas. These mediating moves were not associated with introducing the phenomenon to the students, because this typically consisted of a single statement that communicated to students that they would be observing and identifying a new phenomenon. From there, the teachers would proceed through the modeling moves, most often in the linear order depicted. It was through analyzing the mediating moves that I noticed salient features of divergence in instruction. I illustrate these divergent paths by describing instruction focused on model development.

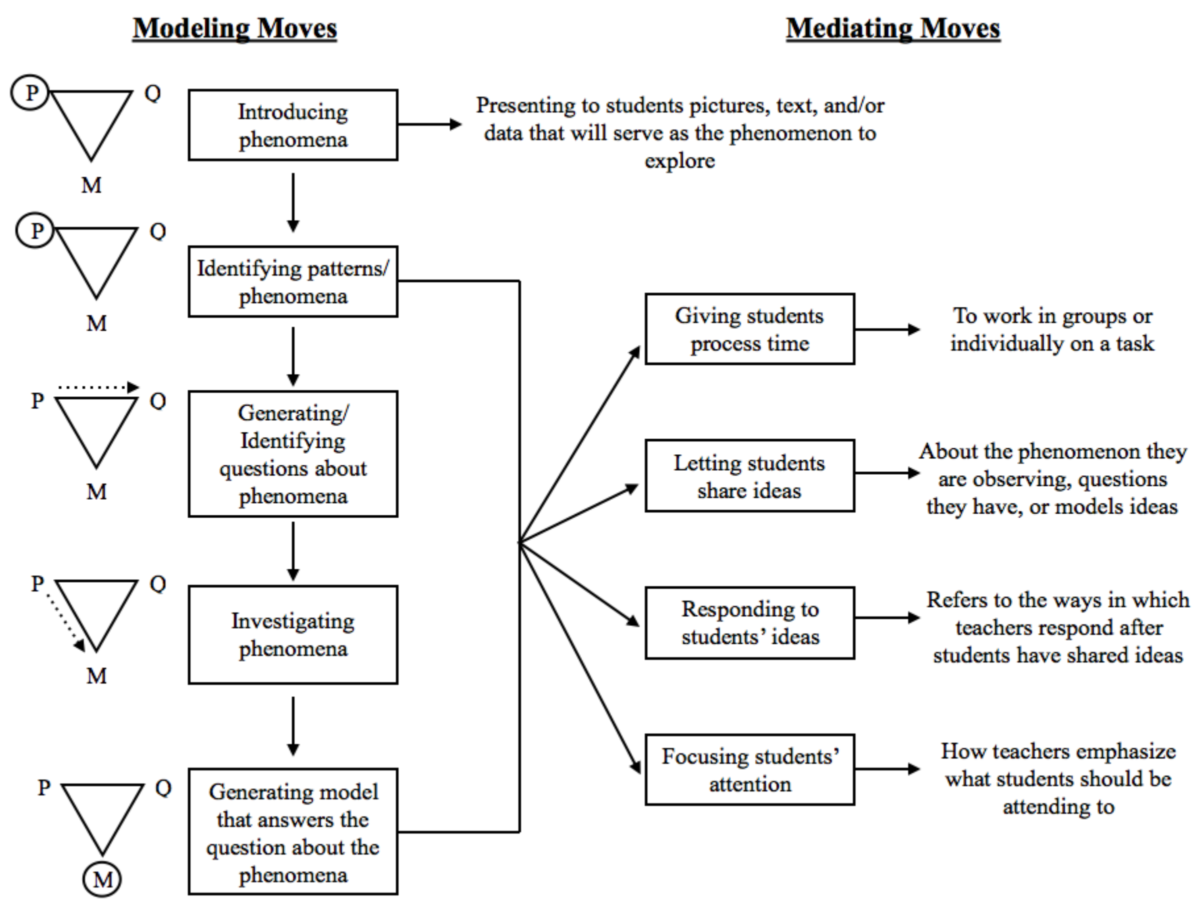


Figure 2-4. *The modeling and mediating moves teachers utilized to facilitate modeling in high school biology classrooms.*

Instruction Diverged through Enactment of the Mediating Moves

In order to illustrate the divergence in how mediating moves were enacted, I present representative sections of classroom discourse focused on model development from three teachers, Eric, Fred, and Catherine. The examples that follow are representative because they illustrate three different paths teachers took for facilitating the development of a model; therefore, they highlight how instruction diverged through enactment of mediating moves.

The first two cases, from Eric's and Fred's classrooms, focus on development of a model of natural selection where students were working towards explaining trait change over time in Galapagos ground finches, specifically the increase in their average beak depth between 1976 and 1978. The students were presented with a dataset based on the work of Peter and Rosemary Grant (Grant, 1999) and were asked to develop a model, in groups, based on evidence interpreted from analysis of the data. Students were given time to process the data and to generate the model together in groups. Following generation of their group models, the students presented their ideas to the class as a means for generating a class "consensus model" that could then be used to explain other related phenomena, such as why black variants of peppered moth were more common than white variants during the industrial revolution. To assist teachers in understanding the kinds of ideas that students might generate based on the data, the curricular materials included an example of a possible model, one similar to that described by Mayr (1982).

In the third case, Catherine's students were working towards generating a model that explained what causes population sizes to change. The modeling lessons focused on the wolves and moose of Isle Royale[4], and students, through analyzing and interpreting data collected over 50 years by scientists and by playing a game that simulated moose birth and death, were expected to generate some ideas that could help explain what causes population numbers to

[4] www.isleroyalewolves.org

fluctuate. However, even though this was the second model as prescribed in our curriculum, Catherine decided to combine it with triangles 9 and 10; therefore, the conversation illustrated took place approximately half-way through the academic year. The possible model included in the curricular materials focused on the relationship between birth rate and death rate.

Eric's Model Development Process. After Eric's students were given time to analyze and interpret the finch dataset, they were asked to generate their model and to create a representation of it on a large, erasable whiteboard. Each of eight student groups wrote and/or drew their ideas and orally presented their models to the class. The model development conversation between Eric and his students took place as students presented their work (~22 minutes) and then continued two days later, when he had a follow-up conversation with the students. To begin the presentations, Eric told the class, "Let's be respectful of each group, which means be quiet between each group so that we can keep going. That way it will go a lot faster and that way you are going to get out of here on time." This first mediating move served to focus students on the task, but did not help students to attend to the purpose of it. For the first group, Eric let them present without responding to their ideas, but he did ask the class if there were any questions before moving on. Following the second group presentation, the following conversation occurred[5]:

1 ***Eric:*** Does anyone have any questions?
2 ***Student 1:*** So, the reason the beaks are bigger is to get the seeds underneath the ground?
3 ***Eric:*** Any other questions?
4 [Many students respond in unison]
5 ***Eric:*** So, do we actually have information in our data that tells us where the seeds were located, where they were on the surface of the ground or underground, or on the bush itself?
6 ***Student 2:*** Oh wait, yeah we do.
7 ***Eric:*** Do we? Where does it say that?
8 ***Student 2:*** In that little paragraph thing you gave us. It was like, it described the

[5] Each episode is numbered sequentially for the sake of clarity; however, that does not imply that each episode immediately followed the other. Further context is provided in-text.

[inaudible] it has one that was a vine, and... [interrupted by Eric]
9 ***Eric:*** Yeah, but does it say where the seeds are actually located? Like where does the bird actually get the seed? Does the seed fall on the ground and they have to pick them up off the ground, or are they buried underground and they have to grab them underground? Or is it grabbing them off the bush, or does it really even matter?
10 ***Student 1:*** It probably don't because it says that most of the birds forage and that usually happens on the ground.
11 ***Eric:*** Ok, so good inference. It's probably on the ground, which we don't know if it's necessarily underground or not but bottom line is if they can't eat the seed, what happens to them?"
12 ***Students:*** [choral response] They die.

This moment in instruction represents a series of alternating moves: Eric is letting students share their ideas and he is responding to them in varying ways. In this early conversation with his students, his responses illustrate his attention to whether or not students' ideas align with Mayr's model of natural selection (1982). Specifically, in lines 5, 7, and 9, he identified flaws in student reasoning by broadcasting the lack of evidence to support their claim. Moreover, his evaluative stance comes across when he asks for clarification in line 11. Here, he is telling the students that they have made a good inference of the data, but he is also asking them to further clarify what is causing the differential survival in the finches.

There were also moments where he does not explicitly evaluate student responses, and instead asks them to further explain their reasoning. The following episode occurs a few minutes later after the next group presents their model ideas:

13 ***Eric:*** "Just for a clarification. You were saying that the birds with the larger beaks, or smaller beaks I mean, just couldn't eat the seeds. Is that what you are saying?
14 ***Student 3:*** [Nods head, "yes"].
15 ***Eric:*** And so what happens to them? What happens to the birds?
16 ***Student 4:*** Die off.
17 ***Eric:*** Now, I asked you guys earlier, individually as a group, specifically, does that mean that they all die off?
18 ***Student:*** No, most of them.
Eric: So you're saying that some of them are going to die off so they are less common.
19 ***Students:*** [Chorally respond] "No." and "Yes."
20 ***Eric:*** Good. Next group.

Following this third group's presentation, Eric asks the group to clarify their claim that the birds with smaller beaks were unable to eat (line 10), and he does so again in line 14. Moreover, Eric missed an opportunity to ask students to further clarify their reasoning when they responded with "no" and "yes" (line 19). Later, following another group's presentation, he asks a clarifying question of a group that has recognized that birds with larger beaks tend to have offspring with larger beaks. These instances of Eric asking students for clarification, during natural selection, tend to occur when the groups have described ideas that are aligned with Mayr's model. In the excerpt above, the group has recognized that there is differential survival due to a particular trait, beak size. In the instance that followed, the students have recognized that traits, such as beak size, can be heritable.

Throughout the model development conversation, Eric also helps his class to focus their attention on model ideas. Following the moment where Eric asked the group to clarify their statement about heritability, he focused the classes' attention on the idea to foster additional discussion:

21 ***Eric:*** Ok, so why would this change take place only between 1976 and 1978 and why didn't it take place at some other time earlier?
22 ***Student:*** Because. I don't know. Like it's skipping. I don't know, they made love in that year.
23 ***Eric:*** Anybody else have an answer to that last question? Because that's a question I haven't asked any other group yet.
24 ***Student:*** What was the question again?
25 ***Eric:*** So, let me repeat the question again: The question was, it has to do with this idea that the seeds are causing the beaks to change. Why didn't it happen at any other time? Why didn't it happen prior to 1976 if, as they said, little beak bird gets together with big beaked bird and they have babies that end up with bigger beaks. Why wouldn't that have happened prior to '76? Alright, [student] let me hear what you have got to say. And I want you guys to listen to him so you can see if you agree with him or not.
26 ***Student:*** Because of the drought, the problem is that the smaller birds started dying so they have less, like small birds to mate with so then they had to mate with bigger birds only in that time period of the drought.

Eric's move in lines 23 and 25 focus everyone's attention on the idea previously shared about heritability, helping students to attend solely on that component and to recognize the connection between the drought, survival, and reproduction (line 26). However, when a student offered his reasoning in line 22, Eric missed another opportunity to respond and ask for clarification. In the end, on day three of model generation, after providing students with numerous opportunities to share their ideas, he presented them with three questions intended to focus their attention on two big ideas: population variation and environmental change. Discussion of these questions took the form of him focusing students' attention on patterns in data; letting students share their ideas, and his responses to students tended to be evaluative.

In total, Eric's model development conversation with students lasted for approximately 36 minutes spread over two class periods. Throughout this time, he made 95 mediating moves, a summary of which are displayed in table 2-6.

Table 2-6. *Number of mediating moves used by Eric during model development conversations with his students.*

Mediating Moves			No. of Instances
Giving Students Process Time			0*
Letting Students Share Ideas			42
Unclear			1
Responding to Students	Asking for Clarification	Evaluative	3
		Not Evaluative	10
	Identifying Flaws in Reasoning		8
	Providing Answers		11
	Summarizing or Repeating	Evaluative	2
		Not Evaluative	5
Focusing Students' Attention	On a model or model idea		8
	On a phenomenon		0
	On a question		0
	On patterns in data		3
	On vocabulary		0
	On the goals or purposes of the task		2

*This move, for triangle 1, did not occur during the modeling generation discussions for any teachers in this study; however, it did arise during other model development conversations throughout the year.

As described in the table, Eric made a total of 24 responses that illustrate a potential instructional stance towards building up the "correct ideas" (asking for clarification, 3 evaluative; providing answers, 11; identifying flaws in reasoning, 8; summarizing or repeating, evaluative, 2). This priority was further emphasized when he ultimately provided students with what he perceived to be the model. Next, I illustrate a different evaluative stance towards model generation: a focus on the generality of model ideas, rather than their scientific content.

Fred's Model Development Process. In Fred's classroom, the model development conversation took place after all groups had presented their model representations via a gallery walk and after students had been given time to discuss in groups what they considered to be the important model ideas. To start the model development conversation, Fred tells his class, "I'm going to go around by [group] and if you have an idea, you can throw it out there. I might ask you to refine it a little bit. If it's not general enough I might ask you to try to think about what would be more general." In this initial move, he is focusing students' attention on their model ideas, specifically, their generality or specificity in relationship to the phenomenon. Because students had been interacting with graphs that focused on the specific phenomenon of an increase in average beak depth, he wanted them to consider how the model ideas relevant to the finches could also apply to other species. The following episode illustrates the conversation that he had with his students.

1 ***Student 1***: We said there was a big change in the environment.
2 ***Fred:*** Ok, so there was a change in the environment. Good. In this case, that's a very general statement, right? We talked about that example yesterday, and that's fine. And in this case, what was the change?
3 ***Student 1:*** The drought.
4 ***Fred***: The drought. Did the drought cause other changes to the environment?
5 ***Students:*** [chorally] Yes.
6 ***Fred:*** What were some of the other changes due to the drought?
7 ***Student 2:*** [couldn't hear]
8 ***Fred:*** Ok, seed sizes changed.
9 ***Student 3:*** Population.
10 ***Fred:*** Ok, the population...
11 ***Student 1:*** Dropped.
12 ***Fred:*** Ok, dropped. So there's all these other things and that's the changes in the

environment. That's a good job of making a generalized statement. [Calls on table 6]
13 ***Student 4:*** The finch population decreased.
14 ***Fred:*** Ok, the finch population decreased. I'm sorry but that's really specific, so what's a specific statement about finches. So, are we going to explain the population? how do you think the population changed.

In this small episode, Fred is using alternating moves: he is providing his students with opportunities to share their ideas, and he is responding by asking for clarification (lines 2 and 14) or by summarizing and repeating (lines, 4, 8, 12, and 14). He also focuses students' attention on the idea of changes in the environment, foregrounding the idea and positioning the class to discuss it further (line 4). His lines of clarifying and summarizing and repeating, however, are evaluative (lines 2, 12, and 14). But, rather than evaluating the content of the students' statements, Fred was evaluating their generality or specificity. Fred's conversation with his students continues in this vein throughout the entire natural selection model development process. Interestingly, other model development conversations that Fred has with his students throughout the academic year tend to focus on the generality of model language rather than the content specifically.

In the end, the natural selection model that students ultimately generated in Fred's classroom was identical to Mayr's model (1982); therefore, Fred also utilized moves that focused students' attention on ideas as a means to build on them or to set them aside. An example of this occurred towards the end of class, when he recognized that there were ideas that students had discussed in their groups, but that had not been considered during their whole group conversation.

15 ***Fred:*** I want to address something that was talked about by a bunch of tables so. Something that was talked about by a lot of groups that I talked to. You said that birds changed. That individuals changed. Ok, is that what's going on here?
16 ***Students:*** [chorally] Yeah.
17 ***Fred:*** Huh?
18 ***Students:*** [chorally] Yeah.

19 ***Fred:*** So what's happening? Why is the population getting larger?
20 ***Student 5:*** Oh, because they are reproducing but it's only the ones with the bigger beaks because they survived and the other ones died.
21 ***Fred:*** Ok, so only the ones with the bigger beaks survived and they are the ones that get to reproduce because the other ones died, right? So what does the, so think about it though? Why was that the case? Why was there some that was able to survive?
22 ***Student 6:*** Because of the [cannot hear the rest]
23 ***Fred:*** Ok, but within the population, what existed?

In line 15, Fred begins to focus students' attention on an idea that he considers important for the model, and this continues in lines 19, 21, and 23. In these lines he is driving the class towards the idea that variation within the population existed; therefore, those that already had larger beaks tended to survive the drought because they were able to eat the harder seeds. Although these moves are similar to asking for clarification, they were used as a means to facilitate whole class conversation, rather than to pursue a dyadic interaction with a particular student or subset of students. Moreover, they represent one of the ways that teachers arbitrate ideas, by focus on building on an idea that had been discussed when students were given time to work together in groups. In total, for natural selection, Fred's model development conversation with his students lasted approximately 18 minutes, and he utilized a total of 101 mediating moves. The breakdown of mediating moves used is displayed in table 2-7.

Table 2-7. *Number of mediating moves used by Fred during the model development conversation in natural selection.*

Mediating Moves			No. of Instances
Giving Students Process Time			0*
Letting Students Share Ideas			43
Unclear			1
Responding to Students	Asking for Clarification	Evaluative	8
		Not Evaluative	15
	Identifying Flaws in Reasoning		0
	Providing Answers		6
	Summarizing or Repeating	Evaluative	4
		Not Evaluative	11
Focusing Students' Attention	On a model or model idea		8
	On a phenomenon		0
	On a question		0
	On patterns in data		3
	On vocabulary		0
	On the goals or purposes of the task		2

*This move, for triangle 1, did not occur during the model generation discussions for any teachers in this study; however, it did arise during other model development conversations throughout the year.

In contrast to Eric, we see that Fred was evaluating the generality of students' ideas, rather than their scientific content. Additionally, I found no instances of Fred identifying flaws in students' reasoning, whereas there were 8 instances in Eric's conversation with his students. In sum, both Fred's and Eric's cases illustrate the divergent means that mediating moves were used. Eric was following a path towards a model that he would give the students, and Fred was following a path to a general model that could be used to explain phenomena related to trait change over time. In order to further explicate my findings, I present a case of model development from Catherine's classroom. This took place nearly four months after enacting natural selection and represents yet another divergent path that teachers took in enacting mediating moves. In the example that follows, Catherine's conversation with her students is focused on generating a list of students' ideas, rather than evaluating correctness or generality.

Catherine's Model Development Process. Catherine's approach to facilitating modeling conversations was different than that of the other teachers we observed, even though she was utilizing the same kinds of mediating moves. She did provide students with opportunities to work and discuss data in groups (giving students process time), and she provided them with opportunities to generate model ideas together; however, she ensured that every student had an opportunity to share an idea during whole class conversations. She did so by using a random name generator application on her tablet, and she went through each student before giving the students a final opportunity to revise the model. Moreover, she began the modeling conversations by focusing students' attention on their model ideas, and maintained a focus on their thinking and reasoning without being overly evaluative.

The following episode begins at the start of the "final" modeling development conversation. In the minutes prior to this, students had already generated some ideas about the moose, but were now beginning to consider ideas about the wolves. Additionally, the class had already decided that abundance of food was not a factor leading to wolf decline, because of the high number of moose present on the island.

1 ***Catherine:*** Ok, ok, are we ready? Oh my gosh I can't wait to hear your awesome idea; you never cease to amaze me. Ok…[calls on a student using a random name generator]
2 ***Student [Br]:*** [cannot understand]
3 ***Catherine:*** Lack of climate. Do you want to say like, what kind of lack of climate? What could happen? This is almost at Canada, right? So what would be the problem? I'm going to write climate. And maybe you can tell me more about it.
4 ***Student [Br]:*** [cannot understand].
5 ***Catherine:*** Breed in wintertime. Ok, so then what would be a problem in the climate?
6 ***Student [Br]:*** [cannot understand].
7 ***Catherine:*** Heat. Too warm. So what [Br] said if you couldn't hear her is she said don't bulls normally breed in winter time? What do you guys remember about the story, do they? So she's wondering if it's maybe too warm. Do you want me to write breeding issues on here, too? Is that a separate topic?
8 ***Student [?]:*** [cannot hear]
9 ***Catherine:*** Ok. And you guys can add or edit, you know how to do this.
10 ***Student [Do]:*** Old age.
11 ***Catherine:*** Alright, so um. Most die of old age all the time, right? So, can you tell me why this might be different in this circumstance?
12 ***Student [Do]:*** [cannot hear, no?]
13 ***Catherine:*** Ok, we'll add to it if we need it. If you guys can think of anything to add to that. So, [Xa]? Why would there be so few wolves if it's not about lack of food?
14 ***Student [Xa]:*** From disease.

15 ***Catherine:*** Ok. So maybe there is something that wiped out the population? Ok. [Ja]?
16 Student [Ja]: Oh, um, it was breeding.
17 ***Catherine:*** Breeding. What do you want to tell me about breeding, what's the problem here?

In line 1, Catherine begins the conversation by focusing students' attention on their ideas, potentially insinuating to the students that she appreciates the ideas they generate. In line 3, Catherine sets the stage for the typical way in which she facilitates modeling conversations, by asking for students to clarify their reasoning as she writes down the idea. All ideas that students share get incorporated into the model in some way, regardless of the content. She utilizes clarifying moves in lines 11, 15, and 17, asking students to expand on their ideas. Also, line 7 is see an example of a moment where a student asks a question, and Catherine focuses the class' attention on it and then conversation continues from there. In other classrooms, including in Eric's and Fred's, I saw examples of this happening, but rather than positioning the class to answer it, I oftentimes saw teachers moving to provide answers to the students. In this case, a student has asked if moose bulls breed in the winter, and Catherine asks the class to consider the ideas related to it. In line 19, she not only helps students to attend to potential changes to their model, but she focuses' their attention on the question they are trying to answer.

By the end of this ten-minute conversation, the students had generated a list of several ideas that could explain why the wolf and moose population size changes. In the provided curricular supports, the model was described as containing two main ideas: birth rate and death rate; however, Catherine allowed student ideas to remain and explained to them that they would continue to collect evidence and revise this model as they examined other related phenomena later in the year. This approach to model development was similar to what she had done earlier in the year when facilitating development of the natural selection model. She was the only teacher who facilitated the development of a model that could later be revised in light of new evidence uncovered by the students. Table 2-8 describes the 94 moves utilized by Catherine when enacting development of the model explaining population dynamics. There are no instances of identifying flaws, and only 17 total instances of evaluative responses.

Table 2-8. *Number of mediating moves used by Catherine during a model development conversation in population dynamics.*

Mediating Moves			No. of Instances
Giving Students Process Time			0*
Letting Students Share Ideas			43
Unclear			1
Responding to Students	Asking for Clarification	Evaluative	5
		Not Evaluative	13
	Identifying Flaws in Reasoning		0
	Providing Answers		3
	Summarizing or Repeating	Evaluative	8
		Not Evaluative	11
Focusing Students' Attention	On a model or model idea		8
	On a phenomenon		0
	On a question		0
	On patterns in data		0
	On vocabulary		0
	On the goals or purposes of the task		9

*This move, for triangle 2, did not occur during the modeling generation discussion presented here; however, it did arise during other model development conversations throughout the year.

Comparing Three Model Development Conversations. Although I have chosen to illustrate model development by presenting three cases, Eric's, Fred's, and Catherine's discourse is demonstrative of the kinds of moves utilized by all teachers throughout the academic year. As described earlier, Eric's and Fred's responses were primarily evaluative, yet the focus of the evaluation was on correctness of ideas and generality, respectively. In Catherine's classroom, I observed mediating moves used to understand students' ideas and to build on them. Overall, each teacher navigated the discussion in different ways: they diverged in the paths they took to enact the mediating moves, despite converging on and using the same mediating moves. In addition, the ways in which they responded to their students highlights how modeling could be portrayed to varying degrees as a means for delivering content or for engaging students in sense-making. In the discussion section, I return to my theoretical framework and consider how these convergent and divergent uses of mediating moves may have affected the portrayal of modeling in the high school classrooms observed.

Discussion

In this study, I saw evidence that the teachers were able to facilitate modeling in ways that allowed opportunities for students to make sense of phenomena and to develop complex biological models; however, salient inconsistencies arose that may have had implications for how modeling was portrayed. I define inconsistencies as instructional moves that had opposing implications on the perceptions of modeling continuum–teachers were not consistent in their use of modeling as a means for engaging students in sense-making. My close examination of modeling instruction extends the current understanding of the discourse moves teachers make to evaluate and extend student ideas as they enact modeling. The findings suggest that within the MBER curricular context, the five teachers utilized the same four kinds of moves that mediated modeling. The participants gave students opportunities to process tasks individually or in groups; share their ideas in varying ways; they responded to student ideas by either summarizing and repeating, asking for clarification, identifying flaws in reasoning, or providing solutions; and they helped to decide what was important to focus on. In this section, I focus on the inconsistent moves teachers made with respect to enacting modeling as a means for sense-making; thus, I return to the perception of modeling framework and discuss how teachers' instructional moves may have affected the portrayal of modeling.

Responding to Students: Inconsistencies in Opportunities for Sense-making

Through analysis of instructional moves, I noticed inconsistencies in how teachers provided students with opportunities for making sense of phenomena through dialogue. This is important because engaging in science is inherently a social act. The nature of the discipline requires the externalization of ideas and emphasizes the importance of communication (Lemke, 1990); therefore, science in the classroom should reflect these components of the scientific enterprise (Norris & Phillips, 2003). By affording students opportunities to work together in groups, to share their ideas and questions, and to make them public in some way, the teachers in this study may have fostered student sense-making. Driver, Asoko, Leach, Mortimer, and Scott (1994), Ford and Wargo (2012), and Lemke (1990), all describe the relevance of talking in science, and that when teachers give students opportunities to engage in dialogue about those ideas, it helps students to make sense of them. Moreover, peer interactions focused on collaborative problem solving can shift students' conceptual understanding (Polman, 2004). That each of the teachers in this study consistently provided students opportunities to collaborate and generate ideas together, and to publicly voice their ideas to the class, is important because, traditionally, these kinds of dialogic interactions are oftentimes underutilized in science classrooms (Weiss, Pasley, Smith, Banilower, & Heck, 2003).

These affordances, however, may have been constrained by opposing moves that followed, potentially shifting instruction from a sense-making orientation of modeling towards an orientation focused on delivering content. For example, teachers would often begin the process of sharing ideas by saying, "there is no right or wrong answer", but some of their responses to students could have illustrated that there is a correct answer, particularly when teachers evaluated students' ideas, when they identified flaws in their reasoning, or when they provided answers. These kinds of responses are not unique to the teachers in this study, but are akin to traditional forms of "school science" and the initiate-respond-evaluate patterns described by Mehan (1979) and triadic dialogue structures described by Lemke (1990). Question and response patterns such as these have been shown to restrict the productiveness of classroom conversation (Treagust, 2007; Weiss et al., 2003) and to eliminate student voice (Carlsen & Hall, 1997). Therefore, when the teachers in this study utilized these evaluative moves, it is possible that they were restricting student negotiation power and removing the students from the modeling process. In general, it appears that responding to student ideas was a key mediating move that may have impacted opportunities for sense-making. Through utilizing instructional moves that may have opposed one another in both affording opportunities for engaging students in sense-making and constraining sense-making (i.e., shifted instruction towards delivering content), the teachers were inconsistent in their portrayal of modeling.

Inconsistencies in Promoting and Setting Aside Ideas

In addition to being a social act that requires the communication of ideas, the act of modeling necessitates an orientation towards a student-centered classroom with a lens towards building on student ideas to facilitate instruction (Halloun, 2007). As such, teachers must make decisions, often in-the-moment, about how to build on student ideas so that students can gain a conceptual understanding of the phenomenon under investigation (Hammer & Schifter, 2001). These decisions are reflected in the instructional moves they make (Harris et al., 2011), and in addition to finding inconsistencies in the opportunities teachers provided to students for sharing and discussing their ideas, I also noticed inconsistencies in the ways in which teachers promoted and set aside the ideas during whole class discussions. For example, when teachers responded to their students, their focus of the evaluation varied, as illustrated by the dialogue in both Eric's (see pp. 47-51) and Fred's (see pp. 51-54) classrooms. In contrast to Eric, Fred prioritized ensuring that student ideas were general enough that they could be applied to other related phenomena. By promoting abstraction of ideas, Fred may have emphasized to students that models can help to explain classes of phenomena (Giere, 1988, 2004; Morgan & Morrison, 1999). In terms of modeling, this focus on the model and its utility–the for what? of the model–may have continued to further students' engagement in sense-making because it afforded students with opportunities to recognize the relationship between epistemic practice and scientific content. This coordination between practice and content is an important component of the vision set forth in NGSS (NGSS Lead States, 2013).

However, it is also possible that by emphasizing generality, he could have portrayed modeling as a means to generate more general words, which could reflect a focus on delivering content. Generally, however, when teachers attended to the content of the model, they were distilling it into disciplinary facts that on their own are not necessarily explanatory, and is in stark contrast to what is called for in NGSS. It is only when ideas are used in a dynamic and cohesive manner, that can become a powerful means for explaining complex phenomena (Gouvea & Passmore, 2017; Passmore et al., 2014). Thus, the inconsistency in modeling, through evaluating content and evaluating generality that I observed in each teacher's classroom, may have had implications for how modeling was portrayed. An orientation towards abstracting ideas could have furthered student sense-making, whereas an orientation towards the content of the model may have shifted the portrayal of modeling to one that emphasizes disciplinary knowledge.

Further illustrating the complexity of this dynamic practice is that as teachers focus students' attention on particular ideas, they are making the decision about what will or will not be productive for model development (Halloun, 2007). This is always an evaluative move; however, as with the other mediating moves that I found, there were variations in the way this move was used. In Catherine's classroom, for example, I found it used in ways that acknowledged students' thinking, such as when she positioned students, as a whole class, to engage in conversation about questions or ideas posited by students who had shared them. By helping students to attend to a particular idea, it may have provided opportunities for all members of the class to build on it or to set it aside. Conversely, there were times when this move was used to deliver the model to the students, such as when Eric emphasized the data they had about variation in the finch beak size. While trying to help students attend to patterns in data, he ultimately provided students with the ideas he wanted them to remember–variation within a population and environmental change. These inconsistencies in modeling instruction could have implications for the location of the disciplinary authority in the classroom (Ford, 2008)–either with the teacher or with the students. Consequently, this impacts who is engaging in the modeling. Figure 2-5 illustrates the inconsistencies in instructional moves that I observed throughout the year, and how each may have affected the portrayal of modeling.

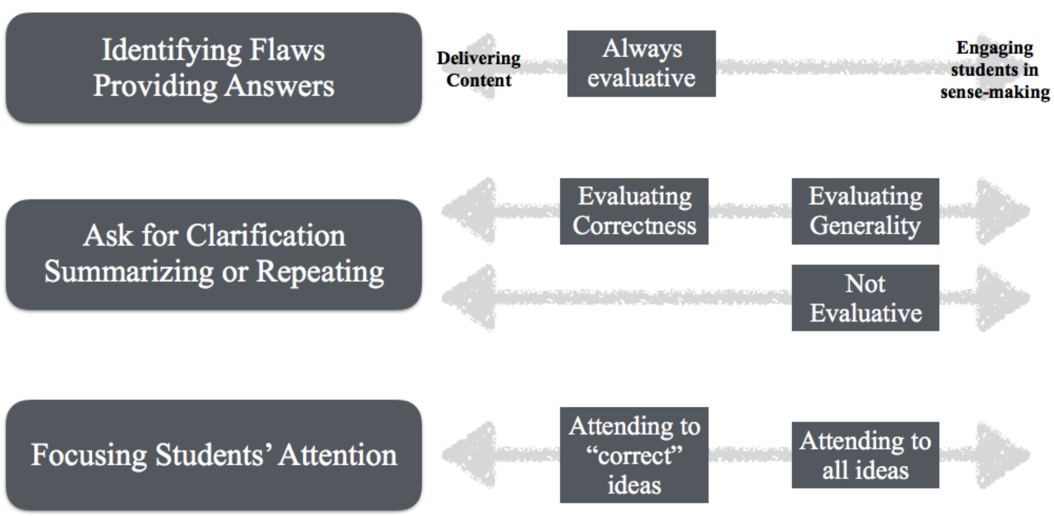


Figure 2-5. *The inconsistences in usage of mediating moves in the high school biology classrooms we examined.*

In the figure above, I illustrate two kinds of mediating moves, responding to students and focusing students' attention, and the varying ways in which the usage of the moves may have affected modeling. When responding to students by identifying flaws in reasoning or by providing answers, teachers were being evaluative and modeling for delivering content. In comparison, when asking students to clarify their ideas or their reasoning, or when summarizing and repeating ideas, the location of instructional moves on the continuum was dependent upon whether or not the responses were evaluative and for what purpose were the ideas being evaluated. With respect to focusing students' attention, the kinds of ideas teachers attended to mattered with respect to what modeling was being used for–if modeling was a means to engage students in sense-making, then the teachers could provide students with opportunities to attend to all ideas, rather than just those that were correct.

Inconsistencies in Instruction Foreground Tensions in Enacting Modeling

Overall, inconsistencies in the usage of mediating moves foreground a noticeable tension during instruction: when is it productive to let students share their ideas and when is it productive as a teacher to step in and moderate or arbitrate the conversation? Each of the five teachers in this study provided students with multiple opportunities to process tasks in groups, which included analyzing and interpreting data that would assist them in generating models; however, the general tension between the students generating a model and the teachers wanting the students to have the "correct" scientifically aligned model is particularly emblematic of the classrooms I observed. Williams and Clement (2015) observed a similar tension in their examination of physics teachers facilitating model generation, and found that final model ideas varied along a spectrum of student-generated ideas versus teacher-generated ideas. O'Connor and Michaels (1993) found that in math classrooms, some of the moves teachers made, particularly in summarizing or repeating student answers, may have given students opportunities to participate in the conversation, giving them access to the sense-making endeavor. But, by including their own inference, similar to when the teachers in this study added an evaluative layer to their responses, they were moving students towards ideas aligned with disciplinary understandings.

None of these results are surprising given that a necessary outcome of teaching is student learning, and that teachers will want their students to have disciplinary knowledge. However, combined, these findings bring to bear a larger question: do these differences in teachers' enactment actually matter? Although I have not fully explored data that can answer this question, I can consider what some of the consequences for these varying enactments and tensions might be.

First, as the teachers in this study shifted their instruction along the act of modeling continuum, it could have resulted in disjointed experiences in science practice, or fragmented epistemological understandings of science that are common in "traditional school science" classrooms (Engle & Conant, 2010; Roth et al., 2006). What I ultimately recognized is that a classroom that "looks" like a modeling classroom, because of the opportunities for students to grapple with data and to generate the model, may not actually be a classroom that fully actualizes modeling as a means for engaging students in sense-making. However, I want to emphasize that this does not necessarily inhibit conceptual understanding. The questions students asked and the ideas that they shared, indicate that the students may have been attempting to engage in the tasks set forth to them. In contrast, inconsistent instruction could have inhibited epistemological learning, as it is possible that by delivering content the teachers were reinforcing their disciplinary authority, but further analysis of student learning outcomes is necessary to understand what students took away from their experiences. However, once again, this tension brings to bear another important question that warrants further investigation: does the difference between access to sense-making and engaging in sense-making actually matter for student learning? Intuitively, I surmise that, yes, these differences do matter, but empirical support is warranted to support this claim.

Furthermore, it is important to note that despite this close analysis and description and critique of instructional moves used in MBER classrooms, I make no claims about *how* engaging or *how* focused on delivery the teachers were in relating the moves to the act of modeling. I do posit that in utilizing the moves in different ways, the teachers' instruction was shifting on a continuum, in ways that either portrayed modeling as a means for sense-making or as a means for delivering content. Additionally, in illustrating these affordances and constraints, the goal here is not to evaluate whether or not students learned, but to describe the kinds of moves teachers made that may have affected how modeling was portrayed.

Conclusion

In this chapter, I investigated teachers enacting a modeling curriculum, and found that their instruction varied through the mediating moves they made. Altogether, these moves provided a lens through which I could investigate how teachers afford or constrain the portrayal of modeling in high school biology. This perspective allows for not only a better understanding of how teachers build on ideas, but can also guide the education research community towards a closer examination of the kinds of supports teachers need to productively leverage student ideas in the classroom. As teachers implement NGSS (NGSS Lead States, 2013) and begin to shift instruction from that of traditional methods towards a more student-centered approach, work such as that presented in this chapter, is necessary to begin to uncover and describe the ways in which practices-based instruction, namely modeling, may afford or constrain opportunities for students to make sense of phenomena. Therefore, this work is part of a much broader agenda for understanding instruction and its impact on students' access and engagement in sense-making.

Although the teachers in this study were willing and able to enact modeling based on the curricular materials and supports provided to them throughout the academic year, it is inevitable that there were additional affordances and constraints that may have influenced the types of mediating moves that they utilized and the ways in which those moves portrayed the act of modeling. Treatment of those factors is outside the scope of this chapter; however, they will be taken up in chapter 3. Furthermore, my analysis in this chapter focused on the moves the teachers made without closely attending to the students' actions. A fine-grained analysis of the kinds of ideas students generated within this context and their relationship to teachers' repertoires of moves would further illustrate the complexity of modeling instruction. In addition, I have not explored the role these instructional moves may have had on classroom equity; however, an investigation that aligns equity with perceptions of modeling could prove productive for further understanding the implications of NGSS instruction. Overall, I hope that these findings can lead to additional productive examinations of teachers' pedagogical moves in modeling classrooms.

Chapter 3 Factors Influencing Enactment of Modeling in High School Biology Classrooms

Abstract

In this yearlong study, I examined the factors affecting implementation of modeling in high school biology classrooms. Data were collected within the context of a National Science Foundation curriculum development project that centralized modeling as a means for engaging students in authentic scientific practice. Video-recordings of instruction, stimulated-recall interviews, semi-structured interviews, and teacher reflections were used as means to understand why enactments of modeling varied. Analysis focused on affordances and barriers to implementation perceived by the teachers and by the research team as we observed teachers utilizing modeling in their classrooms. Overall, I found four broad categories of factors that may have affected how modeling was enacted and how modeling may have been portrayed: teachers' intentions, beliefs, and values; teachers' real-time instructional considerations; teachers' views and understanding of science; and teachers' perceptions of the role of the curricular materials. The results of this study have implications not only for better understanding the complexity of practices-based instruction, but also for providing teachers with support in enacting practices-based instruction.

Introduction

The field of science education finds itself in a transitional phase as teachers in sixteen states are early in the process of implementing the *Next Generation Science Standards* (NGSS Lead States, 2013). Consequently, there is a need for research exploring how the standards are translated and implemented into science classrooms, as the reform calls for a different approach than has been previously recommended (National Research Council, 2012). This practices-based approach, wherein teachers coordinate scientific practice with content, requires teachers to shift their instruction to be more student-centered and to provide students with opportunities to generate scientific understanding in ways that parallel science (Berland et al., 2015). However, translating scientific practice into the classroom is not an easy task, because the work that scientists do is inherently complex.

The primary cognitive activity of scientists is to construct knowledge about the natural world. To do so, they engage in a variety of practices that allow for the systematic evaluation of both new and historical understandings. In other words, there is no one "scientific method" (Rudolph, 2003, 2005), but one of the ways in which scientists do construct knowledge is through the systematic generation and evaluation of scientific models. These models provide a foundation for explaining real-world phenomena (Giere, 1988; Nersessian, 2002; Passmore et al., 2014).

There is little argument that the reasoning behind models can be a powerful means in which to engage students in the sense-making process (Passmore et al., 2014; Schwarz & White, 2005; Windschitl et al., 2008). Nonetheless, research is needed to better understand the ways in which teachers enact the practice of developing and using models in their classrooms (Louca & Zacharia, 2012; Oh & Oh, 2011). As such, this investigation takes place within the context of a

National Science Foundation funded project that provided to teachers a yearlong biology curriculum that foregrounded the practice of developing and using models as a core means in which to engage students in sense-making. In a previous study, I identified the instructional moves teachers made as they enacted the curriculum (see Chapter 2), and here I further explore the factors, perceived by our research group and by teachers, that may have influenced the varying enactments we observed. I report on alignments and misalignments that I identified between what teachers described in interviews and in writings, and in what I observed through their instructional moves. The question guiding the design and analysis of this study is: what factors impact modeling instruction in high school biology classrooms?

Theoretical Background: Perceptions of Models and Modeling

This study is situated within research on models and modeling and the varying perceptions of modeling that are portrayed in the science studies and science education literature. I build on these perceptions and present a framework for analyzing the factors that may influence enactment of modeling in high school biology classrooms.

Differentiating Between a *Model* and *Modeling*

Reform efforts over the last two decades have argued for a shift in what students learn in science classrooms (National Research Council, 1996, 2012). Namely, they have called for students to be more actively engaged in the scientific inquiry process and to be reasoning with science rather than just learning disciplinary facts (Anderson, 2002; Ford, 2015). One of the ways in which students can be engaged in this sort of reasoning is through the development and use of scientific models (J. K. Gilbert, 2004; Passmore et al., 2014; Windschitl et al., 2008). When students are given opportunities to generate models, they can be positioned to engage in authentic scientific practice (S. W. Gilbert, 1991; Gouvea & Passmore, 2017; Windschitl et al., 2008), because science is a "model-building enterprise that continually extends, refines, and revises knowledge" (National Research Council, 2007, p. 2).

Although there appears to be a consensus that models and modeling are important to scientific practice (e.g., Giere, 1988; S. W. Gilbert, 1991; National Research Council, 2012) and for positioning students as generators of knowledge (e.g., S. W. Gilbert, 1991; Louca & Zacharia, 2014; Passmore et al., 2014; Passmore et al., 2009); there are varying accounts of what models are and what constitutes a model (e.g., Adúriz-Bravo, 2012; Bailer-Jones, 2003; Giere, 1988; Giere, 2010; Harrison & Treagust, 2000; Johnson-Laird, 1983; Nersessian, 2002). Within the models and modeling literature alone, the word *model* is used to refer to mental, expressed, consensus, scientific, curriculum, or historical models (J. Gilbert, Boulter, & Elmer, 2000, p. 12), and to different typologies of models used in science classrooms (Harrison & Treagust, 2000). Similar problems arise when trying to define what models should be used for in science classrooms (e.g., Brewe, 2008; J. K. Gilbert, 2004; Halloun, 2007; Passmore et al., 2009). For the purposes of this study, we utilize a dynamic and pragmatic definition wherein models are used for explaining natural phenomena. Thus, models are "epistemic tools *for* (emphasis in original) making sense of the world" (Gouvea & Passmore, 2017, p. 56). A purposeful and pragmatic definition of models is important for understanding how they can be used in the science classroom; if students are generating the model and using it to reason with and about science, then they are doing model-based reasoning (Passmore et al., 2014). This also means that students should be the cognitive agents doing the sense-making as they develop the model.

In Chapter 2, I explicated the difference between the *model*–the epistemic tool–and what it means to engage in the *act of modeling*–the iterative process of generating a model (p. 17).

This distinction is important for examining the perceptions of models and modeling found in both the science studies and science education literature.

As I have already described, there are varied understandings from researchers' perspectives, therefore, it is not surprising that what teachers perceive to be models and modeling varies as well. Studies examining teachers' understandings about models have found that teachers typically perceive models to be representations or replicas, such as the ubiquitous replicas of cells or anatomical structures (Justi & Gilbert, 2002a, 2002b, 2003; Van Driel & Verloop, 1999, 2002). Consequently, some teachers have been shown to perceive modeling as a means for communicating to their students science disciplinary knowledge (Justi & Gilbert, 2002a, 2002b, 2003). Additionally, teachers' understandings and uses of models have been shown to be inconsistent. For example, even if teachers viewed models as reasoning tools, they would either underutilize them in the classroom, or use them as a means to transmit content to their students (Justi & Gilbert, 2002a, 2003; Van Driel & Verloop, 1999, 2002). Therefore, how teachers engage their students in what they perceive to be modeling, may or may not conflict with the pragmatic purpose and utility of scientific models or with their beliefs about models and modeling and their importance to scientific practice. In figure 3-1, we illustrate how these varying perceptions can be mapped onto a continuum that represents the kinds of instruction reported by teachers and observed in their classrooms. In the next section, I describe what modeling classrooms could look like when aligned to agent-based conceptions of modeling (Giere, 1988, 2010; Gouvea & Passmore, 2017; Passmore et al., 2014), i.e., instruction that lies on the right side of the continuum.

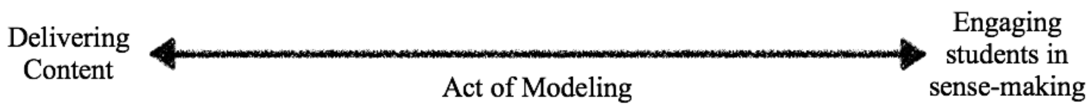


Figure 3-1. *Depiction of the various perceptions of modeling that are described in both the science studies and science education literature.*

Enacting *Modeling* in Science Classrooms

I described the difference between a *model* and the act of *modeling* (see chapter 2, p. 17) and the varying perceptions found within the literature, but now I describe what modeling can be in science and how it can be translated into science classrooms. First, science is a human endeavor (Giere, 1988; Lemke, 1990; Nersessian, 2002) that requires the communication of ideas (Lemke, 1990), and scientists utilize models as a means for communicating the relevant sets of ideas that explain a phenomenon to the scientific community. Scientists thus rely upon these external accounts as mediators in facilitating their construction, evaluation, and application of models. In classrooms, students comprise the scientific community (Lemke, 1990), and should be given opportunities to publicly share their ideas in ways similar to scientists, whether that is through public sharing of ideas, through writing, or through other means for communication (Norris & Phillips, 2003; Pearson, Moje, & Greenleaf, 2010). In addition, opportunities for synthesizing information through peer-to-peer dialogue are important for facilitating conceptual understanding (Driver et al., 1994; Lemke, 1990; Polman, 2004).

As students work together and share their ideas, teachers need to respond to students in ways that expand on their thinking (Hammer & Schifter, 2001). Accordingly, they need to make decisions about what kinds of questions to ask of students that might be productive for building on their ideas (van Zee & Minstrell, 1997). This is different from what has been termed "traditional school science" (Rudolph, 2003), where teachers communicate what students should know, or where teachers engage in dialogue with students in initiate-respond-evaluate like patterns (Mehan, 1979). Also, in traditional science classroom, student-to-student talk is largely absent (Weiss et al., 2003). Therefore, in modeling classrooms for students to be engaged in the reasoning or sense-making process, teachers must shift from traditional orientations of teacher-centered classrooms towards an orientation that is more student-centered. As a teacher is mediating the modeling, they are doing so by acting as a *moderator* or an *arbitrator* of knowledge. Halloun (2007) states that,

> As *moderator* (emphasis in original), the teacher solicits ideas about a particular topic, and then guides students to compare ideas and resolve possible incompatibilities... the teacher does not intervene directly in the process to resolve the matter in favor of one idea or another...The teacher gets more involved in the mediation process as an *arbitrator*...The teacher would then bring concerned students first to a conscious state of *cognitive disequilibrium* (emphasis in original), and direct them afterwards to negotiate things with their colleagues so as to get them resolved in favor of a particular position that is viable from a scientific perspective (p. 681).

Throughout the mediating process then, teachers are helping students to negotiate and build on or set-aside ideas, respectively (Halloun, 2007). If teachers are providing students opportunities to dialogue with their peers for understanding phenomena and are affording students chances for developing a model, then it is possible for them to engage students in modeling as a means for sense-making.

In chapter 2, I reported on the kinds of instructional moves that teachers used that afforded or constrained opportunities for engaging students in sense-making, illustrating how the moves related to the different perceptions of what constitutes the act of modeling. As such I presented a framework for categorizing teachers' instructional moves that was based on five teachers' implementation of a modeling curriculum. In the study presented in this paper I build on those findings to examine and understand why teachers may have utilized varied and inconsistent instructional moves. This work is needed to extend the practices-based research in science education, particularly in light of the newest reform context of NGSS. Moreover, aside from two studies focused on these issues around the scientific practice of argumentation (e.g., Martin & Hand, 2007; McNeill et al., 2016), there appears to be no research that considers what influences enactment of modeling instruction.

Methodology

This study began in the summer of 2015 and concluded in the spring of 2016. A team of seven researchers drew on qualitative methods to observe participants teaching the modeling curriculum, to interview participants, and to collect participant writings. In this section I describe the study context, the participants, our data collection scheme and my methods for analysis.

Study Context

The National Science Foundation-funded MBER Biology curriculum development project was a multi-year, collaborative endeavor that included a team of education researchers, scientists, and high school biology teachers. Our goals for the project were two-fold: (1) to develop high-quality research-supported curricular and pedagogical supports; and (2) to create a yearlong high school biology sequence that centered on the practice of developing and using models. Therefore, the curricular materials were designed to engage students in authentic scientific practice as a means for generating and evaluating science knowledge. Based on previous work in the field of modeling in science education (e.g., Gouvea & Passmore, 2017; Passmore et al., 2014; Passmore et al., 2009), we focused our lesson design on three components: the phenomenon to be investigated; a question about the phenomenon that can bound the activities and lessons in service of developing an explanatory model; and the model that serves as a framework for creating explanations that answer the question about the phenomenon. Ultimately, in the instantiation of the curriculum during the study year, we created a sequence that included twenty-four biological models that foregrounded an understanding of the mechanisms for evolution. In year one we designed the sequence and curricular materials; in year two, two teachers who assisted in the development of the sequence and materials piloted the curriculum, and in year three, ten additional teachers were selected to implement and assist in the revision of the curricular materials. This study took place during the 2015-16 academic year, which was year three of the project.

Study Participants

Ten teachers from three high schools in two school districts within the greater Sacramento Valley were selected to participate in this project. To participate in MBER, teachers submitted a questionnaire and a letter of support from their respective principals. The questionnaire asked for basic demographic information including their teaching experience, credentialed discipline, and courses taught. Additionally, they answered three short-answer questions about their recent professional development experiences concerning NGSS, their reasons for applying to participate, and their comfort with technology. In total, eighteen teachers applied. In reviewing the applications, we were purposeful in choosing participants that represented a range of experience with NGSS, with modeling specifically, and in years teaching; therefore we strove for maximum variation in our sampling (Miles & Huberman, 2013). Additionally, there were location constraints, and a convenient sample was necessary to ensure that researchers could easily access school sites (Miles & Huberman, 2013). Based on these criteria, ten teachers were selected from the applicant pool. Table 3-1 provides participant information.

Table 3-1. *Demographics of MBER Teacher Participants in Year 3.*

Name	Years Teaching	School	Teaching Credential in Biology	Bachelor's Degree in Biology	Advanced Degree (MA or PhD)
Connie	30	Spring H.S.	Yes	(unknown)	unknown
Lori*	20	Wildwood H.S.†	Yes	Yes	No
Steve	13	Wildwood H.S.†	Yes	No	No
Amanda	14	Wildwood H.S.†	Yes	No	No
Eric*	14	Wildwood H.S.†	Yes	No	No
Catherine*	20	James K. Polk H.S.	Yes	Yes	No
Margo	7	Davidson Charter	Yes	No	Yes (MA)
Frances*	12	James K. Polk H.S.	Yes	No	Yes (MA)
Leslie	16	Navy H.S.	Yes	No	Yes (MS)
Fred*	1	Valley H.S.†	Yes	Yes	Yes (MA)

Note: Teaching experience is the number of years prior to participation in MBER.
*Teachers that I will focus on in this dissertation.
†Same district.

In this study, I focused on five of the participating teachers (indicated with asterisks in table 3-1). I was purposive in choosing Catherine, Eric, Fred, Frances, and Lori for further investigation because they represent similar contexts, yet had a range of teaching, modeling, and NGSS experience. Additionally, they were convenient (Merriam, 2009) because of their geographic locations. Eric, Fred, and Lori worked within the same district, and Catherine and Frances taught within the same school as Clair, a co-creator of the curriculum. Moreover, the data collected for Catherine and Frances proved to be rich for examining modeling instruction because they had previously enacted some of the MBER lessons prior to the year in which we collected this data.

Before teachers implemented the curriculum they received six days of professional development spread over two weeks in the summer before implementation began (Summer 2016). The focus of the sessions was to engage the participants in some of the MBER lessons as a means of illustrating what we, as curriculum designers, perceive to be productive ways to engage students in modeling. They also received instruction on the reasons behind our design choices and how to access the curricular materials via a website. Although the teachers only received six days of "formal" professional development, we provided them with additional resources and assistance, as requested, throughout the academic year in which we collected this data. We also met with them five times for after-school meetings to provide them with a space for discussing concerns and problems of enactment and to make them aware of new resources we had created.

Data Collection

Over the academic year in which we conducted this study, we amassed a large corpus of data that was collected by seven researchers involved in the development of the curriculum and in planning the professional development. Although we tried to maintain a mostly observer-as-participant stance (Merriam, 2009), there were occasions when the teachers asked us for assistance or clarification about the curricular materials, and there were times when we interacted with the students as they worked in groups to process tasks. Therefore, our roles in the classroom can best be described as participant-observers (Merriam, 2009).

The primary sources of data for this study are interviews that were conducted throughout the year. Each of the teachers was interviewed a minimum of two times: once after enacting the first model (natural selection) and another after enacting the nineteenth model (Mendelian genetics), but Fred was interviewed three additional times and Eric four. The first interview was semi-structured (Seidman, 2013), and focused on the teachers' experiences in implementing the first model of the academic year. In addition, we were interested in getting the teachers to identify moments in which they utilized MBER ideas or resources. The rest of the interviews (with the exception of one; described below), were semi-structured and included a stimulated recall component (Calderhead, 1981). For these interviews, we were also interested in the teachers' experiences in enacting the curriculum, but we also wanted to focus on why the teachers made particular instructional decisions. We asked the teachers to watch a clip of themselves instructing and we asked them to consider what they were doing in the videos and why they may have done what they did? If anything came to mind, they were asked to stop the video and explain. The video clips they viewed were of them enacting a component of a modeling lesson that we had observed. We also conducted one narrative interview (Seidman, 2013) with Eric and asked him to describe to us his lesson planning process so that we could get a better understanding of how he was interacting with the website and the curricular materials. We chose him for this interview because, out of the five teachers included in this study, he had been the most vocal in his critique of the MBER website and the presentations of the curricular materials. Appendices C-E contain the interview protocols used for the semi-structured and stimulated recall interviews.

In addition to the interviews, we collected written or typed responses to written prompts from the five meetings that we had with the teachers throughout the academic year. The teachers were also asked to write reflections once per week and to post them on the website along with any of the curricular materials they modified. Both the reflections and prompts were intended to better understand teachers' intentions behind components of enactment. Moreover, a large component of our data corpus consists of video and audio recordings and associated field notes of observations that were conducted throughout the academic year. In a previous study (see Chapter 2), we utilized the video observations to delineate instructional moves teachers used to enact the modeling lessons; however, along with field notes, they were used in this study as a means of providing context for the barriers perceived by us and by teachers in enacting modeling. Table 3-2 contains a summary of all data collected for the 2015-16 academic year.

Table 3-2. *Data collected for each teacher for the 2015-16 academic year.*

Cases	T1	T2	T4	T5	T6	T7	T9	T10	T11	T14	T16	T19	M1	M2	M3	M4	M5
Catherine	V, I, C	V, C	—	V, C	V, C	V, C	V, C	V, C	—	—	—	V, I	R	—	R	R	—
Eric	V, I, C	—	—	I†	V	V, I	—	—	V	—	V	V, I	R	R	R	R	R
Frances	V, I, C	—	V	—	—	—	—	—	—	—	—	V, I, C	R	R	—	R	R
Fred	V, I, C	—	—	V, C	—	V, I, C	—	—	—	V	—	V, I, C	R	R	R	R	R
Lori*	V, I, C	—	—	V, C	—	—	—	—	—	—	—	V, I	R	R	R	R	—

Table Key: Curricular reflections collected for the corresponding triangle (C); Interview conducted about instruction within the corresponding triangle (I); Reflection prompts collected during group meetings (R); Triangle for which the data was collected (T, see Figure 3); Instruction video-recorded for the corresponding triangle (V)
Group Meetings (M) took place on 10/20/15 (1), 12/14/15 (2); 2/10/16 (3); 4/26/16 (4); 6/7/16 (5) [Due to the differences in teachers' schedules, there is no triangle that directly corresponds to each meeting date.
*Lori also provided a copy of a notebook she kept for the entire year that include her ideas for instruction and notes about the curricular materials.
†This interview was conducted while Eric was implementing triangle 5, but the focus of the interview was to better understand his lesson planning process and how he utilized the resources on the MBER website.

Data Analysis

To begin analysis of the factors influencing teachers' implementation of modeling, interviews were transcribed by both our research team and by a transcription service. For those transcribed by us, we used InqScribe software and then imported the resulting transcripts into NVIVO qualitative analysis software. Those created by the service were also imported into NVIVO. Because I was interested in what teachers perceived to be influencing their instruction, my analysis focused on discourse related to the teachers' beliefs, their views, or their intentions related to implementing the MBER curriculum. My first pass through the interview data focused on reading through the first interviews that we conducted–those following implementation of natural selection. As I read through the interviews, I wrote analytic memos that included preliminary jottings of words and phrases (Saldaña, 2016) that I noticed the teachers using that appeared to be related to their beliefs, their views, or their intentions related to implementing the MBER curriculum. Additionally, I began to consider how the ways in which they discussed their instruction related to my perceptions of modeling framework (see figure 3-1). Moreover, in this first pass, I looked inductively through the data, jotting down other words or phrases that I perceived to be common, or not, across the teachers' interviews. Some examples of patterns I recognized through this first pass (and their resulting codes in parentheses, described next) included:

- Teachers perceived their students to be engaged from the beginning of implementation (student engagement)
- Teachers described that their students and themselves sometimes needed a cognitive break (cognitive fatigue)
- Teachers discussed their role in the classroom (teachers' role)
- Teachers identified the reasoning students were doing to be important ("critical thinking"), and also described the importance of students grappling with data (student "struggle")
- Teachers described what they perceived model-based reasoning to be and overall viewed it positively (definition of MBR/MBER)
- Teachers described the amount of time involved in planning and in enacting (time involved).

Following this initial pass through the interview data, based on what I had written in my jottings and memos, I created a combination of codes: *in vivo* codes used the language of the participants; process codes labeled actions the teachers described; and descriptive codes summarized topics the teachers described (Saldaña, 2016). I then made a second pass through the same interviews, as well as the others that had been conducted throughout the academic year. I applied codes to sections of data, adding and combining codes as necessary. I attempted to categorize all portions of the interview, creating additional *in vivo,* descriptive, or process codes as needed. As analysis continued, some code labels were changed to be more reflective of what was emerging in the data. For example, the teachers would discuss classroom norms that had been set-up (process code; referring to norms) and I found that they would oftentimes discuss classroom management styles (descriptive code, classroom management); therefore, as analysis proceeded I created a broader descriptive code entitled “classroom culture” that I felt best reflected what the teachers were discussing. Additionally, I double-coded portions of the interview when more than one code applied. For example, the following excerpt from Lori’s Interview on 9/24/16 was coded with both “student interactions” and “student struggle” to reflect that she was discussing two kinds of factors that could affect implementation:

> I like having the data to where kids can struggle a little bit with it at first, because it's really great to see when the light bulbs go on. And, it's nice to see other students, when their peers aren't getting it. Then to go, no wait, don't you see this and have to become the teacher in that small pod. (Lori, Interview, 9/24/16)

After I completed refining the codes, I made a third pass through the interviews to recode or add codes to sections of interviews where necessary. The final list of codes created from my first cycle of coding and examples of each are described in table 3-3.

Following the third pass through the interviews, I transitioned into a second cycle of coding, whereby I began to look across similarly coded passages. In this pattern coding phase of analysis (Saldaña, 2016), the goal was to condense the large number of first cycle codes into a smaller number of units for further analysis (Miles & Huberman, 2013). Therefore, I condensed first cycle codes into what I perceived to be related categories. I was intentional in looking at themes related to teachers’ beliefs, views, and intentions as they related to the perceptions of modeling framework, but I tried to keep an open mind in regard other themes that may help to explain the data (Becker, 1998). However, it became clear to me through this pattern coding process that many of the first cycle codes (see table 3-3), such as “students’ capacity” and “students’ understanding” were subfactors that may be affecting implementation of modeling, and that others, such as “teachers experience” represented some of the larger, subsuming themes. The results of second cycle coding were four overarching themes related to factors affecting implementation of modeling in high school biology classrooms: teachers’ intentions, values and beliefs; teachers’ real-time instructional considerations; teachers’ views and understanding of science; and teachers’ perceptions of the role of the curricular materials.

Table 3-3. *Refined codes emerging from first cycle analysis of interviews.*

Code	Description	Example
Adapting	• Describing how they changed instruction and/or materials in response to what they perceived the students needed.*	"…I tried it with one class where I took out two pages of a data set...and very quickly, some questions popped up where I felt like they needed that data. So, I abandoned that idea the next period and gave them all the data. And I actually felt like it went a little bit smoother having all of the data." (Eric, Interview 9/24/15)
Assessment	• Describing the ways in which they make student thinking visible to them, and also relates to summative and formative assessments	I was going through my gradebook at the end of the year, and I was like, what am I basing my grades on? There was just not much there. Um, so, I did a final exam and I did the full multiple choice, kind of went through everything since fall final and, trying to be more kind of conceptual, but also trying to include more vocabulary. Um, and it was a little rough. But, um, I don't know. Just assessing them because what I was asking them to do? To memorize all this stuff or to use it? So, I don't know." (Fred, Interview, 06/07/2017)
Authenticity to science	• Describing what it means to have instruction aligned to what real scientists do	"They're trying to come to some understanding based on the data and I-it's really refreshing for me to see this change, and I think it is most authentic to my work as a researcher that I used to do. So, when I'm thinking my job like ten years ago in the biotech industry, it is like what we're doing in class with EMBER. It's sharing those ideas about proteins, or about you know, anti-biotics. We don't know the answer but we're trying to com-create a group understanding. (Frances, Interview, 6/07/17)
Classroom culture	• Problems referenced in regards to organizing the classroom, norms for interactions, positive/negative experiences of students working together.	"Most essential to an MBR style class is an established relationship between teacher and student and student to student of respect. I am a work I progress and am willing to take risks and I ask the same from them and they expect a safe environment to do this in." (Catherine, 4/26/17, Written Prompt Response)
Collaboration	• Describing teacher-teacher collaboration and its impact on practice	"There were probably times where I just got overwhelmed focusing on one of my other class periods and I'd go over to Heather's room and she'd say, well okay here's what I did. And I'm like, oh perfect, that makes sense. And that eased some of the thought process for me." (Eric, Interview, 6/06/16)
Cognitive fatigue	• Perceptions that students are exhausted from engaging in modeling. Also applies to the teachers	"Or, it's just, I think part of it is just mental exhaustion. It's not easy for [students] to process this stuff and they are having to push themselves." (Fred, Interview, 9/24/15)
Curricular planning	• Used when teachers refer to using the materials to plan, or modifications that they made. Or, could just be referring to planning in general	"Staying ahead of the students with the lessons and the 'MBER script'. It is teaching in a sequence that is new so I find myself planning constantly so I can anticipate questions, roadblocks, etc., and provide the students with a little direction if needed." (Lori, Written Prompt Response, 10/20/2015)

Table 3-3 *(continued)*

Code	Description	Example
Defining MBER/MBR	• Used when teachers are describing what they perceive MBER, or MBR/modeling to be all about	"…we try to get kids working through, explanations of that phenomena, how do they explain what they've experienced or observed or something like that…" (Frances, Interview, 6/07/2017
Driving Questions	• Teachers describing the usefulness of a driving questions, its purpose, or the process of generating it, or what happens when it is missing	"Students did a good job of identifying patterns, some that I hadn't even seen when I first looked at the graphs to do with organism density. We went around the room to build ideas and it was interesting to see the variations on the central concept that students identified. I regret not developing a driving question here to bring together the phenomenon that the class was seeing." (Fred, Curricular reflection, 3/1/2016)
Iterative nature of the curriculum	• Teachers referring to the nature of the MBER sequence, its iterative component,	"I would like to get through more. I would like to bring it full circle, because, that's where I think traditionally, doesn't always do that. Which is, we give them this, then this, then this, and, the whole idea at the beginning of the year with this, is how it is so interwoven, and I would like to get more accomplished so I can truly bring us back around to, so now you have these alleles, what determines if they're good or bad. Or, you know, or that kind of thing." (Lori, Interview, 5/18/2016)
Lab experiences	• Teachers describing their satisfaction and/or dissatisfaction with lab experiences in the classroom	"I think just more some of the stuff that we talk about, but, trying to bring it into also, doing that idea of the lab. Like, [MBER] is very hands on because, they're talking and they're writing posters, but I would like to see where – and I'm not saying that I have all these labs in my head. But, like research could I find a good lab for this. That's like with the genetics. One of the problems I've always had with it is, if you don't do DNA, electrophoresis or we don't do inserting plasmas like they do in A-P then, our regular kids kind of like what can you do?" (Lori, Interview, 5/18/2016)
Pre-MBER modeling	• Teachers discussing how they used models and modeling in their classroom before MBER	"Most of it has really been time, the time that I have to spend, 'cause I'm already super full with my life, and the absences, and I've been using model-based reasoning here and there anyway, but when you do it all the time, there really is no, like, "Here's the worksheet, kids." (Catherine, Interview, 10/13/2015)
Pre-MBER students	• Teachers describing their students in the years before they began implementing the MBER curriculum	"And I just think that from last year my students would not have done that [shakes head no as he speaks]. They would have shied away. Well, you didn't tell us what skin it made of, how do we know that? You know, so, I thought that was cool." (Fred, Interview, 6/07/2016)
Scaffolding	• Teachers describing how they broke down particular tasks in the classroom, or how they would break down tasks after enacting*	"I would start using some more vocabulary strategies as well. So, maybe when these ideas come up, and then we're saying okay, we're gonna call this genotype, we're gonna call this phenotype. Then, um, once we've developed some vocabulary, step back and do some like just vocabulary exercises so that they have that to reference." (Frances, Interview, 6/06/07)

Table 3-3 *(continued)*

Code	Description	Example
Student capacity	• Teachers discussing their students ability to accomplish or not accomplish a particular task, their ability to make sense of science, or issues concerning their prior knowledge.	"The realization that my kids have far more knowledge and skill than I thought." (Catherine, Writing Prompt Response, 10/20/15)
Student Engagement	• Describing how they perceived student interest or participations in tasks and/or activities.	"I feel like if I spend too much time trying to come up with a consensus right now I start to lose them. Like, they're ready to move on. Okay, we got it, we got it. And so, it's not worth taking the class time right now." (Eric, Interview, 9/24/15)
Student to Student Interactions	• Describing what teachers observed when students worked together or what they perceived to be happening	"Because it's really great to see when the light bulbs go on. And, it's nice to see other students, when their peers aren't getting it. Then to go, no wait, don't you see this and have to become the teacher in that small pod." (Lori, Interview, 9/24/15)
Student struggle	• Used when teachers are describing the important of letting students struggle and/or sink while trying to do sense-making. Also used when teachers described students who had difficulty understanding a particular concept or model.	"…there was also some strength in having them really struggle with it, where the kids were passing around, and I heard some great discussions between kids where they were like, "Well, wait a minute. But look at this." And they were really discussing what was going on in the graphs, and they were figuring that out. And there was a certain power that came from that experience for certain kids." (Eric, Interview, 9/24/15)
Student understanding	• Used when teachers describe whether or not students are understanding particular thing such as content or models.	"And they were incorporating previous models into their currently developing model and that was really great to see that they were doing that and they didn't even think about it. It had become their model. And to just see that it was that knowledge base that they could pull from was great." (Eric, Interview, 6/07/2016)
Teachers' Experience	• Describing how their involvement in MBER has affected their teaching	"The most challenging for me, is having to think about what I'm doing in a way that um, I feel kind of like I'm this new teacher again." (Lori, Interview, 5/18/2016)
Teachers' role	• Teachers describing how they perceive their role in the classroom	"And so that's where I've gone from now so I really like that I'm not giving answers and I think that they realize that. They're not looking to me for like, 'okay just wait, wait, wait, is she going to tell us exactly what the right answer is?' Because I haven't been doing that." (Frances, Interview, 10/14/15)
Teacher Content Knowledge	• Describing how their own content knowledge played a role, or moments when we perceived content knowledge to be playing a role.	"When we got to talking about like inputs and outputs and all that, I had never done any of those things that way and I loved it. But I wasn't as comfortable so I guess I didn't know what the end result was going to be as well." (Eric, Interview, 6/07/2016)

Table 3-3 *(continued)*

Code	Description	Example
Time Involved	• Teachers discussing time as a challenge for both planning and implementation	"…in the beginning, I feel like we had all the time in the world and as you start going through the end of the year, it's like, "Oh my gosh, we need to get through this faster", you know? I feel like I took more time for students to generate ideas and contract their ideas as a class, and then contract their ideas as a series of four classes. Where later in the year, I didn't give them that opportunity." (Frances, Interview, 6/07/2016)
Understanding of Models/modeling	• Describing models or modeling. May sometimes overlap with Defining MBER.	"More like understanding DNA and replication. It's like you can take any model and figure out how other concepts get woven in. And so once I started seeing that in the natural selection model, which I think I had them doing the longest, started opening up that vision to me about how to connect all the ideas. And it helps the kids remember things." (Catherine, Interview, 6/07/2016)
Understanding of phenomena	• Describing phenomena, what are phenomena	"So, phenomenon with patterns is we're trying to look at... We're trying to explain patterns in phenomena and these patterns occur regularly. Pattern... And, answer the question [LAUGH]. Let's see. Let me think, let me think. Okay. Um, I think it's... From when I was listening to it, I put down understanding the purpose. So, the purpose is to try and set up a purpose. Like, we are trying to explain this pattern" (Frances, Interview, 6/07/16)
Values MBR	• Teachers describing the power or value they see in using model-based reasoning in the classroom	"The most rewarding part for me is getting students to share their ideas. That was really like a first for me. To really focus on that, just in depth like we really were. And to do it in a way that I felt allowed students to gain that confidence so they didn't feel like, "Oh my gosh, I don't have the right idea. I'm not gonna share that idea." And then I tried to raise expectations like, "Okay, you gotta share something." You know, either confirm that idea, or refute that idea, or agree, or disagree. At least something so that they felt like, "Okay, I have to share something or at least I have to say something and participate in the process". So, the sharing of ideas was my favorite piece that I really liked." (Frances, Interview, 6/07/16)

*"Scaffolding" is different from "adapting" because scaffolding pertains to *a priori* or post-instructional scaffolds the teachers believed to be necessary. "Adapting" is related to in-the-moment decision-making based on teachers' perceptions of students' needs as enactment occurred. However, both could have been used on the same interview excerpt if adaptations resulted in new or different scaffolds.

Upon completing categorization of themes and first cycle codes, I analyzed the teachers' writings (curricular reflections and responses to written prompts) in NVIVO. These were analyzed in order to provide additional context and to triangulate findings (Miles & Huberman, 2013). In doing this final analysis, I utilized the same categories and codes as in the first and second cycles of interview analysis. Appendix F contains a summary of the number of instances of each subfactor coded in this analysis. In the findings, I report on each of the emerging themes, providing evidence from interviews, observations, and teacher writings.

Findings

I have organized this section around the four main categories of factors perceived by us and by teachers that may have affected implementation of modeling in the high school biology classrooms we observed. Figure 3-2 displays these categories and the subfactors contained within. The four rectangles depict each of the four categories, and listened within are the related subfactors. The rectangles rest on a foundation of modeling to illustrate that each of these categories influenced, in some way, implementation of modeling in the high school biology classrooms I observed. Although this is the way that I have chosen to categorize and illustrate the data, the factors are not necessarily mutually exclusive. As I will further describe in the findings, there could be multiple factors affecting implementations of modeling at any given time, and those factors could also transcend categories.

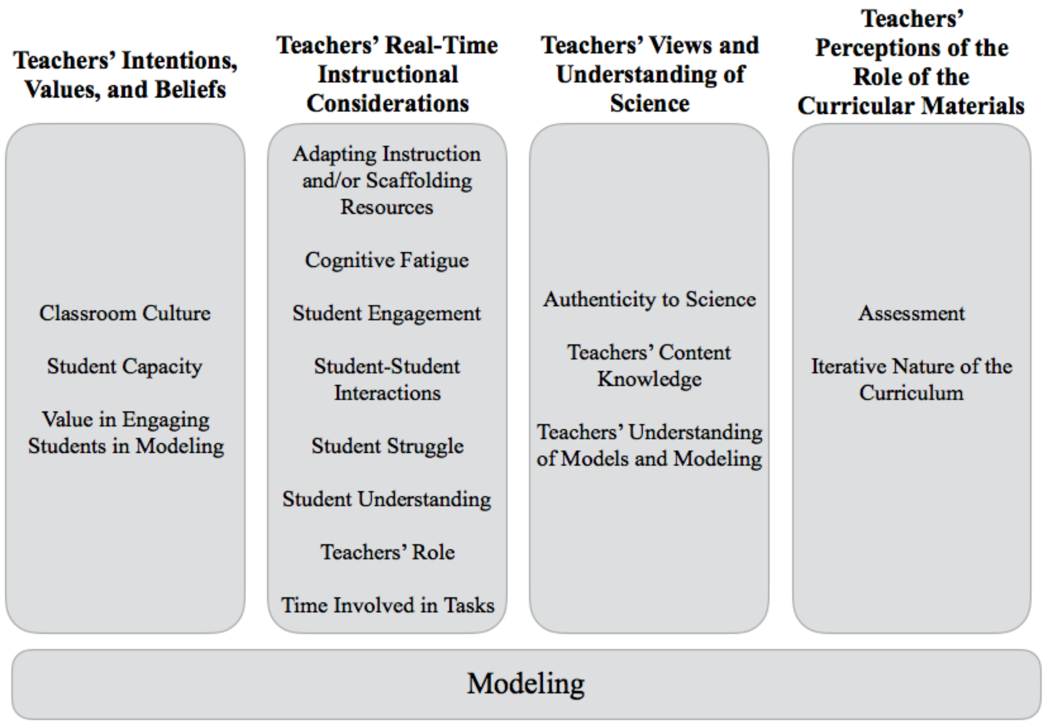


Figure 3-2. *Categories of factors affecting implementation of modeling in the high school biology classrooms I observed. Subfactors of each category are listed within each representative rectangle.*

Teachers' Intentions, Values, and Beliefs

The teachers in this study discussed and wrote about aspects of their instructional intentions, their values, and their beliefs, all of which appeared to have influenced enactment of modeling. In particular the teachers noted their beliefs and intentions about classroom culture, beliefs about the role collaboration played in their enactment, their beliefs about students compared to previous years, beliefs about student capacity to engage in modeling, and their perception of the value in utilizing modeling in the classroom.

Classroom Culture. Each of the teachers in this study described the importance of having a classroom where students felt supported, particularly in sharing ideas about the model and in working with one another to process modeling tasks. The development of a supportive atmosphere seemed to be of particular importance at the beginning of the academic year, when each of them implemented activities focused on developing norms for interacting with one another. Although this process of “setting the stage” was explicitly recommended in the curricular materials, the teachers articulated, in their own words, how they perceived this instructional component to influence the classroom. For example, Frances, in her first curricular reflection of the year, stated that she was “itching to get to solid content” yet knew that “these first few weeks of establishing routines, practicing protocols, and building student relationships will be the launching point for a successful year.” The development of a supportive classroom culture appeared to bear out for Eric, Frances, and Lori by the end of the academic year. The following quotes illustrate the perceived consequences of setting the stage:

> The most rewarding part for me is getting students to share their ideas. That was really like a first for me. To really focus on that, just in-depth like we really were. And to do it in a way that I felt allowed students to gain that confidence so they didn't feel like, ‘Oh my gosh, I don't have the right idea’. I'm not gonna be able. I'm not gonna share that idea." And then I tried to raise expectations like, ‘Okay, you gotta share something.’ You know, either confirm that idea, or refute that idea, or agree, or disagree. At least something so that they felt like, ‘Okay, I have to share something or at least I have to say something and participate in the process.’ So, the sharing of ideas was my favorite piece that I really liked. (Frances, Interview, 6/07/16)[6]

> My favorite part has been watching the kids truly interact together in groups. Where you see the light bulbs start to come on. So, when they are looking at something that’s fairly complex and they are able to talk it out, with sometimes not a lot of prior knowledge, and you see one or two start to get it and then helping the others, kind of like ‘no, if you look at this way’. That, for me, is the best teachable moment because they are starting to teach each other. (Lori, Interview, 5/18/2016)

> It’s important to create an environment where kids feel safe being wrong. They have to feel safe putting out their ideas. They have to be in an environment where they can work through lots of possibilities. And I think one of the important parts is having students understand that every idea whether it’s right or wrong is valuable, because it eventually leads to that correct answer. If you have an idea that was a bad one at least you know that’s that not a possibility anymore, you can just rule that out…and so kids have to work through that process and you don’t have to do that in regular, traditional classes. Literally just, you know, look up the answer, regurgitate. (Eric, Interview, 6/07/2016)

[6] Quotes have been formatted for ease of reading without detracting from the perceived meaning.

Managing student behavior also appeared to be a factor that teachers perceived as affecting their implementation of modeling. Both Catherine and Fred discussed difficulties in managing student work groups and keeping them on task. Catherine's means for curtailing these issues were to organize her students into "pods". When not working in groups, their desks were in rows, but as tasks required group discussions, groups of four students would turn their desks to form a square. This strategy was also taken up by Eric towards the end of the academic year. Originally, his way of organizing the classroom was to have his students' desks in groups of two with four seats total, but he returned to the traditional style of rows because he perceived that his students were not focusing or listening when he was teaching (Observation notes, 5/10/2016). For Fred, student behavior continued to be an issue for him throughout the year. We observed classroom behavior that detracted from his instructional time, so much so that by the end of the year, he asked us to observe a different class period because he felt that the students were more well-behaved, and he felt the class best reflected model-based reasoning (Observation Notes, 5/12/2016).

Student Capacity. Teachers' beliefs concerning students' capacity to engage in modeling also played a role throughout the academic year. I observed this in instruction and in what all five teachers described in interviews. An example where Eric referenced his beliefs about students' capacity occurred at the beginning of the academic year when Eric expressed surprise to the students about their ideas. He said that their,

> …misconceptions (about natural selection) were just plain false. I haven't been correcting you guys. I've been specifically allowing you guys to self-correct in a lot of ways. And it didn't work that great. We didn't even get to a point where we could agree and get those ideas up on the screen for everybody. (Eric, Video Recording, 9/23/16)

Although this appeared to be a means for focusing students' attention on the model ideas, it is possible he led students to believe that they would be unable to complete the modeling task without him telling the students what the model ideas were. In contrast, he did talk and write about the reasoning his students were doing and how he was impressed with the ideas students could generate or the connections they could make. For example, in response to a prompt asking teachers to pinpoint an example of students engaged in model-based reasoning, he said that "during an investigation into why there were two variations of guppies in different ponds, students went immediately to applying their model of natural selection…before developing a new model, they relied on a previous model to do their reasoning." (Eric, Written Prompt Response, 4/26/16). In his final interview, he continued to reiterate this point, stating that when students were developing models to explain patterns of inheritance, the students were incorporating previous models into their thinking "just to see that there was that knowledge based that they could pull from was great" (Eric, Interview, 6/07/2016). His evolving conceptions regarding students' capacity to engage in modeling indicates that teachers' beliefs may be dynamic, particularly when confronted with student reasoning that differs from their expectations.

Fred also exhibited similar beliefs towards students' capacity to engage in modeling tasks, despite a similar orientation towards letting students share their ideas and providing them with opportunities to generate explanatory models (see Chapter 1). In a stimulated recall interview, he stated that his students were willing to share and develop ideas, and that even his mentor teacher was impressed with what he could get his students to do, but at the same time, he felt that a big challenge in the classroom was that,

> …conceptually…, half the students haven't figured it out and the others have no clue, the other half doesn't really know where we're going, just doesn't know how to get there. It just gets, when we get to that point, it seems to happen when there's just too much. I think that there's too much stratification of the class as far as, previous knowledge and ability is concerned. Which is something that I had in my class last year. There were just these guys and these guys [moving hands up and down levels], because

> they are pushing them in English and they get no Science. So they get English and Math and then they get Science in the junior high. There's no elementary science. So, for those kids that that happened to, they are coming into me with nothing, which was a challenge last year. But, it's easier actually, with this, because it's accessible to more students. I think, but, it's still a challenge. (Fred, Interview, 1/27/15)

This tension between seeing the value in providing students with opportunities to develop and share ideas versus believing students have the capacity to do so or have prior knowledge to do so was described by and observed in all five classrooms; however, it does appear that when teachers had a positive orientation towards student capacity then they were more open to seeing the kinds of ideas that students had. In the quote above from Fred, for example, he states that some students may be facing different challenges than other students; however, he ultimately feels that modeling is "more accessible" to those students.

I will describe scaffolding in more detail when discussing teachers' real-time instructional considerations; however, I found that scaffolding appeared to correlate with beliefs about students' capacity. For example, Eric, Fred, Frances, and Lori described scaffolds that they developed to help facilitate instruction; however, these components were often described as a means to overcome student capacity issues. For example, when asked if there were any instructional supports she wished the curriculum included, Frances responded that she would have liked more frames or prompts to guide students in creating model-based explanations:

> Simplifying it quite a bit and then giving them a word bank where they have to appropriately put in variation into the sentence. Does that make sense? Maybe like reproduction or the word population and then they'll be able to see, 'ok, it's kind of framed out for us already but do these words make sense in this sentence.' So I am in the process of generating something like that and I think I also have another one, a second version where again it's the sentence stems so it's like the story [explanation], but sentence stems, and they just need to finish the sentence. So it might say something about, maybe the finches with the larger beaks had a blank variation and then they would have to add the word advantageous variation 'cause that's going to be one of their vocabulary words. And then maybe the next sentence would be: 'because they were successful in their environment their numbers increased or decreased,' so they'll have to choose between that in the population. So kind of little helpful frames for that as well.

I'm trying to make it as accessible as possible. (Frances, Interview, 10/14/2015)

What Frances is describing is a fill-in-the-blank worksheet with a word bank. She also says that students would need to find the word that makes sense in the sentence, which would not necessarily require a model of natural selection to answer. Overall, it appears that the teachers in this study held mostly positive orientations towards students' capacity to engage in modeling; however, sometimes their perceptions of students' needs or their beliefs about students prior knowledge impacted the design and implementation of modeling.

Another component related to student capacity, mentioned by Catherine, Fred, Frances, and Lori during their final interviews was the differences they observed between "traditional students" and "modeling students." Fred, Frances, and Lori each mentioned that they recognized shifts in how their students approached problems and classroom tasks. Fred noticed that his students were "willing to take a stab" (Interview, 6/07/16) at explaining novel phenomena. For example, following the generation of a model that explained development and cell differentiation, he asked students to explain how skin can grow back after it is scraped. In response to his students' explanations he said,

> I told them they would apply their development and differentiation model and just go, like just take a stab at it. And they were willing to. That was pretty cool, I thought. And, just the willingness to put their ideas out there, even though they didn't know that, that they weren't very right, but they were pretty close some of them. And they had some of the ideas right, but they were willing to take a stab at it. And I just think that from last year my students would not have done that. They would have shied away. 'Well, you didn't tell us what skin it made of, how do we know that?' You know, so, I thought that was cool. (Fred, Interview, 6/07/2016)

Lori noticed her students were willing to engage more in discussion with one another than in previous years. She suggested that modeling instruction was more effective in providing students with opportunities for this since "they can be the ones driving questions" (Lori, Interview, 5/18/2016). Frances also noticed this difference in her students in comparison to previous classes, saying that by the end of the first model development process, "[students] were clapping for themselves for doing such a good job. (Frances, Interview, 6/07/16). It is possible that these observed differences foregrounded for the teachers the kinds of reasoning that students were able to do when engaged in modeling tasks.

Value in Engaging Students in Modeling. Each of our case study teachers applied to participate, implying that they had an interest in improving their praxis and in implementing modeling in their classrooms. Overall, this interest was sustained throughout the academic year; in fact, in their final interviews, each teacher stated that they would continue to use the modeling curriculum in the following academic year. Similarly, the teachers described in their interviews and in their reflections the reasons why they perceived modeling to be important. Eric stated that he believed modeling provides students with opportunities to develop conceptual understanding (Reflection, 6/15/2015), and that, "the other rewarding part is those moments when you see students have that ah-ha moment. When you experience that in the class as a teacher and the kid just gets it, you're just like, 'yes.'" He went on to say that, "those are the most rewarding parts. It doesn't happen when it's in a traditional [classroom], reading stuff out of a textbook and trying to decipher vocabulary and do that kind of stuff, you don't see those a-ha moments…" (Eric, Interview, 6/07/16). Lori also saw value in modeling, not just for her students, but for herself. In her final interview, she said that enacting modeling has been "a good learning experience for me as well." (Interview, 5/18/2017). Based on the participants' discourse, it is likely that a positive orientation towards modeling is key to continuing to provide students with modeling experiences.

Teachers' Real-Time Instructional Considerations

Throughout their interviews and in their reflections, the teachers mentioned factors that seemed to impact decisions they made in-the-moment as they implemented the modeling curriculum. I also observed some of the ways in which these factors bore out during instruction. Instructional features that teachers noticed and that I observed included: when and/or how to adapt or scaffold instruction based on student needs; cognitive fatigue in students; student engagement; student to student interactions; students grappling with data or with questions; and student comprehension. Additionally, they recognized the impact of their instructional role, time for planning and for instruction, and their perceptions of what the students were experiencing.

Adapting Instruction and/or Scaffolding Resources. There were instances where each teacher made changes to their instruction based on events that happened in the classroom; however, these appeared to be more prominent to the teachers in implementing the first model. There were few instances of them describing these changes in other interviews or in reflections throughout the year. We observed adapting and scaffolding happening during a lesson where students analyzed and interviewed a set of graphs. Eric gave some classes the graphs all at once and in other classes he spaced out the time over which he handed out the graphs (Observation Notes, 9/21/15). When asked about why he changed his instruction over the course of the day, he said he first gave a class just part of the data, and that,

> …very quickly, some questions popped up where I felt they needed that data. So, I abandoned that idea the next period and gave them all the data. And I actually felt like it went a little bit smoother having all of the data. But there was still some hiccups along the way. There were certain graphs that the students just had trouble understanding. (Eric, Interview, 9/24/15)

He also said that the next day he noticed that students needed additional help in understanding the graphs, so he spent additional time scaffolding the activity and walking students through each graph in order to establish "what are the facts we're basing [the model] on." (Eric, Interview, 9/24/15). For this same lesson, Lori described a similar series of adaptations and scaffolds. She said that she perceived that students would be overwhelmed since they do not often look at datasets. However, she only provided scaffolds for one of the two biology classes that she taught. She said that,

> …with my fifth period it was kind of ok, though. Because they kind of had to figure it out. They just had to look and see, but, I knew with my sixth, I'd have more kids kind of struggle. So it was easier for them to explain the four graphs, six would have been almost a little too much. Because at least one person could be accountable for their one graph. So I think that worked a little, better off for sixth period. Fifth we just kind of went with it and then, but I truly think it wouldn't hurt, and maybe I need to do this more kind of frontload in the beginning of the year, um, graphing. (Lori, Interview, 9/24/15).

In this quote, Lori is explaining her reasoning behind the scaffolds she created for her sixth period class–that she perceived the students would struggle with interpreting the data. Moreover, this is another example of how beliefs about student capacity sometimes interacted with the adaptations and scaffolds teachers discussed. Fred indicated that his students needed scaffolds because "they haven't had a lot of science. (Interview, 6/07/15). In his final interview, Eric also described the interaction between beliefs about student capacity and scaffoldings, mentioning that it is integral to student learning:

> You really have to think [the MBER curriculum] through. How do you scaffold a lesson with these kids, because you can't just throw out the phenomenon and expect them to come up with perfect explanations? There's a building process to that and figuring out the building process is so important and when you get that wrong you hit a dead end and the kids just aren't getting it. (Eric, Interview, 6/07/2016).

In addition to being related to student capacity, scaffolding and adapting instruction sometimes appeared to be related to student engagement, cognitive fatigue, or how teachers perceived the students' experience, both of which we will discuss in sections that follow.

Cognitive Fatigue. The modeling curriculum was designed to include intellectually demanding tasks (Kang, Windschitl, Stroupe, & Thompson, 2016), and as a result, the teachers, excluding Catherine, reported that they observed cognitive fatigue in their students. For instance, Fred noted that at the beginning of the natural selection modeling tasks, the students were "sucked in pretty good", but that by the end of tasks, they were not as engaged. "I think part of it is just mental exhaustion. It's not easy for them to process this stuff and they are having to push themselves." (Fred, Interview, 9/24/15). As a result, the said that he found himself adapting instruction and trying to find strategies for "pulling back and digging into" the lessons. "[Students] get distracted when you push hard. There are days where you kind of [makings a shrugging motion]." On the other hand, he said he found students to be "ready to accept more each day (Fred, Interview, 9/24/15)." When asked what kinds of supports would have helped in enacting the curriculum, Fred noted that "broken down ideas" may have helped "because we do ask them to think in big chunks of time and sometimes that is a little too much for them (Interview 6/07/16)." Similarly, to Fred, Frances also mentioned that students were willing to engage in the activities, writing that "students are challenged with the different style, but they are willing participants. (Written Prompt Response, 10/20/15).

Interestingly, teachers' discussion of student cognitive fatigue decreased as they proceeded further into the academic year; however, this was not the case with respect to the teachers themselves. The modeling curriculum was designed to be intellectually demanding on the students, but the teachers also reported feeling cognitively and physically exhausted. Eric said that one of the biggest challenges he faced in enacting the curriculum was that he was "exhausted the entire year (Interview, 6/07/16)" and that he thought all teachers enacting modeling should recognize that it also requires high cognitive demand on the part of the teacher

(Written Prompt Response, 6/07/16). At the beginning of the academic year, he also mentioned this factor, stating that "I feel a lot more energized when I'm in the classroom with the students…the moment the students walk out of my classroom at the end of the day, I'm just like, 'oh my God, I am so tired (Interview, 9/24/17)."

Student Engagement. Overall, the five teachers in this study perceived that their students were engaged more so than in previous years, such as when Lori said that she noticed a difference because students are not outlining notes and filling in worksheets (Interview, 9/24/15). However, there were a few instances where the teachers discussed how engagement affected their instruction. As an example, Catherine stated that she felt like,

> …the engagement was better this year than in past years, but in some particular classes, I felt like I have a long way to go. But, I have made adjustments from class to class. So in other words, when it doesn't go well in one class, I foreshadow, like, what will this look like in an hour from now and I'm like, 'Ok, I'm going to at least improve it.' And I think I told you that when you were doing some other things. I was like 'Well that went 100 times better.' So maybe in another year, I can get that on-the-fly thinking kind of. I can get more of a foundation done and even improve from there. You have to kind of work where you are. (Catherine, Interview, 6/07/2016)

Frances noted concerns about whether or not her urban students could be engaged in activities that were not relevant to them and that she tried to be "as exciting as possible" as a means for increasing student engagement:

> The idea is cultural competency. Do moths and finches and bacteria really relate to these kids? Not really, okay. So I tried to be as exciting as possible. They got the concepts that there was some sort of change, okay? Then we're going to go into the finches. I tried to just kind of loosen that up a little bit about, you know, this is like real research and, you know, this is real data and not like pretend-teacher-data and just trying to get them excited about that. But in the back of my head it's always like, you know, the common kid, they're going to be 'like big deal these are finches. They're birds. Doesn't relate to me today, my neighborhood, etcetera.' And so I'm trying to capture the kids who are interested in just the phenomenon that it's, 'oh yeah, why is that happening' and 'oh yeah, this is real data, interesting.' Capture their attention that way. (Frances, Interview, 10/14/2016).

Similarly, there were instances when teachers noted that their students were engaged in figuring out phenomena that were accessible to them, such as those related to humans. During a stimulated recall interview that included a clip of Fred facilitating the identification of the phenomenon that would anchor the generation of models of inheritance, he described that

> …for this particular activity it was very accessible to everybody, even all my tables, I had people engaged in doing it, mapping it out, plus it's, being human and it being people, these things that they know about. They were engaged with it, and they did, for the most part, they all got the pedigrees and then kind of pointed out the things that didn't follow. (Fred, Interview, 6/072016)

Lori also recognized that students were engaged when examining pedigrees for patterns of inheritance, "just the conversations that they have with one another in trying to reason it, and the idea that this also is real. That, we see people with diseases. We see people in the room that look different than us" (Lori, Interview, 5/18/2016). I also observed student engagement during conversations about human-related concepts. For example, during a lesson facilitating the generation of a biosynthesis model, Eric was discussing with students the kinds of foods that they eat and how much they might eat. As the bell rang, a student said "I eat a lot and I'm not fat." Eric then tells the student that they are going to save the question for the next class. A researcher who observed this class wrote in their observation notes that the student continued to discuss the phenomenon as he left the room, and that overall the students and Eric were engaged in the lesson and appeared to be enjoying themselves (Observation Notes, 1/22/2016).

Another example of student engagement affecting instruction occurred when Fred perceived student engagement to potentially be correlated to what he called "mental exhaustion." Because he perceived his students to be cognitively fatigued and therefore less engaged, he considered instructional strategies for lessening the cognitive demand on students. This also illustrates another example of how more than one factor could be influence instruction at any given time.

Student-Student Interactions. In chapter one, I provided evidence that teachers provided students with opportunities to work with one another to process modeling tasks. In relation to that, it appeared that for each of the teachers, structuring those interactions sometimes affected modeling. Eric described how determining student groups was a challenge for him at the beginning of the year.

> This is one of the more difficult parts of the job because time is really figuring out what the appropriate groups should be. And I know that I don't do it that way. It’s the kids pretty much set it randomly. And then, as I get to know the kids, I might do a few isolated moves here and there. But to really figure out what’s going to work well as a group in those kinds of situations is really challenging. And that takes a lot of time and I feel like we don't have the time to figure that out. But I have a few groups where the kids have really come together well, and I don't want to break them up. But then, I have other groups where they're just like [shrugs]. (Eric, Interview, 9/24/15)

There was also an instance where lack of student-student interactions caused a change in instruction. Frances described how she added student-student interactions as a means for increasing student engagement in an activity. In her curriculum reflection following implementation of a series of lessons focused on developing a model of cellular respiration, Frances noted that she felt the materials were not as student-centered as she would like them to be; therefore, she gave students opportunities to work with one another or to share ideas with one another “just so students can get off their butts” (Curricular Reflection, 12/8-12/11/2015).

Student Struggle. All of the teachers described what they perceived to be students grappling to figure something out. As such, they seemed to think that it was an important feature of modeling instruction. Eric stated that,

> …there was also some strength in having them really struggle with it, where the kids were passing around [the graphs], and I heard some great discussions between kids where they were like, ‘well, wait a minute. Look at this.’ And they were really discussing

> what was going on in the graphs, and they were figuring that out…there was a certain power that came from that experience for certain kids. (Eric, Interview, 9/24/15)

In this quote, Eric posits that the experience in struggling with data provided students with points for discussion that helped with sense-making. Fred also considered this aspect of instruction important, but also suggested that teachers will need to step in and support the students. He said, "I think in the end, you just let them sink before you pull them back up again. And again, drowning is okay. Find little places to peak their heads above water. Little things that can pick them up" (Fred, Interview, 9/24/15). Parallel to Fred's comment about letting students struggle–to a point–, Frances noted that she felt it was "okay that [students] grapple over the questions, but if it starts to prevent them from sharing ideas that they do have, but they just can't understand the question, then that might be an issue (Frances, Interview, 10/14/15).

Student Understanding. The role of student understanding and its influence on modeling instruction was referenced by each teacher more than any other factor. This is not surprising given that conceptual understanding should be a product of modeling in science classrooms. However, it is interesting how some teachers tended to shift their instruction based on what they perceived concerning student understanding. For example, in a curricular reflection following generation of a model explaining photosynthesis, Frances wrote that students' explanations of the phenomenon contained "many misconceptions." To address this, she provided them with an explanation that allowed them to fill-in-the-blanks with missing words related to their model. She noted that the students were then able to accurately explain the phenomenon (Curricular Reflection, 12/15/15-1/13/16). Similarly, Catherine noticed during generation of a model explaining homeostasis that students were struggling to represent their ideas; therefore, on the last day of the lesson sequence, she had students write notes as she gave a traditional lecture. She noted that she had to work hard to make the lecture interesting, but ultimately she felt that students “got the information” (Curricular Reflection 2/16-2/19/16). Aside from illustrating shifts in instruction, these examples also highlight how student understanding and adapting and scaffolding can intersect through the course of modeling.

The teachers also described how they perceived students to understand modeling. Each teacher noted that they believed students understood the flow of the lessons; that each lesson started with a phenomenon, led to a question, and that they would generate a model that answered the question. Although, Fred mentioned that he thought students experienced some difficulty in tracking each of the components of a modeling lesson. Therefore, he began using a worksheet that he believed helped students to keep track of their ideas:

> I thought that my students kind of got the whole [phenomenon, question, model] thing by the end of the year. They were like, ok, that's the phenomena, now we're going to ask a question, and we're going to answer it. They could anticipate those moves and follow along with them…I think having that in there, so they see it all the time, now we're going here. Especially when you're doing something hard thinking-wise, they can kind of, ok, but we did this already, so we can do this. (Fred, Interview, 6/07/16)

In this excerpt, Fred states that since students were able to keep track of what they were figuring out, that it helped them to know where they were going, and were building on information they have already generated.

Apart from influencing in-the-moment instruction, sometimes teachers discussed student understanding in terms of students utilizing models to explain new phenomena they had observed. For example, Eric explained that his students were utilizing previously generated models to explain patterns of inheritance, which was the last model they generated in the academic year (Interview, 6/07/17). Similarly, Fred said that he noticed a change over the year in “students’ ability to utilize the information that they had to develop new information. To use the models, as they should be used, and apply them to new situations (Fred, Interview, 06/07/2016).” Moreover, student understanding was referenced when describing what it felt like to witness an “a-ha moment”. Lori described that one of her favorite parts of the year was “watching the kids truly interact together in groups where you see the lightbulb start to come on.” Here, we also see how providing students with opportunities to work together in groups was something that was valued by the teachers, especially when it led to student understanding.

Teachers’ Role. Overall, each of the teachers described what they perceived their role to be in the classroom and how their perception may have affected their instruction. Each noted the same kinds of instructional moves that we observed through our previous examinations of their praxis (see Chapter 2). For instance, they described the importance of students working together to process modeling tasks, the important of letting students generate their own questions and to share their ideas. However, “it would be a lot easier if I could give [students] the answers,” was a comment that Lori made in her interview at the end of the academic year. Despite this acknowledgement, later in the same interview, she said that she spent planning time on figuring out how to make her class student-centered (Lori, Interview, 5/1816). She said that,

> …you have to give them time to kind of figure it out. Push them in the direction sometimes, when you need to, and allow for that discussion time. Allow them to get those conceptual models in their heads or to see something on paper. (Lori, Interview, 5/18/2016).

Combined, these quotes suggest that Lori may have recognized that her role in the classroom should be that of a mediator, rather than being in the traditional role of providing students with information. Additionally, she concedes that being in that role is not easy.

Catherine also described some of the difficulties in mediating student ideas:

> …just getting them to come up with key ideas was really challenging. And so I was kind of in the middle. I had kids that would make really specific statements that I had to generalize and some kids that made really good general statements. And so I just let them share and the focus in that is encouraging sharing and participation and not shutting down anybody. There are ideas up there that are still not consistent with the model and they’re going to stay up there because that’s their initial model, that’s not our final answer. And so I didn’t find it necessarily to be as hard as I thought it was going to be

> because I also wasn't really focused on any one particular answer. (Catherine, Interview, 10/13/15)

Although Catherine starts by describing her role as challenging, she ultimately says that it was not as hard as she anticipated, potentially because she was not focused on students saying the correct answers; rather, she was interested in providing them a chance to generate their model.

Some of the teachers also recognized when their instruction shifted over the course of a model or a lesson. Frances, for example, indicated that this happened while enacting lessons for generating a model to explain photosynthesis. She described how up to that point in the year, she felt that she had flipped her classroom to be more student-centered, but that "this one felt like I flipped it back where I was still at the front of the classroom leading most of the way." However, she said that student ideas formed the foundation for what she discussed in those lessons (Frances, Interview, 6/07/17). When enacting the first modeling lessons, Fred developed a strategy to use when he recognized that he was shifting his instruction to be more teacher-centered. He said that if he felt that he was "inserting words into [students] mouths" then he would write what the student said on the board, and then move onto the next student idea (Fred, Interview, 9/24/2015).

Time Involved in Tasks. In a written response to a prompt that asked what the most challenging moment had been thus far in the year, Catherine wrote, "basically not having enough time" and that she once realized "in the middle of a class, during a lesson, that I was not prepared enough." (Written Prompt Response, 10/20/15). In general, time was a perceived to be a constraint by all teachers both in enacting modeling and in lesson planning. Fred noticed that as time involved in a task increased, he tended to become more evaluative in responding to students' ideas, sometimes providing them with more answers. During a stimulated recall interview, he mentioned that he had already spent a week longer on the photosynthesis modeling task than what he had intended, and that he was feeling pressured to cover content. When the interviewer asked him if he regularly felt pressed for time, he responded that he typically feels it towards the end of a lesson:

> …towards the end of one of these [lesson] segments where…you've got some people there and some people not there. You're trying to get it done, but knowing that if you want to get it done, and you want them to understand, then you've gotta push for two more days…And I know that it does take more time, but yeah, I mean, at some point you gotta run, because you have a lot of stuff to cover. (Fred, Interview, 1/27/16)

Frances also reported that she truncated students' opportunities to generate the model ideas when she perceived that modeling was taking too long. In her final interview, she described how her perception of a time barrier affected her instruction over the course of the academic year:

> …in the beginning, I feel like we had all the time in the world and as you start going through the end of the year, it's like, 'Oh my gosh, we need to get through this faster', you know? I feel like I took more time for students to generate ideas and contract their ideas as a class, and then contract their ideas as a series of four classes. Where later in the year, I didn't give them that opportunity. It's like, 'okay, I've contracted them for you, you know. These are the model ideas that all of the classes came up with.' So, yeah, I started to shave off the beauty of what it could be a little later as you know, I feel like, 'Oh, I gotta get it done.' The time thing, right? (Frances, Interview, 6/07/16).

Although she felt that she began to eliminate student voice at time, she ultimately said that she felt that she never shifted her instruction towards direct teaching.

Overall, each of the teachers noticed in their curricular reflections that instruction tended to take longer than expected. Even seven months into the school year, Fred was noting that conversations about ideas took longer than he anticipated and that he needs to "start learning to expect this" (Curricular Reflection, 3/2/16). Just two days later he said that "I never seem to get through these models in the estimated time, but I don't feel like I could go faster than I do without pushing students and not letting them develop ideas" (Curricular Reflection 3/4/16). This suggests that even though he found time to be a barrier to implementation and felt pressured to cover content, he ultimately valued providing students with the extra time to generate their ideas.

Lori also perceived time to be a constraint, but like Catherine, she felt that she did not have enough time for lesson planning. She said that this made her feel like a new teacher again, despite her knowledge:

> I've got the knowledge base, but I'm trying to follow a script that, now is not my own–to a point. And so, in doing that, I'm finding I have spent a lot of time in preparing what it is I want the kids to do. And what it is, I need to do to get them there. Whereas, I've been teaching a long time so I can come in and say, 'Oh, we're gonna do DNA.' Without thinking I can go, 'we're gonna do this and then this, and then, we're gonna do that lab.' (Interview, 6/07/2016).

In this quote, Lori is describing the difference between what she had previously been able to do when teaching science versus what she is doing now in enacting modeling. Her time spent planning made her feel like a new teacher, potentially because she was spending time considering what instruction would look like. Eric, described this challenge in terms of "cognitive load," stating that, "even with the curricular materials and the sequence given, it still takes a lot of time to plan. I think the first time you're doing any model, there's a huge cognitive load on the teacher." He also felt that he did not always "have a clear picture of the path" which "adds to the stress level" (Interview, 6/07/2016). Yet, at the same time, because he had previous experience in implementing modeling lessons, he stated that "I was probably able to fly by the seat of my pants."

Teachers' Views and Understanding of Science

Throughout the academic year, I observed and the teachers perceived how their understanding of science, including their content knowledge and their understanding of models and modeling, and their views of what counts as inquiry and authenticity to science, influenced their enactment of modeling.

Authenticity to Science. Authenticity was a topic that arose often throughout the academic year, and appeared to be something that Eric, Frances, and Lori wanted, and felt was foregrounded more during the year they enacted modeling than in years past. Based on the ways in which teachers described the curriculum, it is possible they took this view because it was based in real-world phenomena and included authentic datasets. Both Lori and Frances were the most vocal in describing that they wanted their students to be experiencing science as scientists do. Lori stated that in previous years she felt that her students were "missing the connection of how science really works in the real world" and that she understood modeling to "really connect the kids to real world science, versus a list of vocab and a little of what I call 'paper labs' even if its hands-on in the class. (Lori, Interview, 9/24/15)." Yet, at the same time, she noted that she was "more interested in producing critical thinkers" than scientists:

> I think that what we're doing by giving them data, by asking them to really assess what it means to create this, either conceptual model or maybe it's physical in the future. So, that they can really understand and then be able to maybe explain to somebody else. (Lori, Interview, 9/24/15)

Later, at the end of the academic year, Lori continued to explain that authenticity was an important feature of the modeling curriculum:

> MBER biology is utilizing real world phenomenon that the kids can look at, see, and start with questions before we give 'em the answers. So, in understanding that science is – it's phenomenon. It's the best scientists, you know, see something and wonder why. And, getting the kids to think critically about their world, not just to say, "Well, I was told this is the answer. So, this must be the answer. (Lori, Interview, 5/18/16)

Frances also was vocal about ensuring that her instruction was authentic to science, and she even voiced this to her students. While implementing the first modeling lessons of the year, she provided students with a set of data for them to analyze and interpret. As she did so, she told them that they would be creating an explanation "not something that is made up, but that is based on the evidence that you pull out of those graphs. You're doing exactly what scientists do. (Frances, Video Recording, 10/06/15)." She reiterated this point at the end of the academic year, relating what she does in the classroom to her previous experiences as a researcher in biotechnology:

> [Students] are trying to come to some understanding based on the data and it's really refreshing for me to see this change, and I think it is most authentic to my work as a researcher that I used to do. When I'm thinking my job like ten years ago in the biotech industry, it is like what we're doing in class with MBER. It's sharing those ideas about proteins, or about you know, antibiotics. We don't know the answer but we're trying to co-create a group understanding. (Frances, Interview, 6/07/2016)

Thus, it is possible that based on teachers' discourse, that they perceived authenticity to science to be important, potentially influencing their continued enactment of modeling in their classrooms.

Teachers' Content Knowledge. Overall, each of the teachers in this study held a science-related degree and a credential in biology; however, Eric and Frances described moments in their instruction where their content knowledge sometimes fell short and affected their implementation of modeling. When he joined the MBER project, Eric was only in his third year of teaching biology; his previous seven years of experience were in teaching earth science. However, he had participated in a previous modeling research project and had prior experience in implementing the modeling lessons focused on natural selection. In an interview, he explained that he felt that his implementation of the natural selection lessons most aligned with his understanding of modeling and that he was most confident in his ability to teach it. But that,

> …when we got to talking about inputs and outputs, I had never done any of those things that way, and I loved it. But, I wasn't as comfortable so I guess I didn't know what the end result was going to be as well. (Eric, Interview, 6/07/2016)

Eric suggests that his inexperience in teaching biology, and having to reorient his understanding of cellular processes to include the ideas of inputs and outputs, could have affected his instruction because he was not clear of what the end product should be. Similarly, when discussing implementing lessons focused on generating models of inheritance, Frances noted that she found the model ideas to be confusing, which then led to students' confusion (Interview, 6/07/16). In addition, when facilitating generation of a model explaining natural selection, she told the students that even she struggled to interpret the graphs (Video Recording, 10/08/15).

Teachers' Understanding of Models and Modeling. When asked what model she felt best exemplified what modeling could be in the classroom, Lori stated two models: photosynthesis and cellular respiration (Interview, 5/18/15). However, earlier in the academic year when she implemented the cellular respiration model lessons, she said she was unsure of how things were going in her classroom and asked the researcher observing her whether or not her instruction was what we expected of model-based reasoning (Observation Notes, 1/07/2015). In her interview, however, she said it felt like modeling because she "did a good job of taking something so hard to visualize like molecules and atoms." However, when asked to describe what the modeling curriculum is, without the context of content, she primarily described it as a process of figuring out something about a phenomenon. This was typical of each of the teachers' descriptions of modeling and/or the modeling curriculum. Frances said that she described modeling to her students in the following way:

> I said, you know, this is what scientists do. And I said, you don't have to agree on that model. Either parts of it you may not, you know, feel like should be in there or it's not clear, but this is what we've come up with out of 150 students. And I said you guys are thinking like scientists. You're developing this knowledge or refining the knowledge you already have. And this is putting inquiry at the center, this is what we're doing for the year. It's not so much about having the exact right answer or having the piece of the model written exactly like I wanted you to write it. It's about the thinking process, the defining process. (Frances, Interview, 10/14/15)

Fred, made a similar statement, saying that, "…it's more of a process than a series of knowledge. It's learning how to take ideas and synthesize them into a model that you can apply to other novel situations" (Fred, Interview, 6/07/15). These quotes also exemplify the interaction between teachers' perceptions of the importance of instruction that is authentic to science and their understanding of modeling.

In addition to describing modeling as a process, the teachers also demonstrated knowledge of what models can be used for and their interrelatedness. For example, Fred demonstrated an understanding of the uses of models when he described how he asked his students to apply a model to a novel phenomenon that was not included in the curriculum:

> We played a short, few minute clip of the rock [pocket] mouse and they did a little snippet about it and I just had them go through and match their working model point by point to see if they could find the same things, those same ideas in their [explanations]. (Fred, Interview, 9/24/15)

And, Catherine recognized how models can work together:

> …it's like you can take any model and figure out how other concepts get woven in. And so once I started seeing that in the natural selection model, which I think I had them doing the longest, it started opening up that vision to me about how to connect all the ideas. (Catherine, Interview, 6/07/16).

Teachers in this study were also aware of the difference between a model and a representation, such as when Eric described that he realized his students did not understand the difference between a conceptual model and a representation (Interview, 9/24/15). Catherine also illustrated that she recognizes that there may be a difference between a model and an explanation:

> …a story is a model. 'I'm asking you to use the data provided and then fill in the blanks with inferences.' So when I say write a story I'm saying write a model. And when I put it that way I think [students] understood that that was what we were doing. And then the work has come up intermittently with the idea of an explanation or a story or a model. (Catherine, Interview, 9/24/15)

In this quote, Catherine is describing that when she talks to her students about writing a "story," what she is asking them to do is to generate a model that is based on evidence.

In their discussion of models and modeling, all five teachers also described the importance of the phenomenon, the driving question, the model, and their relationship to student ideas. As an example, Fred wrote that teachers should know that the connection between the phenomenon, question, and model are important:

> …the phenomenon must stay central to instruction and student thinking about the phenomenon needs to drive the direction and pace of instruction. That thinking takes time and if a teacher pushes past the thinking to the answer then the approach does not work. Neglecting the questions about the phenomenon leads to students being lost as to what they are doing. (Fred, Written Prompt Response, 6/7/16).

Coincidently, Fred was able to point to two examples of enactment where he felt that the students were unclear of what they were modeling, because no clear question had been developed. The first occurred when he was implementing the photosynthesis model lessons–the same lessons where Frances noticed that her classroom was becoming more teacher-centered, and where Lori felt conflicted about whether or not her students were engaged in model-based reasoning. In this case, Fred stated that after students had applied their model to explain a phenomenon (where does the matter come from that allows an acorn to grow into a tree?), he realized that they had never generated a clear question to guide their exploration of the phenomenon. He said the students had only asked "do plants eat?" He went on to say that the question was too broad and needed to be further defined; therefore, he facilitated a discussion to help students "go backwards in order to think about the question they were trying to answer" (Fred, Interview, 1/27/15). Fred may have realized that the ideas he helped the students to generated were similar to those prescribed in the curriculum, but that did not necessarily answer the question generated by the students. The second example occurred when he was facilitating lessons to generate a model to explain how organisms within an Ecosphere get the matter and energy they need to survive[7]. Fred did not have students generate a driving question, and wrote that it was interesting to see the variation in ideas the students voiced about the pattern they had identified (Curricular Reflection, 3/1/16). Aside from indicating that teachers can recognize the

[7] www.eco-sphere.com

implications of incorporating student' questions and ideas about phenomenon, these examples also suggest that curricular materials also play a role in teachers' understanding of models and modeling.

Teachers' Perceptions of the Roles of the Curricular Materials

Each of the five teachers described three curricular components that may have affected their instruction: assessment, curricular planning, and the iterative nature of the curriculum. However, curricular planning was primarily discussed in terms of the amount of time it took to plan for and enact instruction. Here we focus solely on assessment and the iterative nature of the curriculum.

Assessment. Each teacher described the role assessment, or the lack thereof, played in enacting the modeling curriculum. When teachers discussed assessments, they were describing both summative and formative assessments. The summative assessments they talked of did occur or could have occurred following the enactment of a model triangle or at the end of their fall and spring semesters. Summative assessments that took place at the end of a series of modeling lessons, typically took the form of a "model application question" where students would apply their model to a new phenomenon. An example of a summative assessment that was provided in the curricular materials is called "The Biggest Loser." For this assessment, the students were provided with the following prompt:

> All matter transformations must obey the laws of conservation of matter and conservation of energy. Keeping that in mind and using what you have learned in class, explain what happens to the matter and where it goes when a man loses 215 lbs.

Formative assessments included the day-to-day means through which the teachers could have uncovered student thinking. One way that Lori, Eric, and Fred did this was through what they called "openers", where a question was displayed as students entered the classroom. While students waited for class to start, they would answer the question in notebooks. An example of an opener that was used in Fred's classroom was:

> In a mountain valley, there lives a population of marmots. There is a flowing river and plenty of rocks for them to burrow under, there is only a small amount of the grass that they eat. If the population cannot leave, how would you expect the population to change over time in general? What atmosphere does the limited grass create for marmots when their pups are born in the spring and their population triples? (Fred, Observation notes, 10/15/2015).

In his curricular reflection for the day he utilized this assessment, he noted that he thought it "led to a great discussion about why having limited resources is important to our explanation of species change. (Fred, Curricular Reflection, 10/15/2015)." He continued to use these openers in every class that was observed, and in an interview stated that he used them as a means to "help them see what they already know" (Fred, Interview, 1/27/2016).

Generally, all teachers in this study did not talk as positively about assessment as Fred does in the above quote, and by the end of the academic year, Fred exhibited frustration with them:

> I was going through my gradebook at the end of the year, and I was like, what am I basing my grades on? There was just not much there. Um, so, I did a final exam and I did the full multiple choice, kind of went through everything since fall final and tried to be more kind of conceptual, but also tried to include more vocabulary. It was a little rough. I don't know. Just assessing them because, what I was asking them to do? To memorize all this stuff or to use it? (Fred, Interview, 6/07/2016).

In this quote, Fred is struggling with two challenges regarding assessment. The first is that he felt that there were not enough assessments for him to provide his students with a grade. The second challenge was what to assess or how to assess students. Both of these challenges were also described by Catherine, Eric, Frances, and Lori. For example, Eric described the lack of assessment in his first interview that followed enactment of the model of natural selection. He was concerned about what to discuss at parent-teacher conferences due to the lack of grades he had collected:

> What am I supposed to say to them? ‘Your kids are doing awesome because they're thinking in class?’ But, I don't have anything that actually supports what’s going on because I'm not collecting a lot of work from them. (Eric, Interview, 9/24/15)

Although Eric appears to have a positive outlook on the reasoning students are doing in class, he is concerned that he does not have grades to support his claim that the students “are doing awesome.” A potential explanation for this comes from Lori, in the form of a written response to a prompt. At a meeting held with the teachers towards the end of the 2015-16 academic year (M4, see table 1-2) the teachers were given a prompt that asked them to list challenges they faced with assessment. In her response, Lori wrote that she had difficulty with the “timing of summative assessments” and that she continued to search “for that ‘unit’ break” (Written Prompt Response, 5/18/2016).

In regard to the second challenge noted by Fred and the challenge noted by Lori in finding a break for assessment, all teachers wrote statements or described in interviews the problem of when to assess and how to assess students. For instance, Catherine said that,

> I was making up my own assessments which I thought were great and then [students] would just bomb them. Which isn't unusual. I mean, I've seen that in past years, but it's discouraging because I feel like so much learning is happening, but why aren't we getting there? (Catherine, Interview, 6/7/17)

Similarly, Frances and Lori had difficulties in creating assessments. Lori noted that she found it hard to create good questions that aligned with the modeling lessons (Written Response to Prompt, 4/26/2016), and Frances noted that multiple choice questions she has used do not necessarily reflect the reasoning students can do with a model (Written Response to Prompt, 4/26/2016). Similarly, the teachers all appeared to recognize the value in giving students an outlet to write model-based explanations; however, they all wrote or described in interviews that multiple-choice questions were easier to grade and took less time.

Another issue related to how to assess students is the tension between assessing group learning and assessing individual learning. In chapter one, I found that the teachers provided students with many opportunities to process modeling tasks together in groups, but in the following quote, this leads to concerns about how to identify individual learning:

> You're not turning in a group [worksheet]. You can discuss, you can grab answers from your teammate, you can do whatever you want. But, you, are accountable for showing me, in your own words, what you got from the process (Lori, Interview, 9/24/2015).

Comparably, Catherine in her first interview said that "group accountability has a very different feeling than individual" (Catherine, Interview, 10/13/2015). I found that this tension between group and individual assessment remained at the end of the academic year; however, Lori and Eric worked together to create a final examination that included both an individual and a group component. In groups, the students worked to identify an inheritance pattern in a complex pedigree. They were given opportunities to discuss it, and then were asked to individually write a model-based explanation. Lori explained that this was more reflective of science and of what students had done all year: "Allowing them to think out loud, 'cause, we've let them do that all year…That's kind of how science is. We don't just secretively have this great idea and I can't share it."

Iterative Nature of the Curriculum. Less commonly discussed than assessment, yet described by all five teachers, was the iterative nature of the curriculum. As a design principle, we foregrounded evolution as the central model for the curriculum so that across the academic year, students could develop models that would could provide opportunities to better understand mechanisms for evolution. That students could continue to extend their understanding for this important biological process was something that the teachers described as important in their implementation. Lori perceived that this was atypical of other biology classes, stating that, "traditionally, doesn't always do that" (Lori, Interview, 5/18/16). Additionally, she stated that students were engaged, potentially because of the "way [the curriculum] played out…and how we're coming back and forth throughout the lessons." Catherine also noted that the "spiraling" in the curriculum was one of its biggest strengths (Interview, 6/07/16).

Fred discussed this aspect of the curriculum, but rather than talking about it in terms of the interrelated models and the opportunities for building connections across them, he discussed it in terms of energy and matter. He said that he felt that the lessons focused on those concepts,

> …had the most heft to it that you could take and run with in other places. Because I think that energy kept coming back. I mean, that's one of the threads that we're supposed to follow through this curriculum. And like it's one of the NGSS threads. It's one of the big ones through biology. That was something [students] could hang their hat on. They understood that matter and energy were related because of that. (Fred, Interview, 6/07/16).

Catherine's, Fred's, and Lori's insights concerning the different kinds of connections across the curriculum also serve to illustrate the different curricular interpretations that can influence modeling instruction.

Another Factor That Might Be Affecting Implementation of Modeling

Although I found that the majority of factors that teachers described related to four core themes, there was another factor mentioned that did not fall within these categories. Catherine, Eric, and Frances both described how collaboration was an important feature of the modeling curriculum project. Eric, when describing the time spent on planning, said that he would sometimes turn to Lori for help. Lori's classroom was next door to Eric's and throughout the year, they collaborated often and shared lesson plans. Eric described this by saying,

> [Lori] is much more organized than I am and I know she spent a lot of time

> really getting it organized and thinking it through, and that probably actually helped me because we collaborated a lot. And there were probably times where I just got overwhelmed focusing on one of my other class periods and I'd go over to [Lori's] room and she'd say, well okay here's what I did, and I'm like, oh perfect, that makes sense. And that eased some of the thought process for me. (Eric, Interview, 6/07/16).

Fred, Eric, and Lori taught within the same school district and also shared their curricular materials with one another via Google Classroom. Catherine's and Frances' classrooms were also next to one another, and they collaborated often on curricular planning along with a co-designer of the curriculum whom also taught at the same school.

Ultimately, my findings suggest that teachers' implementation of modeling was impacted by a variety of factors that were intertwined in complicated ways. It is important to recognize, however, that the broad categories I identified and the subfactors wherein are not necessarily mutually exclusive. Some factors could be placed within more than one category, illustrating that there are varied and intertwined factors at play that affect the implementation of modeling. In the discussion, I will further consider the factors and explore their relationship to the act of modeling.

Discussion

This study explored a series of factors, observed by us and perceived by teachers, that may have influenced enactment of modeling in high school biology classrooms. Figure 3-3 illustrates the four main categories of factors in relationship to the perceptions of modeling framework. They overlay the framework as a means to represent how they could affect the portrayal of modeling. In coordination with the instructional moves that teachers used to mediate modeling, uncovered in Chapter 2, I focus this discussion on the factors that may have affected the use of those moves, and how those moves are related to the perceptions of modeling framework. As such, I focus on alignments and misalignments: alignments where what teachers describe models and modeling to be and what they do in the classroom aligns with their conceptions; and misalignments where what teachers said were not reflected in their moves. Moreover, I return to the discussion outlined in Chapter 2 and consider some of the possible reasons for why teachers were not consistent in utilizing modeling as a means for engaging students in sense-making, and thus affecting the portrayal of modeling in their classrooms.

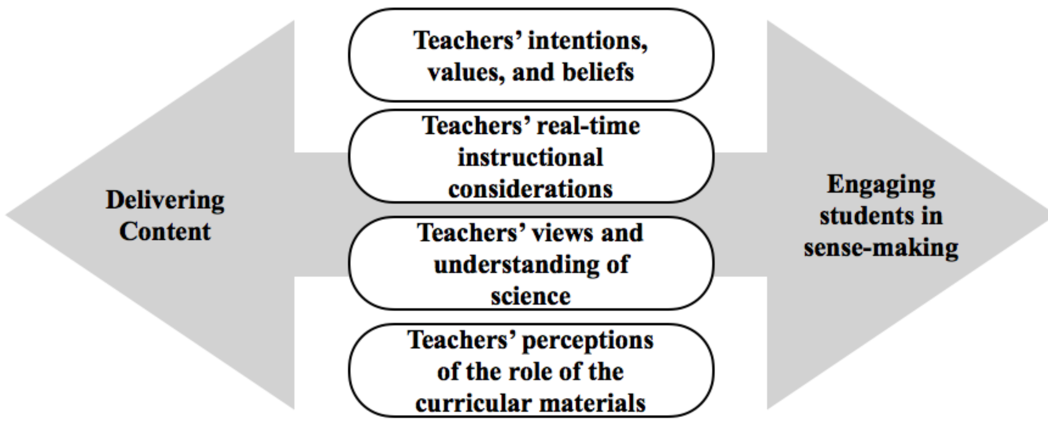


Figure 3-3. The perceptions of modeling framework and the factors that may be affecting implementation of modeling in high school biology classrooms.

Factors Influencing Instruction Result in Salient (Mis)alignments

Through analysis of teachers' instructional moves (see Chapter 2), I found that there were inconsistencies in the actions teachers took to move instruction forward. The inconsistencies manifested as opposing moves used throughout the course of instruction: sometimes teachers would use moves that aligned with engaging students in sense-making and at other times would utilize moves that constrained sense-making. As a result of utilizing opposing moves, the teachers were not consistent in their use of modeling as a means for engaging students in sense-making (see chapter 2, p. 59). Despite these tendencies to occasionally shift instruction away from student sense-making, the teachers did continue to use instructional moves that provided students with opportunities to engage in modeling for explaining phenomena. For example, all of the teachers prioritized providing their students with time for working together in groups to process modeling tasks and for providing students a space to publicly share their ideas. Factors possibly aligned with these moves are the teachers' beliefs about students' capacity, the importance of a supportive classroom culture, and their understanding of models and modeling.

Providing students with opportunities to collaborate and make sense of ideas was an intention set at the beginning of the year when the teachers in this study focused on fostering a supportive classroom culture, a factor which appeared to influence instruction across the academic year. The teachers discussed the value in providing these opportunities for sense-making, and given that the teachers volunteered to participate in this project and were willing to transform their instruction to a model-based approach for an entire academic year, the actions illustrate a sustained commitment to student sense-making. On the other hand, these opportunities for collaboration represent an important, yet easily made, instructional shift that can have consequences for sense-making. That said, the teachers generally held positive views of students' capacity to engage in the modeling process, and believed that students needed to "struggle" with data in order to develop conceptual understanding. They noted the importance of students being at the center of the process and that their ideas and questions should drive instruction, all of which are instructional elements that align with agent-based conceptions of model-based reasoning (e.g., Gouvea & Passmore, 2017; Passmore et al., 2014). In addition, our focal teachers noted the importance of modeling being representative of authentic science and could elaborate on what it means to engage students in modeling and could articulate the paradigm behind the modeling curriculum. Therefore, there are multiple factors that teachers said in their interviews, reflections, and written responses to prompts that aligned with the instructional moves that they utilized.

However, we did notice instructional moves that constrained student sense-making, which, coincidently, could have been affected by some of the same factors that afforded student engagement in the modeling process. Thus, we also observed misalignments in what the teachers said influenced their instruction and then what was done in the classroom. For example, each of the teachers in this study described what they believed to be the value of engaging students in model-based reasoning and also described the reasoning students could do, but they also described scaffolds or instructional adaptations they made that may have oversimplified the tasks, potentially limiting student sense-making. For example, I found that the overly structured word bank example that Frances discussed (see p. 92) could have removed students from the sense-making process. Similarly, in a study describing factors affecting implementation of argumentation, McNeill et al. (2016) found that teachers self-reported positive views towards students' ability to engage in argumentation; however, they also created or described the needs for supports that could have reduced the intellectual demand of the task. In an earlier study, McNeill (2009) also describes how reducing the complexity of a task could be a means for removing students from the sense-making process. The scaffold created by Frances might not motivate the need for a model to develop an explanation of a phenomenon, thus decreasing the intellectual demand originally built into the model-based explanation task. Despite describing her students' ability to engage in modeling tasks, Frances, through the actions she took, demonstrated a possible misalignment in her views of students' capacity when overly scaffolding modeling tasks. As such, these conflicting moves may have impacted the portrayal of modeling. Figure 3-2 depicts this misalignment, and how beliefs about students' capacity may interact with the instructional moves (as indicated by the arrow between boxes). Moreover, the figure illustrates how the over-scaffolding of tasks has the potential to shift instruction away from engaging students in sense-making towards more of a focus on the delivery of content.

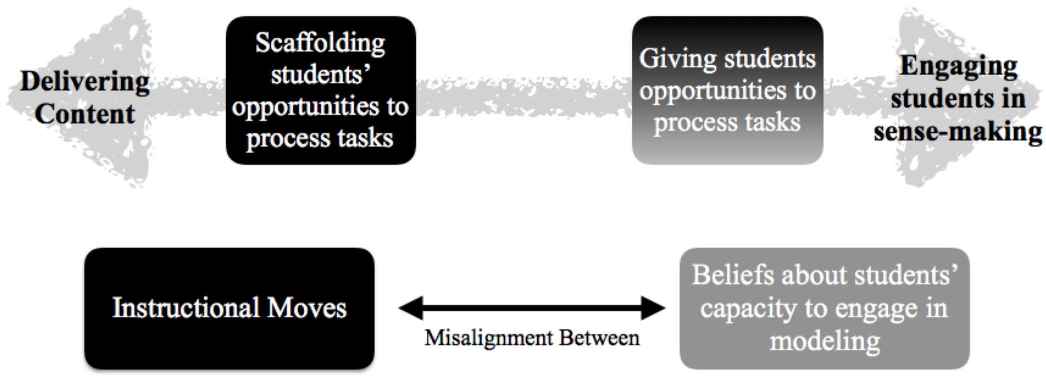


Figure 3-4. *Depiction of the misalignment between beliefs and instructional moves, and how the misalignment could affect student sense-making.*

In addition to shifting beliefs about student capacity, time constraints may have also influenced how teachers enacted modeling in the classrooms we observed. Fred described that he would focus more on content, particularly towards the end of a series of lessons and when the lessons lasted longer than he anticipated. Frances noticed that over the course of the academic year, that she provided students with fewer opportunities to share their ideas, and that she would provide them with the model, rather than it being student-generated. Studies examining factors influencing science instruction suggest an interaction between positive beliefs and time (e.g., Beck, Czerniak, & Lumpe, 2000; Loughran, 1994; Roehrig & Luft, 2004), with time constraints superseding positive beliefs towards student capacity. For example, Roehrig and Luft (2004) found that when teachers perceived time as a constraint they described providing students answers, because they were concerned students may not have come up with the "correct answers" quickly enough. As Lori admitted in her final interview with us, "it would be a lot easier if I could just give them all the answers and we could move through the year (Interview, 5/18/17).” Figure 3-3 illustrates the misalignments that may have been impacted by the time involved in tasks. In this figure, I depict the interaction between the instructional moves and time, suggesting that when teachers gave students opportunities to process tasks and let students share ideas, then their instructional was more student-oriented and focused on their participation in sense-making. However, when teachers perceived that too much time was spent on a task, then they may have started to limit students’ opportunities to collaborate, by being more evaluative in their responses through providing answers or identifying flaws in their reasoning (see chapter 2, p. 62). Thus, potentially shifting modeling as a means for engaging in sense-making towards a means for delivering content.

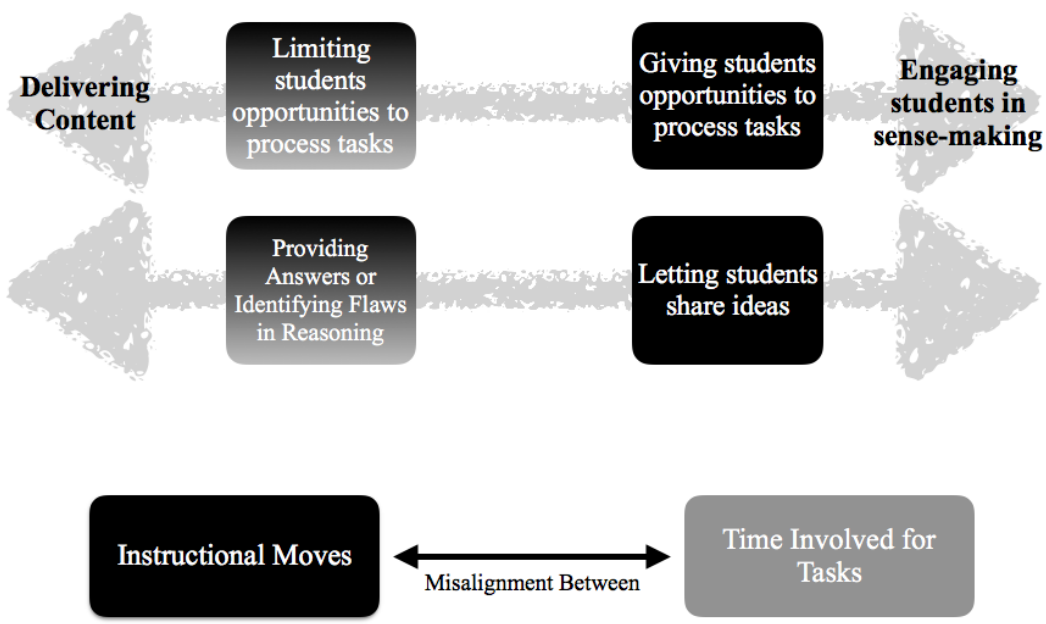


Figure 3-5. *The misalignment between perceived time involved in tasks and its influence on instructional moves and student sense-making.*

These misalignments bring to bear two important questions that warrant further investigations. The first is what kinds of pedagogical supports are needed to help teachers focus their attention on productive uses of instructional time during the enactment of modeling? It is clear that teachers felt that providing students with opportunities to process tasks and to let them share ideas was an important feature of modeling; however, when they perceived time to be running low they sometimes began to focus more on the delivery of content. Supports that could help teachers to prevent the constraining of sense-making could prove useful in modeling classrooms. In addition, research suggests that teachers must see obvious changes in student learning outcomes in order to change their beliefs (Clarke & Hollingsworth, 2002; Guskey, 1995); however, the teachers in this study did articulate observing differences in students learning through this curriculum versus in previous years of instruction. Yet, the misalignments in instruction existed. Thus the second question that arises from these misalignments is how to overcome teachers' perceptions of students' ability to engage in scientific practice?

The Importance of Interacting with and Enacting Reform-Based Curriculum

Curricular materials are an important means for providing teachers with learning experiences (Ball & Cohen, 1996; Kazemi & Hubbard, 2008), including in learning about practices-based instruction (Arias, Bismack, Davis, & Palincsar, 2016). The findings of our study illustrate the importance of curricular materials for enacting reform-based instruction, but also highlight how curricular materials can help teachers to recognize when their instruction may be affording or constraining opportunities for students to engage in sense-making. Through their interviews, curricular reflections, and written responses to prompts, Catherine, Fred, and Frances all noted perceived changes in their instruction. For example, Catherine lectured her students when she perceived a modeling task was not effective for student learning, and recognized that the change in her instruction may have led to decreased student engagement. Frances said that she could recognize when there were fewer student-to-student interactions in her classes, and began to provide more opportunities for students to discuss problems or tasks together. And, Fred, recognized the importance of a driving question in helping to bound the kinds of ideas students shared; this realization arose when he did not have students generate a driving question to assist in the development of a model concerning matter and energy in ecosystems.

The teachers' perceived lack of embedded assessments within the curriculum demonstrates the pressure that teachers feel to assess students for the basis of grades; rather than to assess their learning. All of the teachers in our study gave students opportunities to share their ideas and to make their reasoning public to the classroom community, through dialogue, through "gallery walks", or simply in writing their ideas down in their notebooks or on worksheets, all of which could be considered a type of assessment. Clement (2008) describes how fostering classroom discussions; promoting and setting aside ideas, and providing feedback on reasoning, all of which were mediating moves observed in our study, are a form of assessment in modeling classrooms. However, when the teachers described assessment in their interviews, reflections, or prompts, they were primarily discussing frustration in the lack of summative assessments, concern about when to give summative assessments, or disappointment in students' performance on summative assessments. At the same time, it is not surprising that teachers feel pressured to give summative assessments considering that they are held accountable not only by their administrators, but also by parents and often the students themselves. Take for example, Eric's lament (noted on p. 114) that his students were "doing awesome because they're thinking in class," but that he had no evidence to support the claims and show the parents. Moreover, the teachers expressed a tension in reconciling traditional multiple-choice tests of individual understanding and the kinds of group reasoning and processing that were happening while students were generating models. All of these concerns around assessment in modeling classrooms, point to the need for a shift in what is considered "assessment" in the classroom, particularly for NGSS aligned instruction.

Additionally, the role of time in considering and planning for enactment was a point of concern for some of the teachers in this study. This potentially limited their own sense-making of the materials, such as when Catherine reported that she realized in the middle of a class that she was not prepared (Written Prompt Response, 10/20/2015), or when Eric mentioned that he sometimes did not have a clear idea of the path the lessons were taking (Interview, 6/07/2016). On the other hand, given that the teachers tended to utilize the same kinds of modeling and mediating moves (see Chapter 2), it is possible that the materials communicated to the teachers, techniques for achieving an instructional end, which is an important feature of educative materials (Davis & Krajcik, 2005; Schneider, 2012). However, this was not an explicit focus of this study and is another potential leverage point for further investigations into the uptake of practices-based curriculum. A final note concerning the role of the curriculum is that the teachers recognized the role of their experience in enacting scientific practice and its effect on their instruction, which Coenders and Terlouw (2015) describe as a potential positive consequence of implementation. Examples of this occurred with both Catherine and Eric noted that having enacted modeling lessons before gave them a possible advantage. Catherine said that it made her feel more confident in altering the curricular sequence and changing the curricular materials, and Eric indicated that his prior experience in modeling allowed him to "fly by the seat of his pants" more so than others in this study.

In sum, it is important to recognize that changing instruction from traditional-oriented approaches towards a more practice-oriented approach is going to require teachers to shift their instruction (Reiser et al., 2017), and in this study I described multiple factors that could affect these shifts and that ultimately illustrate the complexity of such an ambitious pedagogy. The factors subsumed by the four categories described in this study represent affordances and constraints that illustrates that teachers are operating against potential barriers. Thus, it comes as no surprise that multiple factors can be perceived to affect a single instructional move and influence the ways in which students are or are not engaged in modeling for sense-making.

Limitations and Conclusion

The practices of scientists are complex, as are the contexts in which teachers attempt to translate them. Teachers' experiences both in the classroom and with science and their participation in model-based reasoning professional development undoubtedly contributed to the ways in which they portrayed models and modeling to their students. I have made every attempt to describe and categorize potential factors that might contribute to teachers' implementation of models and modeling based on the data we collected; however, we may never fully understand the range of variables, intentions, or circumstances that influence classroom instruction because of its inherent complexity. Moreover, I focus solely on the perspective of the teacher, thus I do not discuss student perceptions and the role it may play in implementation of modeling. Students' perceptions undoubtedly play a role, considering that they still tend to view their teachers as knowledge authorities instead of seeing themselves as having the capacity to develop their own understandings of science (Ford, 2008; Herrenkohl, Palincsar, DeWater, & Kawasaki, 1999). As a researcher, I can only characterize and describe the instruction as I perceive it in particular contexts in order to contribute to the emerging literature and to better understand how to best facilitate modeling. Although I identify and described these factors separately in the findings, I recognized that each of these factors are inherently connected and are thus sometimes difficult to differentiate. I have noted those places where applicable.

The goal of this paper was to characterize and describe the types of factors that may be affecting implementation of modeling in high school biology. There are several factors that could have influenced the enactments of modeling that I observed in the high school biology classrooms we examined. Moreover, the interplay that I found between factors illustrates that beliefs, intentions, views, and understandings of science instruction is more complex than simply having a knowledge-as constructed orientation versus of knowledge-as-transmitted orientation (c.f., Zohar, 2008). Many factors could be influencing instruction and this study was my attempt at mapping how those factors could have shifted instruction along a continuum of what it means to engage students in modeling.

Chapter 4 Modeling Phenomena in High School Biology: A Focus on Sense-Making

Abstract

In this practitioner-oriented chapter, I discuss how the coordination between phenomena, questions, and models can serve as a framework for designing and enacting lessons with a focus on student-sense-making. Drawing on examples and findings from research into teachers' implementation of a model-based curriculum, I present the framework with respect to the instructional moves and strategies teachers can use for facilitating instruction that positions students as the disciplinary authorities in the classroom. I situate the examples and strategies within the context of a model-based lesson that promotes students' sense-making about classical genetics.

Introduction

As educators across the nation move forward in implementing the vision set forth by the *Framework for K-12 Science Education* and the *Next Generation Science Standards* (NGSS Lead States, 2013), particular challenges are emerging concerning how to best integrate the three dimensions of NGSS (Reiser et al., 2017). One challenge arises from the expectation that teachers should be providing students with opportunities to explore and answer questions about phenomena by engaging in scientific and engineering practices (Reiser et al., 2017). Moreover, Reiser et al. (2017) state that "to develop and use explanatory ideas," in ways that scientists do through scientific practices, "students need to focus on investigating and explaining *how* and *why* phenomena occur as they do in the natural world" (p 281, emphasis in the original).

Understanding of the natural world stems from interactions and experiences with the environment (Dewey, 1938; Piaget, 1929), and scientists' explorations of the natural world are oftentimes a result of these interactions and experiences. Consequently, at its most fundamental level, the scientific endeavor is about explaining natural phenomena observed in their environment. It stands to reason, then, that for students to be engaging in science in ways that parallel the work of scientists, they should be given opportunities to participate in scientific practice as a means to make sense of the world around them (National Research Council, 2012; Schwarz, Passmore, & Reiser, 2016). As such, they should be provided with opportunities to develop and test ideas about the underlying mechanisms that cause phenomena to occur (Chinn & Malhotra, 2002).

One of the ways that students can explore the causes of phenomena is through the development and use of scientific models, also known as modeling (see chapter 2, p.17; chapter 3 p. 69), a core practice outlined in both the Framework (National Research Council, 2012) and

NGSS (NGSS Lead States, 2013). As a scientific practice, it is described as a means through which scientists "visualize and understand a phenomenon under investigation (p. 56) and through which they "represent their current understanding of a system (or parts of a system) under study, to aid in the development of questions and explanations, and to communicate ideas (p 57)." Broadly, models are sets of ideas, based on evidence that serve as a framework for generating explanations that answer questions about natural phenomena (Gouvea & Passmore, 2017; Passmore et al., 2014).

When students are engaging in modeling, they are generating, refining, and evaluating their own understandings about a phenomenon under investigation (Passmore et al., 2014). This requires a shift from traditional forms of instruction towards a more student-centered orientation (Halloun, 2007). However, as I have illustrated in previous chapters (see chapters 2 and 3), how teachers enact modeling in their classrooms has consequences for students' engagement in sense-making. Instruction is sometimes inconsistent, shifting between using modeling as a means for engaging students in sense-making—a student-centered approach—and utilizing modeling as a means for delivering content—a teacher-centered approach. This chapter then, uses findings from chapters 2 and 3 to discuss how teachers can design and enact modeling with a more consistent orientation towards supporting student sense-making about phenomena. I first describe a framework that foregrounds student participation in scientific practice, and then provide examples from our model-based curricular development project to illustrate how teachers can shift instruction towards engaging students in sense-making.

The Phenomenon-Question-Model Framework for Supporting Modeling

The phenomenon-question-model framework, or PQM, is based on a definition of modeling that considers the practice a means for developing a model for generating explanations that answer questions about phenomena (Gouvea & Passmore, 2017; Passmore et al., 2014). Thus, in designing lessons focused on student sense-making, teachers should consider the phenomenon students will explore, the question students will ask of the phenomenon, and what is the model that helps the students to answer the question about the phenomenon. Figure 4-1 diagrammatically represents the PQM framework as a triangle depicting the relationships between the four components of modeling. In the center is the student, who is doing the sense-making, considering questions about the phenomenon that they answer through developing a model. Thus, the PQM framework positions students as the disciplinary authorities in the classroom. The students' centralized role in modeling is in contrast with traditional forms of teaching "school science" where teachers are typically considered to be the knowledge holders in the classroom (Ford, 2008).

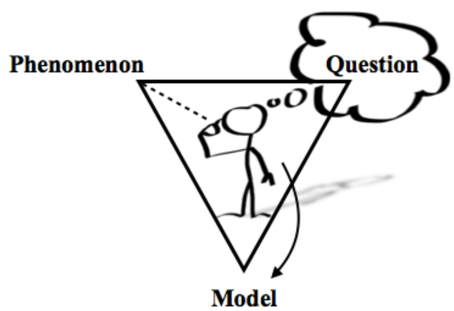


Figure 4-1. *Representation of the Phenomenon-Question-Model (PQM) Framework.*

The phenomenon and question about the phenomenon are placed at the top of the diagram, because they typically serve as the initial means through which teachers engage students in modeling. In science, naturally occurring phenomena are often the source of wonder and intrigue that help to focus the analysis of an investigation. In the classroom, phenomena can serve as puzzling aspects of the natural world for students to observe and wonder about. Similarly, they provide an anchor for student interest and engagement (Cognition and Technology Group at Vanderbilt, 1992; Krajcik, Czerniak, & Berger, 1999; Rivet & Krajcik, 2008). To be productive, phenomena should be accessible to students through either pictures, observations, measurements, text, or experiments. In any case, there should be accessible data of some form in which students can identify patterns. A teacher who enacted the model-based curriculum noted the importance of phenomena in her modeling lessons. She described that phenomena were used, "as a kind of starting point…and explaining the patterns in that phenomenon is what our purpose is." In modeling classrooms that centralize student sense-making, phenomena are events that can be *figured out* or *reasoned about* rather than simply *learned about* (Gouvea & Passmore, 2017; Passmore et al., 2014).

Upon observing and identifying a phenomenon of interest, students may begin to ask questions that they wonder about. *How* and *why* questions are especially meaningful in modeling because they allow students to begin to understand the underlying causal mechanisms that explain why the pattern(s) exists or what caused the pattern(s) to arise. Moreover, in modeling classrooms, the question(s) help to narrow the focus of the investigation and allow the lesson designer to consider the kinds of activities students can engage in to collect data and further analyze and interpret evidence that will answer the question about the phenomenon. For students engaged in sense-making, the question can help them to focus on the ideas that are relevant for explaining the phenomenon (Rosenshine, Meister, & Chapman, 1996), thus the phenomenon is bounded by the questions they have asked. Throughout the modeling process, the question can also serve as a reminder of what the purposes of the modeling tasks are. A question I heard often in the modeling classrooms I investigated was *"what are we trying to figure out?"* Although the phenomenon and question have been positioned at the top of the triangle, it does not necessarily mean that students must always observe a phenomenon first and then ask questions about it. Often the inquiry process can begin with a question that has arisen from previous investigations, and other times, it can even begin with the model itself. Their position at the top of the triangle, however, is intended to foreground their importance in the modeling process.

In figure 4-1, the model is positioned at the bottom of the triangle, because it serves as a foundation for answering the question about the phenomenon. Thus, one of the purposes and uses of a model is for helping students to explain patterns in the data. When a participant in my study was asked how she would explain the model-based curriculum to another teacher, her response illustrated the important link between the phenomenon, the question about the phenomenon, and the model:

> We're trying to teach kids science in the way scientists do science. We start with some sort of phenomena, that's the first thing. And then from there we try to get kids working through explanations of that phenomena. How do they explain what they've experienced or observed or something like that?

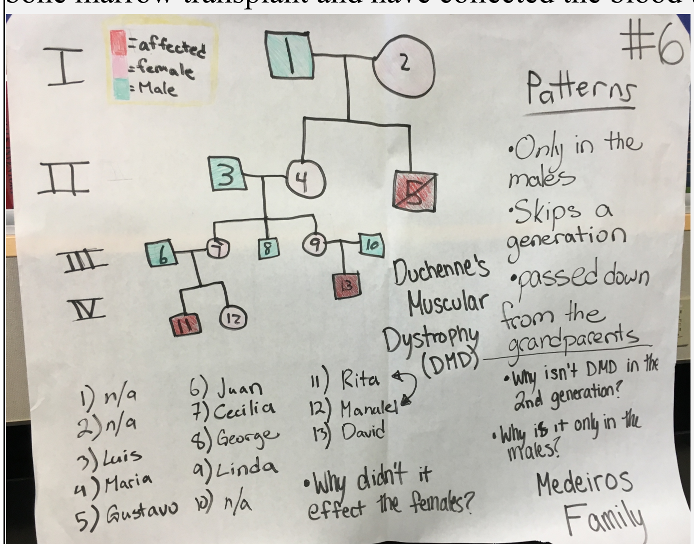
How then, can a focus on phenomena, questions, and models be used to centralize student-sense-making through engagement in modeling? I now draw on findings and examples from my previous investigations in chapters 2 and 3 to illustrate, in teachers' words, how to promote students' sense-making in high school biology classrooms. To provide context, I situate their suggestions within a series of modeling lessons enacted by the participants in our study. The lessons were designed utilizing the PQM framework and were intended to foster students' development of models of inheritance as a means for understanding how traits are passed from generation to generation.

Using PQM to Promote Sense-making in High School Biology Classrooms

Classical genetics lessons in high school biology classrooms traditionally follow a sequence that begins with telling students about Mendel's experiments: that he bred pea plants for several generations, examining discrete traits such as pea shape, pea color, pod size, pod color, etc. From there, the students typically learn how to calculate probability using Punnett squares, and are told the difference between dominant and recessive traits, and what it means to be heterozygous or homozygous for a particular trait. Students may then be given practice problems where they solve trait crosses using known genotypes and are asked to confirm the information they were given. In essence, they are simply *learning about* Mendelian genetics, rather than *reasoning about* how traits can be passed from generation to generation before *reasoning with* that understanding to apply their knowledge to new phenomena. In contrast, in our model-based curriculum, the phenomenon is foregrounded as a means to anchor student interest and to provide them with something to figure out.

“Put the phenomenon first, versus, ‘here, have all this vocabulary.’”

Lori divided her class into groups of three to four students and gave each group a case study that included a brief overview of a family’s history with a disease and medical records for each family member. Each group got one of five different cases: a family with members displaying characteristics and symptoms of phenylketonuria; a family whose members were diagnosed with or exhibited signs of osteogenesis imperfecta; a couple whose daughter needs a bone marrow transplant and have collected the blood types of every family member; a family



with members diagnosed with achondroplasia; or a couple whose son is displaying symptoms similar to Duchenne’s Muscular Dystrophy–they are concerned because others in the family also have been diagnosed with the disease. Lori told the students to read over the family histories and medical records, and to create pedigrees based on the provided information. Once the pedigrees were completed, she wanted them to look for any patterns they see within their given family. As students worked in groups, Lori walked around the room telling students that their objective was to identify a phenomenon, and to write down any questions they may have. A student whose group was examining the achondroplasia case was overheard saying, “if you have the trait, you definitely pass it on.” The picture on the left is an example of a pedigree created by a group of students who were identifying patterns related to Duchenne’s muscular dystrophy. On this poster, they have identified that the trait only exists in male, and they think that it skips a generation. Moreover, they have generated questions, including, “why is [DMD] only in the males?”

Lori was a high school biology teacher with twenty-one years of teaching experience, who participated in the model-based curriculum development project. The beginning of the classical genetics lessons, illustrated in the vignette above, took place towards the end of the academic year. Lori noted that prior to the year in which she participated in this project, that her classical genetics lessons typically followed the traditional path: pedigrees came toward the end of the unit and would be used to confirm what students had learned about Mendelian genetics, rather than as a means to generate understanding and wonder at the beginning. However, she witnessed the student thinking that could emerge when students were first given opportunities to explore and generate ideas about a phenomenon emerging from their interaction with patterns in the inheritance of traits. Moreover, students also appeared to have recognized what phenomena are and what purpose they served in their modeling classrooms. In interviews that took place after the classical genetics unit, two students made the following comments about phenomena:

- "…the phenomenon was the change in something or the difference between one thing from another."
- "…the problem of the whole thing we're doing, the subject we're doing."

By foregrounding the phenomenon, and providing students with opportunities to interact with it, in this case through generating and seeking patterns in pedigrees, teachers were promoting students' sense-making about a phenomenon, and students were possibly recognizing the purpose for engaging in modeling: to figure out a problem, a "difference between one thing from another." This is important considering that a part of the vision of NGSS is to foster "a level of facility in constructing and applying appropriate models" (National Research Council, 2012, p. 59).

“Neglecting the questions about the phenomenon leads to students being lost…”

Following the pedigree task, Lori provides each group with an opportunity to display the pedigrees they created (such as the poster pictured above), and to explain to the class the family and disease they examined along with the patterns they noticed. Afterwards, the following conversation occurs with Lori discussing with the groups what they notice after observing the different pedigrees displayed around the room.

> ***Student 1:*** Nothing is guaranteed, like there's no specific pattern. Like it's not guaranteed what trait you're going to get and stuff like that. So, in my case…we had [achondroplasia], but sometimes even with both parents having [achondroplasia], one of those [inaudible].
>
> ***Lori***: Ok. Excellent observations. Did you guys hear that? [Student 1] said nothing was guaranteed. There was no one certain set pattern in any one when you compare one to another. Using his own data from their family tree. He gave an excellent example and he said "like even when the parents have it, sometimes the offspring did and sometimes they didn't. What else? When you look around the room, what is the phenomenon that you observe in these family histories? There's no wrong answers you guys. Be brave.
>
> ***Student 2***: I was going to say…sometimes parents have it and sometimes they don't.
>
> ***Lori:*** Ok. Sometimes the parents have it and sometimes they don't. And sometimes the offspring have it and sometimes they don't. [Student 3] what did you say?
>
> ***Student 3:*** [inaudible response]
>
> ***Lori:*** What's the-if you had to look around the room and give a qualifying statement to the phenomenon in front of us, what would you say? Or what are some questions. Maybe we need to ask some questions. What are some questions you guys came up with?

In this conversation with students, Lori is letting students share their ideas about the phenomenon and as the conversation proceeds, she appears to recognize the need for a question to clarify what students are observing. Upon asking for questions, a student asks, “can the patterns be different?” It is possible that he has recognized that there are varying patterns of inheritance displayed in the pedigrees: some traits skip generations, some affect only males, and others diseases appear in varying degrees or number of traits. Fred, another teacher I studied, also recognized the importance of questions in modeling, stating that “neglecting the questions about the phenomenon leads to students being lost as to what they are doing." This realization that Fred and Lori each stated in different ways, illustrates two important points to consider for fostering student sense-making: (1) the importance of helping students to bridge their observations of phenomena and the ideas they have by providing them with opportunities to generate questions; and (2) that questions of phenomena can also remind students of the purpose for their modeling work.

This recognition also played a role in earlier modeling lessons in the model-based curriculum. During enactment of a lesson focused on explaining how plants get the matter and energy they need to survive, Fred noted that due to time constraints that he "did not do a good job of developing our driving question. I had students do this on their own…they took longer than expected and ran out of time to have a complete conversation about their thoughts." Several days later, when it was time for students to begin to generate their model for answering a question about the phenomenon, he realized that the students perceived their question to be "do plants eat" rather than a question that was "further defined" such as "how do plants get their food?" As a result of this realization, he asked his students to go through their interpretations of the data they had collected and analyzed and to generate some questions their ideas may help to answer. Following this task, he tells his students,

> "We sometimes bounce around between our model and our question and our phenomenon. And in this case, we went backwards. We had our model that kind of explained what happened, but now we're going back and saying, 'well, what question does that really answer?' It's ok when we do this, to go back and forth…this is our guiding question. This is what we've been figuring out in this whole process."

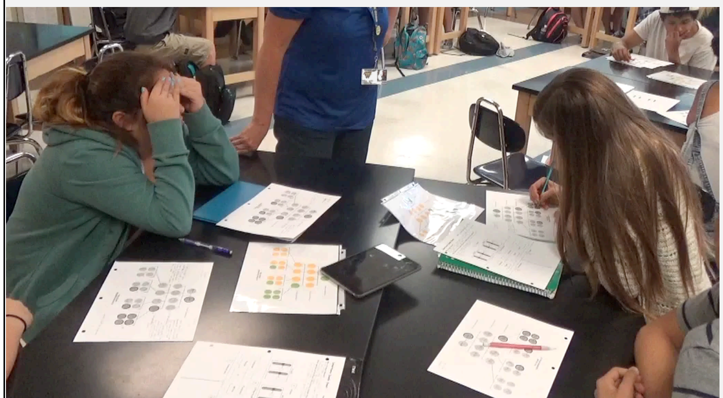
Fred had been trying to engage his students in sense-making about plants, but realized the need for a question to help students recognize what they were modeling and why they were doing it: to figure out how plants get their food. A month later, he reflected that he once again missed an opportunity to develop a driving question and regretted it because it would have been an opportunity to "bring together the phenomena the class was seeing."

Developing phenomenon-based questions can help to facilitate student sense-making. Without a phenomenon, students might be more inclined to ask 'what is it?' Or, 'where is it located?' (Scardamalia & Bereiter, 1992); rather than, 'how does this happen' or 'why does this pattern arise?' Students must also have opportunities to explore both general and specific phenomena and to develop questions for both. For the classical genetics lessons, the overarching question that arises from exploration of the pedigrees is "how are traits passed from generation to generation?" However, in order to further explore this, students examine a specific case first, such as "how do traits skip generations?" Questions that are too broad, make it difficult for students to recognize the important ideas to draw on in answering the question (Singer, Marx, Krajcik, & Clay Chambers, 2000). Thus, it is also important to bring the question to a smaller grain-size. However, the broad question can initially serve to activate prior knowledge (Driver et al., 1994).

When generating questions with students, they will inevitably generate questions that may not be able to be productively leveraged for the subsequent modeling activities; however, one strategy the teachers used in enacting our modeling curriculum was to have a "parking lot" where questions were written and displayed somewhere in the classroom. The teachers would occasionally return to the questions throughout the year, and students would answer them if they had generated some evidence that could help in reasoning about the questions. Or the questions would remain displayed until explanations were created based on models the students had generated. By allowing questions the students generated to remain a focus in the classroom, teachers were promoting students' engagement in modeling as a means for sense-making.

“Develop a series of ideas through…activities to build the answer to a complex question.”

After students were provided with opportunities to share the patterns they recognized and to generate and identify a question about a phenomenon to explore, Lori provided her students with a dataset based on Mendel’s classic experiments. The goal was for students to develop their own ideas about how traits can be passed from generation to generation. In this case, the dataset was a means for them to explore the specific case of simple dominance. She asked them to look at the data and see if they could figure out how a pure-bred cross (homozygous recessive and homozygous dominant) could result in offspring that only show one trait, and how a cross of those offspring could result in offspring that display both traits. The students are given time to discuss the task in groups, and then are given opportunities to share what they figured out to the whole class. The ideas relevant for answering the question are synthesized, and then the students return to their pedigrees to determine if the model they generated can explain the patterns of inheritance observed in their pedigrees. For some, the model will work, but for other pedigrees displaying sex-linked or codominance, the model will not suffice. Therefore, the students will explore other datasets and simulations that may help them to further generate ideas about how to extend their model to account for the other phenomena present in their pedigrees.



By providing students with opportunities to analyze and interpret data for the purposes of uncovering evidence, teachers can engage students in sense-making about a phenomenon. In the case of the classical genetics lesson described above, Lori presented her students with a series of data-driven tasks that supported the students in generating their models of inheritance. Fred described the modeling process in terms of the connection between the phenomenon, the question, and the model:

> We're going to develop a series of ideas through small experiences and activities to build the answer to a complex question that the kids are going to be in charge of. And knowing about and working to synthesize those ideas based on those activities and the phenomena that we present them. It's all going to be phenomena-based and we're going to be working towards answering something about a phenomenon that we observed the whole time and kind of keeping [students] focused on that task.

This quote highlights that if one of the components are missing: either the student, the phenomenon, the question, or the model, then modeling is constrained–it may no longer be a means for students to make sense of a phenomenon. Overall, the actions teachers took to enact these modeling lessons illustrate a departure from the traditional classical genetics lessons used in high school biology. They foreground opportunities for students to make sense of natural phenomena. This agent-based view of modeling (Giere, 2010; Passmore et al., 2014), on behalf of the teachers, represents an important shift in the ways in which teachers might consider who holds the disciplinary authority in the classroom (Ford, 2008).

In chapter 2, I examined the instructional moves teachers made when enacting modeling lessons and found that their instruction typically followed a similar path for all models developed throughout the academic year. Figure 4-2 illustrates the path in a linear flow chart, and is situated within the context of the model-based genetics lessons. The initial move teachers made was to introduce the students to the phenomenon (the first triangle at the top of the chart). This typically took the form of a few sentences describing what students would be looking for as they worked to identify patterns in what they had been given–data, text, pictures, etc. For classical genetics, students generated pedigrees that illustrated varying patterns of inheritance. Students typically then worked together in small groups to explore the phenomenon. Following the students' explorations, the teachers then provided students or groups of students with opportunities to share aloud with the class any patterns they identified and questions they may have had (the second and third triangles). After all students shared the phenomenon they observed and the questions that they had, a question was chosen to guide their subsequent investigations and generation of the model (the fourth and fifth triangles). The models of inheritance that students generated helped to explain simple dominance, co-dominance, and sex-linkage.

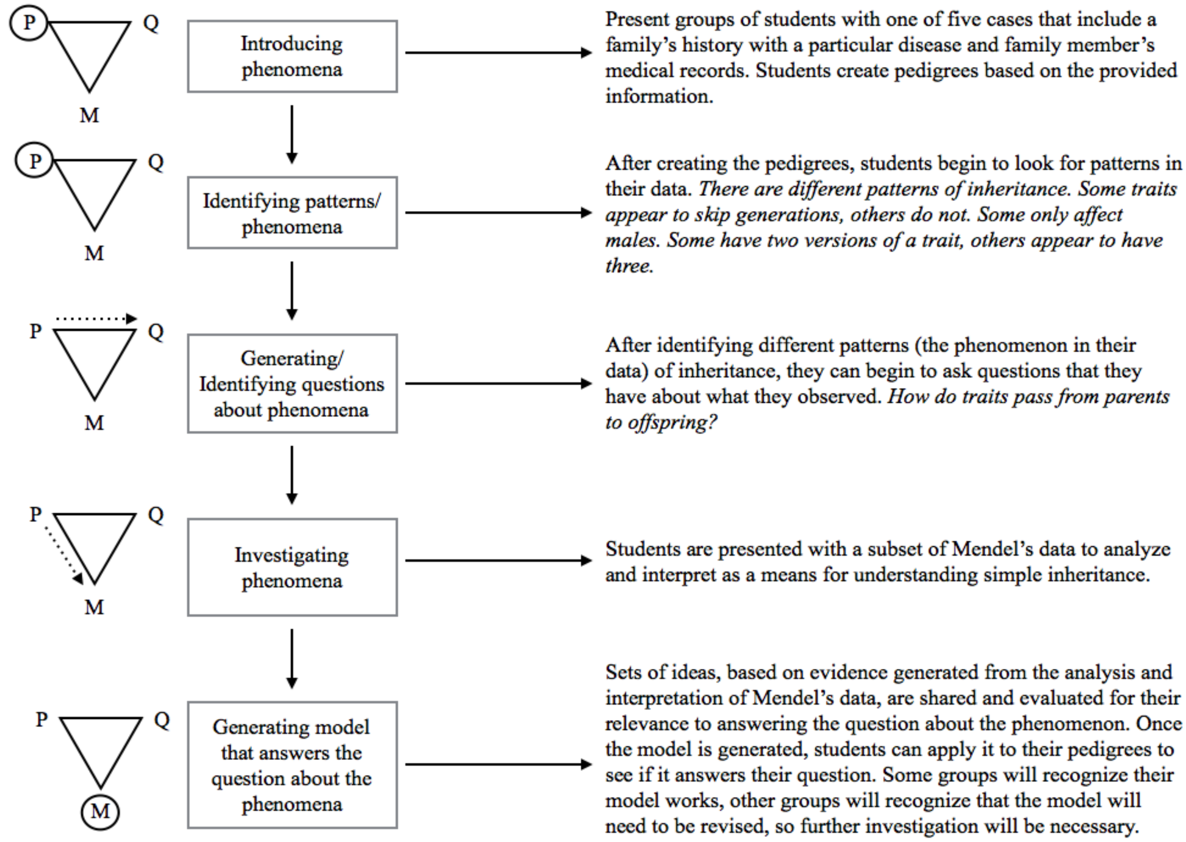


Figure 4-2. *The linear path that teachers follow as they facilitate students' engagement in modeling and thus the sense-making process.*

Summary and Conclusion

As I have illustrated, utilizing a phenomenon-question-model framework can help to guide both students and teachers through the modeling process in ways that consider who is doing the modeling–the students–and what the students are trying to figure out–a question about a phenomenon. Moreover, by positioning students as members of scientific community focused on making sense of phenomena (Lemke, 1990), teachers are affording students with ripe sense-making opportunities. Studies have shown how providing students with time to interact with one another and to engage in dialogue about ideas are important means for helping students to understand what they are investigating (Driver et al., 1994; Ford & Wargo, 2012; Lemke, 1990).

Traditionally, dialogic interactions are not common in science classrooms (Weiss et al., 2003); therefore, through foregrounding students' ideas, teachers can begin to shift their instruction away from traditional forms of school science instruction. Moreover, by providing students with opportunities to develop and apply explanatory ideas, students are engaging in scientific practice aligned with the same practices scientists use to generate scientific knowledge. It is through the coordination between phenomena, questions, and models, that teachers can afford students with opportunities to engage in authentic scientific practice and to generate their own understandings of the natural world.

Chapter 5 Conclusion

There is a consensus surrounding the importance of engaging students in the practice of developing and using models (e.g., S. W. Gilbert, 1991; Windschitl et al., 2008) and the powerful reasoning that students can do when this practice is employed in the classroom (e.g., Louca & Zacharia, 2014; Passmore & Stewart, 2002; Schwarz & White, 2005). However, despite this agreement on the utility of modeling to engage students in sense-making, there is a gap in our understanding of how teachers enact modeling in their classrooms (Louca & Zacharia, 2012; Maia & Justi, 2009). The purpose of this dissertation was to explore this problem space, as a means to both further understand the coordination between scientific practice and content in science classrooms, and to uncover instructional phenomena that may warrant further investigation. In this concluding chapter, I describe the implications of this work and what I perceive to be the key take-home messages. I end with a brief discussion of the kinds of research that can build on the findings contained wherein and that may provide further insights into how teachers and classroom contexts afford or constrain student opportunities for making sense of natural phenomena.

In the first paper, I explored the instructional moves utilized to facilitate modeling while enacting a model-based curriculum. The findings suggest that teachers provided ample opportunities for students to share their ideas and that they attended to the social dynamic of modeling by allowing students opportunities to work together to construct and refine models. At the same time, however, they were inconsistent in how modeling was portrayed through these moves, potentially constraining student engagement in modeling. In addition, the findings indicate that the teachers in this study were focusing their instruction on student ideas, which is important considering that in most science classrooms, students' ideas and questions are not often made public or used to drive instruction (Weiss et al., 2003). Their usage of moves that gave students opportunities to make sense of ideas and to process tasks together and to publicly share their ideas with the entire class illustrate the kinds of shifts teachers can make in their instruction that might lend themselves towards engaging students in sense-making. Ambitious teaching practices, such as the enactment of modeling, are complex, (Windschitl & Thompson, 2011) and as the teachers in this study described, cognitively demanding. However, small shifts in teaching practices, over time, could be key to supporting teachers in their enactment. Future investigations into teaching practice could focus on scaffolding supports for teachers that provide them with opportunities to change instruction over time towards a more focused enactment of modeling.

Moreover, the findings in chapter 2 bring to bear an important consideration with respect to what modeling is and what it should be in science classrooms. McNeill et al. (2016) and Berland & Hammer (2012) both caution educators and researchers against the enactment of "pseudoargumentation" whereby students attend to the components of an argument and/or teacher expectations, rather than the reasoning and evidence behind their claims. Berland and Hammer (2012) claim that this could be a consequence of how the teachers framed the argumentation activities and how students took up that framing. Using models to represent content and modeling as a means to deliver it could be an act of "pseudomodeling" as it could provide students with an incoherent vision of what modeling practice is. Investigations into the role of framing and what students perceive the role of models and modeling to be in making sense of phenomena could go a long way towards providing a foundational understanding of why these differences in modeling perceptions might matter.

Overall, the understanding I came to of what teachers were doing to build on or set aside ideas, does bring to bear some interesting questions, centered on whether or not the consequences of inconsistent enactments even matter? Intuitively I surmise that the answer is yes, but more work is necessary to empirically support this claim. Emerging scholarship on coherence may help to explore this question further. If a goal for educators and researchers is to design learning environments that provide students with cogent and authentic experiences in the sciences, then the research community must understand the consequences, at the student level, of what teachers' instructional moves might be. Although I did not explore this for my dissertation, future work should extend to the intersection of coherence and student sense-making and focus on the differences between access to and engagement in making sense of phenomena.

In the third chapter, I build on my understanding of the modeling and mediating moves teachers utilized to implement modeling and explore the factors that may have influenced the varying enactments that I observed. I found that the factors influencing enactment were centered around four core themes: teachers' intentions and beliefs, teachers' real-time instructional considerations; teachers' views and understandings of science; and teachers' perceptions of the role of the curricular materials. As a whole, time constraints and the need for scaffolds to support students transcended the four categories indicating that the two factors may have been considerably influential in affecting the portrayal of modeling through the moves teachers took. Also related to scaffolding was a belief in student's capacity to engage in modeling. What I found is that having a positive orientation towards students' capacity to engage in modeling is an important characteristic for educators looking to foreground students' ideas. When teachers have an orientation that their students are unable to engage in a particular modeling task, they may overly scaffold the task, placing the focus on the content, or the details or rules for completing the task itself, rather than on the students' ideas. A positive orientation towards students' abilities, skills, and disciplinary authority could help to maintain a focus on student sense-making.

Not included in chapter 3 was the role of students' perceptions and the feedback loop between student and teacher that may have further influenced modeling. Although I did describe factors considering what teachers perceived to be happening in relationship to students (e.g., their understanding and their engagement), investigation of the system in which modeling takes place could provide further insights into the instructional decisions the teachers made and how those decisions influenced modeling.

In the fourth chapter, I explore how a focus on phenomena, questions, and models can help to shift teachers' instruction towards a focus on student sense-making. This chapter is intended for a practitioner audience and emerged from my investigation into the research questions for chapters 2 and 3. In investigating both the moves and factors that influenced modeling, I realized that teachers' definitions of models, modeling, and the model-based curriculum they enacted tended to include the role of phenomena and questions in facilitating student sense-making. Therefore, I drew on examples from my findings and situated them within the context of a modeling unit–Mendelian genetics–to illustrate how a focus on phenomena, questions, and models can serve to pull teachers into a sense-making frame.

Moreover, the exploration I did for chapter 4, made salient to me a second shift in instruction that might impact teachers' uptake of modeling. Lori noted in an interview that she found it powerful to present the phenomenon first, rather than just as a means to confirm students' understanding. And, Fred noted his realization of the differences in students' sense-making with and without a question to focus the modeling. Letting students observe and identify a phenomenon of interest and to generate questions they have about the phenomenon could be an entry into affording students with opportunities to engage in authentic scientific practice and reasoning.

What do I want teachers to know about models and modeling?

The ultimate goal of science education is to provide students with an awareness of and about science (DeBoer, 2000; Hodson, 1992; Hurd, 1958, 1998). As such, scientific literacy is an outcome we all strive for in designing learning environments that support both students and teachers. An understanding of the scientific enterprise and the ways in which scientists go about generating and refining knowledge is more important than ever given the continued arguments over the non-existent link between vaccines and autism and the substantial evidence confirming the increasing global climate crisis (Allchin, 2014). As McComas, Almazroa, and Clough (1998) noted, “at the foundation of many illogical and unreasonable positions are misunderstandings of the character of science” (p. 511). Providing students with opportunities to engage in modeling as a means for making sense of natural phenomena, could be a means towards providing students with such an understanding of science (Louca & Zacharia, 2014; Passmore et al., 2009).

As I have suggested throughout this dissertation and illustrated through examples of enactment, engaging students in modeling is ambitious and important. Aside from the shifts in instruction I have already noted that could provide students with access to sense-making, I now highlight four key points, empirically and theoretically derived, for teachers to consider when enacting modeling in their classrooms.

- *Have a positive orientation towards students’ capacity to make sense of their world.* Students tend view to their teachers as the knowledge authorities in the classroom (Ford, 2008; Herrenkohl et al., 1999; Lemke, 1990), and shifting that view could be facilitated by teachers first believing their students are capable of engaging in scientific practice. A positive orientation towards students' capacity to engage in modeling could help to maintain a consistent frame towards foregrounding students' ideas and allowing their questions to drive instruction.

- *Let students make their ideas public.* In the classrooms I observed, students were given opportunities to share their ideas within their classrooms, or to make representations of their ideas that were shared with other biology classes in their school. These moves served to portray modeling as a sense-making endeavor, and are a means for promoting scientific literacy (Krajcik & Sutherland, 2010; Norris & Phillips, 2003; Snow, 2010). Moreover, it allows students to hear others' reasoning that may help them to make sense of their own ideas (Driver et al., 1994). It can also serve as a means to foster argumentation (Passmore & Svoboda, 2012), another important, and integrally related scientific practice (NGSS Lead States, 2013; NRC, 2012)
- *Give students time to process.* As educators, we are taught that "wait-time" (Mehan, 1979) is an important means for giving students time to consider their responses to a question or idea posed by the teacher. However, in modeling classrooms, I observed the importance of giving students time to process, both individually and then in groups, what patterns they have observed, questions they have, or ideas they consider important for their model. Working together to make sense of a phenomenon could accurately portray to students that science is a social and a human endeavor (Lemke, 1990). Additionally, it could allow for ideas to be shared and built on. Dialogic interactions also serve as an important means for making sense of phenomena (e.g., Driver et al., 1994).

- *Consider your responses to students.* Although students' ideas and reasoning are important for the sense-making process, the teachers' role is to guide students in deciding what ideas are important and what ideas are not important for answering a question about a phenomenon (Halloun, 2007). Therefore, once students have shared their ideas, they must be responded to in some way, as a means of acknowledging the students' contribution to the larger goal of developing a model, and for helping them to negotiate the model generation process. However, there are responses that could constrain sense-making, such as those that identify flaws in student reasoning or that provide them with the correct answer.

Concluding Thoughts

In an essay first published in the late 1980s, Kliebard (1992) surmised that the "failure" of educational reform measures was related to the highly situated nature of teaching, stating that "pedagogical practice is highly contextual, making the success of every reform contingent on the extent to which it can be interpreted and adapted in the light of particular conditions (p.110)." Part of what I believe he is stating here is that ultimately, teachers are making the instructional decisions that are enacted in the classroom, but these instructional decisions are based on context-based factors and interpretations that trickle down from those that authored the reform down to the teachers in the classroom. NGSS will be no different, and teachers, teacher educators, professional development coordinators, and administrators will need help in understanding what NGSS aligned instruction is and what some of the affordances and barriers are to this type of instruction. This dissertation aimed to provide a foundation for the kinds of discussions that are necessary to move forward with support at all levels in enacting this reform.

As I draw this dissertation to a close, I want to circle back to the quote in my title: "model-based reasoning is not a simple thing." Fred noted this in his final interview when asked what he perceived to be an example of exemplar instruction from his classroom. He could pinpoint examples, but ultimately exclaimed some of his frustration with the complexity of the pedagogy. As evidenced in my findings, this practice is indeed difficult to actualize. However, with the advancement of pedagogical supports born out of this understanding of the ways in which teachers navigate their instructional roles and facilitate modeling, teacher educators and professional developers will be closer to better assisting teachers in their implementation of this ambitious practice and pedagogy.

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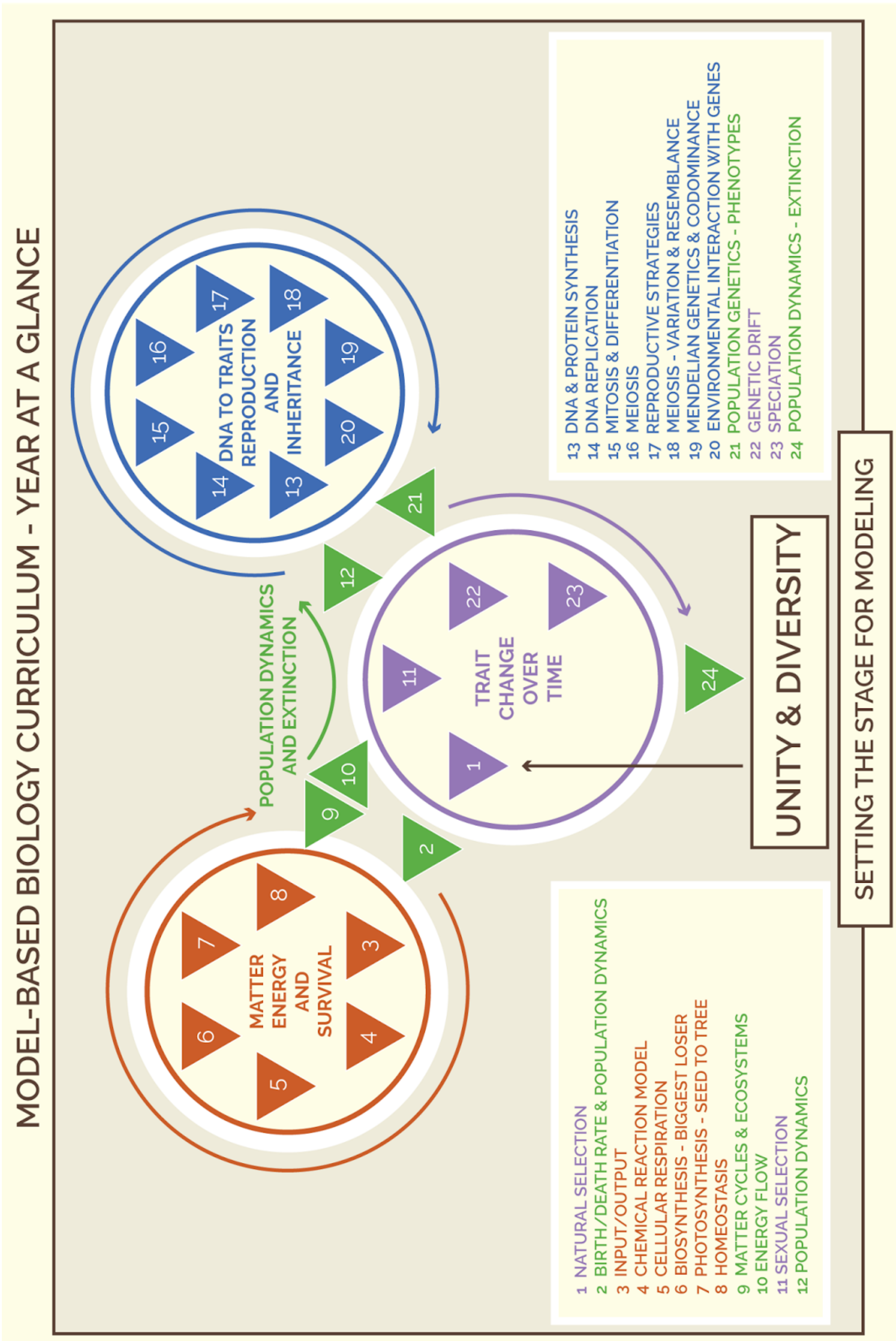
Appendix A: MBER Curricular Sequence



Appendix B: MBER Data Overview

Data collected for each teacher for the 2015-16 academic year. Bold text indicates data sources that were used for this paper.

Cases	T1	T2	T4	T5	T6	T7	T9	T10	T11	T14	T16	T19	M1	M2	M3	M4	M5
Catherine	V, I, C	V, C	—	V, C	V, C	V, C	V, C	V, C	—	—	—	V, I	R	—	R	R	—
Eric	V, I, C	—	—	I†	V	V, I	—	—	V	—	V	V, I	R	R	R	R	R
Frances	V, I, C	—	—	—	—	—	—	—	—	—	—	V, I, C	R	R	—	R	R
Fred	V, I, C	—	—	V, C	—	V, I	—	—	—	V	—	V, I, C	R	R	R	R	R
Lori*	V, I, C	—	V, C	V, C	—	—	—	—	—	—	V, C	V, I	R	R	R	R	—

Table Key: Curricular reflections collected for the corresponding triangle (C); Interview conducted about instruction within the corresponding triangle (I); Reflection prompts collected during group meetings (R); Triangle for which the data was collected (T, see Figure 3); Instruction video-recorded for the corresponding triangle (V)

*Lori also provided a copy of a notebook she kept for the entire year that include her ideas for instruction and notes about the curricular materials.

†This interview was conducted while Eric was implementing triangle 5, but the focus of the interview was to better understand his lesson planning process and how he utilized the resources on the MBER website.

Group Meetings (M) took place on 10/20/15 (1), 12/14/15 (2); 2/10/16 (3); 4/26/16 (4); 6/7/16 (5) [Due to the differences in teachers' schedules, there is no triangle that directly corresponds to each meeting date.

Appendix C: Pre-Interview Protocol

[These interviews took place following implementation of Triangle 1: Natural Selection]

General Guidelines for Interview
It's important to identify during the classroom observation and interview instances in which the teacher attempted to use MBER ideas or resources. We want to probe teacher's understanding of how those ideas/resources are used in the classroom and ask the teacher to point to specific moments from the lesson when explaining their ideas. Example questions and prompts have been provided.

1. What was the learning goal of the lesson and how did you hope to achieve that goal?
    a. How do you think it went?
        i. What went well?
        ii. What would you have done differently?

Example Probing Questions – (should be contextualized based on observed lessons/interviews)

2. Activity
    a. When you had the kids do X, what were you trying to accomplish?
    b. What question were the students trying to answer?
        i. Where did those questions come from (e.g. building on prior activity/learning, teacher/student-initiated question)?
        ii. What resources are the students supposed to draw from to answer that question?
    c. By the end of the activity, what did you want the students to produce/learn?

3. MBER Idea
    a. During the class, I noticed you using the term X (e.g. model/story/driving question).
        i. What did you mean by that?
        ii. When the students hear/use that term X, how do you think the students interpreting that idea?

4. Role of the Teacher/Students
    a. During class/interview, you noted that your role has shifted to become more of a facilitator. What does that mean? Can you provide an example from the lesson in which you served in this role?
    b. When you are facilitating, how has what the students are doing changed?

Experience using MBER Approach/Materials

5. What has your experience been so far as you've tried to use the MBER Bio approach in your classroom?
    a. Have there been any particular challenges?
    b. How does this compare to what you did last year?

6. How have you been using the materials on the website to plan your lessons?
    a. Have you found the material helpful and easy to adapt for your classroom?
    b. Is there anything that we can do to make it easier for you?

Appendix D: Mid-Year Stimulated Recall Interview Protocol

The point of this is for us reflect on what an ideal situation would be like and try to figure out what's really happening in the classroom. It's to help both of us learn and figure out, how we can improve upon what's happening in the classroom, and for us to think about what we can do to further support you.

You spent several days implementing triangle 7, but we're going to focus on the challenge question that I observed.

1. So, to get us started, I want you to think about "an ideal situation", that is, in an ideal world, with an ideal classroom, what would the challenge question look like in your classroom, from the time you set-it up to what happens after the gallery walk.
    a. What would you be doing? What would your instructional moves be?
    b. What would the students be up to?
    c. What do you do when the students are working in groups?
    d. What do you do when you talk to students working in groups?
    a. What types of questions or feedback might you ask or give students to help facilitate their understanding about the seed-to-tree phenomenon*?*
    b. If students aren't sure where to start, what would you recommend to them?
    c. *Like if they are stuck?*
    d. What would you expect their explanations to look like? What information would be included? What would you expect to see on the poster? *What do you expect the output to be?*
    e. **What do you do after the gallery walk?**
        a. What would a debrief look like? What would your moves be to facilitate this debrief?
        b. What types of conversations would you want the students to be having?

Additional prompts for this question to help:
How would you ideally set-up the activity?
What do you tell them that gets them ready for sense-making?

We're going to take this "ideal situation" and hold it up to what happened in the classroom. Along the way, I'm going to show you some video and we're going to take a look at some of the work produced by your students. As we go through, I'll have some questions for you, but please stop the video if there is anything you notice that you might want to discuss or explore.

The first video we're going to watch is the introduction to seed to tree.

2. **Based on how you set-up the task (so this is separate from the ideal)**, what would you expect students to do?
    a. What is the students' next move, and what is your next move?
    b. What do you expect students' explanations to look like?

3. Ok, so now we're going to skip forward to the gallery walk. You give them a rubric. What's the point of the rubric?
    a. What would you expect students to do at the gallery walk based on the rubric?
    b. Is that what you saw happening?

Show clips. Maybe see if they notice what's being emphasized? Are you noticing anything?

4. Now we're going to watch some video of student presentations.
    a. I'd like you to stop the video when you see something you'd like to discuss—related to student learning or whatever you find interesting.
    b. What grade did you give this poster? Why?
    c. What about this poster/presentation demonstrates student learning? What doesn't? What kinds of ideas were you looking for?

5. Earlier you mentioned you would do X following the gallery walk, what actually happened? Why?

Appendix E: Post-MBER Teacher Interview Protocol

[These interviews were conducted with all participants with the last few weeks of the 2015-16 academic year.]

1. What was the most rewarding part of doing MBER bio this year?
2. What was the most challenging part?
3. If you were to explain to a colleague what MBER bio is all about, what would you say?
4. Which triangle did your enactment best exemplify your explanation?
5. During which triangle do you think your enactment exemplified the focus on the modeling practice most effectively? Why?
6. [stimulated recall segment or…]

    a. Show clip teachers that was shown to students.
        i. When you set up the task, what did you consider? What did you want the students to get out of the task/activity? What evidence do you have that it was/was not successful?

    b. Imagine you walk up to a group of students working on a genetics problem. You know that the underlying inheritance model is co-dominance. When you arrive the students are playing around with 3 alleles. What do you do and why?
7. Imagine you gave the following assessment question to students:

    a. In the Kendrick Family showing the inheritance of albinism there are parents who have normal pigment who have a child who is albino. Explain how this could happen.

    b. What would be your reaction to the following student responses. Be specific about your thoughts on their understanding of the things you care about and about the kind of feedback you would give each student.

        i. ANSWER ONE: The two parents in the cross must be heterozygous for the trait so their children have a 50/50 chance of receiving the recessive allele from either of their parents. The Punnett square shows that the probable ratio of normal pigment to albino children will be 1:3.

        ii. ANSWER TWO: The parents in the cross are heterozygotes.

        iii. ANSWER THREE: The mom and dad must each have the gene to be albino hidden in them as one of the two forms they have in their cells. That means they can give it or not to their kids. If both of them happen to give it, then the kid will be albino and if not then they won't.

    7. When you teach biology next year will you continue to use the MBER materials? What will you modify and why?

8. Final?
9. PQM

Appendix F: Summary of Coded Instances of Factors Affecting Implementation of Modeling

		Instances of Factors by Teacher*				
Categories of Factors	**Subfactors**	**Catherine**	**Eric**	**Frances**	**Fred**	**Lori**
Teachers' intentions, values, and beliefs	Classroom culture	6	2	3	3	1
	Student capacity	13	3	5	10	2
	Value in engaging students in modeling	2	5	2	3	4
Teachers' real-time instructional considerations	Adapting instruction and/or scaffolding resources	1	9	20	11	7
	Cognitive fatigue	0	5	1	5	2
	Student engagement	13	3	4	13	2
	Student-student interactions	2	2	2	2	5
	Student struggle	3	1	2	1	5
	Student understanding	22	16	23	33	6
	Teachers' role	4	4	12	4	13
	Time involved in tasks	9	6	4	17	2
Teachers' views and understanding of science	Authenticity to science	0	4	4	0	3
	Teachers' content knowledge	0	2	1	0	0
	Teachers' understanding of models and modeling	0	7	3	3	2
Teachers' perceptions of the role of the curricular materials	Assessment	8	4	4	5	6
	Iterative nature of the curriculum	5	1	2	4	3
Other	Collaboration	2	3	2	0	0

*See table 3-2 and Appendix B for an overview of the data analyzed for Chapter 3.