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Epistemic Aims, Considerations, and Agency: Lenses for Helping Teachers Analyze and Support Students' Meaningful Engagement in Scientific Practices

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Abstract

The reforms called for by the Next Generation Science Standards (NGSS) (National Research Council, 2012; NGSS Lead States, 2013) involve students using scientific and engineering practices to construct disciplinary knowledge with others. For this work to be *meaningful*, students need to understand what they were doing and how their actions will help them achieve their scientific goals (Berland, Schwarz, Krist, Kenyon, Lo, & Reiser, 2016).

This dissertation research examined two related questions. The first question investigated the successes and challenges that emerge when teachers attempt to support students' meaningful use of scientific practices and their role in shaping the class consensus knowledge. To do so, I developed a framework composed of three analytical lenses that embrace the epistemic issues that are important for guiding and supporting students' meaningful use of scientific practices: 1) *Epistemic aim: What is the goal of the knowledge-building work?* 2) *Epistemic considerations: What ideas or questions are guiding students' decisions?* and 3) *Epistemic agency: Who is responsible for doing this work?*

The second question investigated how teachers could use these analytical lenses to enhance the students' role and the meaning that students applied to their engagement in scientific practices. Using the framework, I engaged in cogenerative dialogues with classroom stakeholders (teacher, students, and researcher) to co-construct understandings of classroom events, reflect on the extent to which students' use of scientific practices was meaningful, and co-develop solutions to identified issues. Through iterative cycles of reflection and experimentation, Kami noticed how her planned trajectory for achieving the lesson's content goals constrained her students' opportunities to shape the consensus knowledge of the classroom. In addition, Kami noticed the need for students to have epistemic authority to assess the validity

and reconcile competing ideas to reach consensus. In both cases, Kami used her interpretation of classroom events to address the identified issues. Taken together, the findings from this dissertation research provide empirical support for how this analytical framework could be useful not only for researchers, but also for practitioners to analyze and enhance the meaningfulness of students' engagement in scientific practices.

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Dedication

For Jenny, Isaac, and Chloe

For Mom, Dad, and Emily

Table of Contents

Copyright 2

Abstract 3

Acknowledgements 5

Dedication 6

Table of Contents 7

List of Figures 10

List of Tables 12

Chapter 1: Introduction 14

1. Goal of NGSS Reforms: Learning science-as-practice 16
2. Challenges with existing classroom practices 23
3. Research Questions 25
4. Efforts to promote authentic scientific practice in classrooms 25
5. Approaches to supporting meaningful scientific practice 31

Chapter 2: Overview of Dissertation 44

Chapter 3: Framework for analyzing students' meaningful engagement in scientific practices 49

1. Overview of Framework 50
2. Epistemic aim: What is the goal of the knowledge-building work? 52
3. Epistemic considerations: What ideas or questions are guiding students' decisions? 56
4. Epistemic agency: Who is responsible for doing this work? 65
5. Framework Summary 74

Chapter 4: Study 1 Methods 77

1. Participants 77

2. Lesson Context 80
3. Lesson 4 Sequence 82
4. Features to support ambitious pedagogy 88
5. Study 1 Data Collection 89
Chapter 5: Analytical Methods 93
1. Organizing data for analysis 93
2. Overview of Analyses 100
3. Epistemic Aim: What is the goal of students' knowledge-building work? 106
4. Epistemic considerations: What ECs guided the development and evaluation of students' models? 112
5. Epistemic agency: How do students' ideas and questions influence the knowledge-building work? 125
Chapter 6: Successes and Challenges: Constructing and Evaluating Students' Models 140
1. Classroom enactment differences 141
2. Epistemic aim: What goal guided students' work? 146
3. Epistemic considerations: What epistemic considerations are guiding students' and teachers' decisions? 155
4. Epistemic agency: Who's responsible for achieving the epistemic aim? 185
Chapter 7: Discussion of Successes and Challenges 215
1. What's the epistemic aim guiding our work? 215
2. Epistemic challenges related to persuading others 217
3. Supporting student agency 224
4. Conclusion 232

Chapter 8: Study 2 Methods 235

1. Study Context 236

2. Study Design 238

3. Perspectives on Teacher Learning 239

4. Professional Learning Design 244

5. Research Design 250

Chapter 9: Illustrative shifts in Kami's classroom 253

1. Shift 1: Helping Kami notice how she responded to and used students' ideas during instruction 253

2. Shift 2: Helping Kami notice students' attempts to exert epistemic authority in the classroom 267

Chapter 10: Discussion of Noticing Shifts 280

Chapter 11: Conclusion 285

References 288

Appendix

Appendix A: Teacher Modeling Interview 305

Appendix B: Sample Embedded Assessment 306

Appendix C: Student Interview Protocol 308

Appendix D: Transcript Chunking Example 309

Appendix E: Presentation of Becky's Model Analysis 315

Appendix F: Vision Statement Prompt 319

Curriculum Vitae 320

List of Figures

Figure 1.1. Goals of NGSS reforms 21

Figure 1.2. Diagrammatic model explaining how odor moves across the room 34

Figure 3.1. Framework for analyzing students' meaningful engagement in scientific practices 52

Figure 4.1. Lesson 4 sequence 84

Figure 4.2. Common student conceptions of air 86

Figure 5.1. Rob's diagrammatic model explaining how and why could detect odor 119

Figure 5.2. Eric's model showing air's location after some air removed 123

Figure 6.1. Laura's enactment of Lesson 4 143

Figure 6.2. Kami's enactment of Lesson 4 144

Figure 6.3. John's enactment of Lesson 4 145

Figure 6.4. Lenny's air model 165

Figure 6.5. Hillary's air model 167

Figure 6.6. Analysis of topics discussed during John's initial air model discussion. 169

Figure 6.7. Analysis of topics discussed during Laura's initial air model discussion. 170

Figure 6.8. Steven's air models. 171

Figure 6.9. Jessi's models showing the removal of air from the sealed the flask. 182

Figure 6.10. Patterns of interaction during focus lesson. 186

Figure 6.11. Ariana's model 192

Figure 7.1. Synergies between *audience* and *justification* considerations for persuading others 221

Figure 7.2. Sample synergies between analytical lenses 234

Figure 8.1. Operationalization of Grossman et al. (2009)'s *Framework for Teaching* 243

Figure 9.1. Flask and Water Demo 255

Figure 9.2. Kami watching video of her classroom. 258

Figure 9.3. Inqscribe screenshot 259

Figure 9.4. Consensus list of characteristics 268

Figure 9.5. “Is odor a gas?” activity sheet 275

List of Tables

Table 3.1. Framework for analyzing meaningful engagement in scientific practices 76

Table 4.1. Study 1 Teachers and School Demographics 79

Table 4.2. Summary of Lesson 4 Sequence 83

Table 4.3. Lesson 4 classroom observations 91

Table 5.1. Overview of analytical methods for epistemic aim 102

Table 5.2. Overview of analytical methods for epistemic considerations lens 103

Table 5.3. Overview of analytical methods for epistemic agency lens 105

Table 5.4. Types of model-based epistemic aims 108

Table 5.5. Teacher's efforts to ascribe meaning to students' modeling work 111

Table 5.6. *Audience* consideration coding 117

Table 5.7. Sources of evidence 122

Table 5.8. Analyzing patterns of interaction 127

Table 5.9. Teacher supports for enhancing students' knowledge-building role 130

Table 5.10. Analyzing how teacher's attention to content goal influenced what ideas were discussed 138

Table 6.1. Summary of Lesson 4 enactment differences 142

Table 6.2. Analysis of proportional attention to Berland et al. (2016)'s ECs during whole-class model discussions 158

Table 6.3. Analysis of what ECs students and teachers attend to during *audience-persuasion* discourse 161

Table 6.4. *Nature of account* consideration coding 179

Table 6.5. Number of student presentations during Lesson 4 187

Table 6.6. Relative attention profiles for students and teachers during whole-class model discussions 189

Table 6.7. Students' and teachers' relative attention profiles during *audience-persuasion* 191

Table 6.8. Proportion of *nature of account* discourse related to content goal 208

Table 8.1. Kami Data Collection 2011-12 250

Table 8.2. Kami Data Collection 2012-13 251

Chapter 1: Introduction

The reforms called for by the Next Generation Science Standards (NGSS) (National Research Council, 2012; NGSS Lead States, 2013) involve students using scientific and engineering practices to construct disciplinary knowledge with others. Schwarz et al. (2009) defined *scientific practices* as the "social interactions, tools, and language that represent the disciplinary norms for how scientific knowledge is constructed, evaluated, and communicated" (p. 633). Much work involved in promoting authentic science reforms has involved incorporating disciplinary goals, norms, and practices in classrooms (Engle & Conant, 2002; Ford & Forman, 2006). However, it is easy for students to go through the motions without understanding why these goals are important or how their actions would help them achieve their scientific goals. In contrast, Berland, Schwarz, Krist, Kenyon, Lo, & Reiser (2016) argued that students' engagement in scientific practices should be meaningful from the perspective of the discipline and students: *scientifically meaningful*, in that students are using disciplinary practices and norms to investigate questions valued by the discipline, and *personally meaningful*, in that students understand how and why their decisions would help them accomplish their scientific goals.

I argue that learning *science-as-practice* could be a fruitful approach for promoting meaningful student learning in K-12 classrooms. As students construct scientific knowledge with others, they develop an understanding of the disciplinary norm, conventions, and practices that guide, rather than dictate, their knowledge-building decisions (Lehrer & Schauble, 2006b). Developing this epistemic knowledge could prevent students from using scientific practices by rote and promote increasingly sophisticated and meaningful uses of scientific practices. In addition, students are more likely to develop robust, conceptual understandings because they understand the underlying justification for their ideas and why they are more valid compared to competing ideas (Driver, Newton, & Osborne, 2000; Engle & Conant, 2002; Osborne, 2010). However, what does it mean for students to engage in a practice — or more specifically an epistemic practice involving the construction of scientific knowledge?

Science classrooms are examples of *communities of practice* in which students and teachers have shared goals for constructing knowledge and a shared understanding of the norms governing how to achieve those goals (Lave & Wenger, 1991). Thus, knowledge construction is not an individual endeavor; rather, it involves students working together with some shared understanding of what it is they are up to and how their collective efforts would help them achieve their shared goals. However, meaningful use of scientific practices does not involve students simply observing others doing this work or passively receiving knowledge from others. Instead, students need to be socialized into the ways of knowing that are distinct to the discipline of science and provided the opportunity to legitimately participate in the knowledge-building work (Driver et al., 2000; Duschl & Osborne, 2002). In summary, meaningful use of scientific practices involves students understanding the goals, criteria, and norms governing how students and teachers should interact with one another in service of constructing and evaluating scientific knowledge.

In this chapter, I provide an overview of the key shifts and challenges involved in implementing NGSS reforms for students and teachers. Grounded in the literature, I put forward a vision for how framing classroom instruction around the development and use of explanatory models and providing explicit opportunities for students to construct and evaluate each other's ideas could be a fruitful approach for promoting meaningful student learning in K-12 classrooms. There are two strands of research in this dissertation. First, I investigate the successes and challenges involved in supporting this type of instruction. Building on these findings, this dissertation research explores theoretical approaches to help teachers enhance the meaningfulness of students' engagement in scientific practices and promote shifts in students' and teachers' classroom practices.

1. Goal of NGSS Reforms: Learning science-as-practice

I argue that supporting students in learning science-as-practice involve a shared understanding of the shifts from traditional science teaching and learning.

- **Shift 1: What is the goal of the knowledge-building work?** Do students and teachers have a shared understanding of how this work is different from what is currently done in classrooms and why this work is worthwhile?
- **Shift 2: How are students to meaningfully achieve their scientific goals?** How can students develop a shared understanding of the conventions and norms that should govern how this work is to be accomplished?
- **Shift 3: Who is responsible for doing this work?** What specific knowledge-building roles are students and teachers to adopt in these communities of practice? How are these roles different from existing classroom practices?

In what follows, I use these questions to explain these shifts, why they are important, and the challenges involved in implementing such shifts in classrooms.

1.1 Shift 1: What is the goal of the knowledge-building work?

The first shift involves the goal of acquiring explanatory knowledge rather than discrete scientific facts. When learning science-as-practice, students construct important disciplinary knowledge through developing and using *explanatory models* of phenomena. Explanatory models are composed of the relevant components and underlying processes that explain how and why related phenomena occur as they do (Harrison & Treagust, 2000; Lehrer & Schauble, 2000; Lesh & Doerr, 2003). Thus, models should be sufficiently general to explain multiple phenomena.

Part of supporting meaningful engagement in scientific practices involves students understanding why an epistemic aim is worth pursuing from the perspective of the discipline and the students. Compared to traditional classroom goals of reproducing or acquiring factual knowledge, developing explanatory models has more *epistemic value*, or worthiness from the perspective of the discipline (Chinn, Buckland, & Samarapungavan, 2011), because students can use their knowledge to explain and make predictions about new scientific phenomena, a key goal of the scientific endeavor (Berland et al., 2016; Lehrer & Schauble, 2006b; Passmore & Svoboda, 2011; Schwarz et al., 2009). At the same time, students' understanding of how and why knowledge is useful for their own learning enhances the aim's epistemic value and students' ability to use learned knowledge in other contexts.

1.2 Shift 2: How are students to meaningfully achieve these scientific goals?

Although reforms have called for increased student participation in the construction of explanatory knowledge, Ford (2008) cautioned that students' knowledge-building work ought to be moderated by *disciplinary accountability*, in which students use socially-negotiated, disciplinary norms and criteria, rather than relying on everyday reasoning alone. However, our attempts to promote students' use of disciplinary norms and practices ought to consider students' opportunities to develop meaningful understandings of what they are doing and why they are doing it. For example, many teachers ask students to provide two pieces of evidence to support their claims. Although this rule is grounded in a disciplinary norm that having multiple pieces of evidence improves an argument's persuasiveness, following this rule does not necessarily help students learn how to choose appropriate evidence or assess the sufficiency of their evidence for supporting or convincing others of the validity of one's claims.

To prevent rote use of scientific practices, Manz (2014, 2015) argued that students need to understand the *function* that scientific practices play in achieving one's knowledge-building goals. McNeill and Krajcik (2008) found that the quality of students' written explanations improved when teachers modeled how to construct an explanation and explained the rationales, rather than just the definitions, for each component of their explanation.

Russ (2014) further argued that focusing on productive uses of scientific practices could enhance student agency because students are equipped to make informed decisions for achieving their scientific goals. Thus, the goal of school science shifts from having students learn and use disciplinary practices of scientists to expand students' toolkit, a set of resources that scientists and students use in informed ways to accomplish their shared goals.

> If […] we believe that science education serves the goal of helping learners become better at constructing knowledge about the world around them, then explicit ties to the disciplinary practices of science become less important. For this goal, professional science shifts from being the desired end product to being one of many tools that support sense making. (Russ, 2014, p. 394)

Berland et al. (2016) further argued that supporting students' meaningful use of scientific practices involves teachers making explicit the *epistemic considerations* or the epistemic questions or ideas that should guide students' scientific decisions. In doing so, students not only understand the function that actions play in the context of scientific practice, but also understand the epistemic issues or "rules of thumb" that ought to guide their decisions. For example, meaningful use of evidence involves students understanding the epistemic considerations that guide students' choices and use of evidence: Does this evidence justify the claim that I am trying to make? Is this evidence likely to convince my audience that my idea is valid compared to competing ideas?

Attention to these epistemic considerations in the context of scientific practice could improve students' ability to achieve their scientific goals. For example, Ryu and Sandoval (2012) found that students' arguments improved when students attended to the extent to which their models could explain the phenomenon and were justified using evidence. Understanding the epistemic considerations related to students' use of evidence also has implications for promoting science literacy and supporting students' ability to construct and evaluate scientific claims in their everyday lives.

In summary, these epistemic considerations make explicit the epistemic issues that should guide, rather than dictate, students' decisions. In other words, these epistemic considerations do not tell students that they must include two pieces of evidence, a rule used as a proxy for the sufficiency of evidence. Instead, teachers provide guidelines to help students choose appropriate evidence and assess for themselves whether they have sufficient evidence to support the desired claim. Thus, the teacher's job becomes less about communicating what steps students should take to achieve a scientific goal and more about communicating to students the epistemic considerations that ought to guide students' decisions and helping students respond to these epistemic considerations in increasingly sophisticated and normative ways.

1.3 Shift 3: Who is responsible for doing this work?

In contrast to passively receiving from authoritative sources, such as the teacher or the textbook, learning science-as-practice involves positioning students as the *epistemic agents* or individuals with responsibility for defining, addressing, and resolving problems that will shape and advance the knowledge of the classroom community (Engle & Conant, 2002; Stroupe, 2014). By providing students with opportunities to build disciplinary knowledge through formulating and investigating questions that are of interest to them, Engle and Conant (2002) argued that students are more likely to perceive themselves as having the authority to construct knowledge and have ideas and questions that are worth investigating.

The construction of explanatory models is a social endeavor that involves students using evidence and argument to reach consensus (Driver et al., 2000; Osborne, 2010). Michaels, O'Connor, and Resnick (2008) argued that this knowledge-building work is mediated by students' engagement in productive, accountable talk, "Ideas must be explicated so that others can interrogate them, challenge them, build upon them, or support them" (p. 292). This talk is *productive* in that students are making progress towards achieving a scientific goal (Michaels et al., 2008) and *accountable* in that students must account for and cannot dismiss each other's ideas without appropriate rationale (Engle & Conant, 2002).

When evaluating each other's ideas, Ford (2012) identified two student roles: *constructor*, in which students defend and evaluate their model's ability to explain the phenomenon, and *critiquer*, in which students use *epistemic criteria*, or the standards by which scientific knowledge is constructed and evaluated, and social practices to identify flaws in students' arguments and consider alternative explanations for evidence. Engaging in argumentation with others allows students to construct robust and reliable knowledge by reconciling the validity of their own ideas amidst competing ideas (Driver et al., 2000; Engle & Conant, 2002; Osborne, 2010). In doing so, students are more likely to understand the justification for their claims and refine their understanding of the phenomenon (Herrenkohl, Tasker, & White, 2011).

As the agents responsible for constructing and evaluating knowledge, it is important that we consider the extent to which students' engagement in scientific practices is meaningful. In doing so, it is important not only for students to understand why the goal of the knowledge-building work is worth pursuing for their own learning, but also for students to develop an understanding of how to use disciplinary norms and practices to accomplish their scientific goals. To develop this *grasp of practice*, or the ability to participate in the discourse and activities used to construct and evaluate knowledge, and the ability to determine what counts as scientific knowledge, Ford (2008) argued that students need to be active participants in the construction of scientific knowledge.

1.4 Summary

In summary, NGSS reforms involves three core shifts: 1) shifting the goals of school science from accumulating scientific knowledge towards the construction of explanatory knowledge; 2) shifting how knowledge is learned so that students are not using scientific practices by rote, but using disciplinary norms and practices in meaningful ways to construct and evaluate scientific knowledge; and 3) shifting the responsibility for constructing and evaluating knowledge from the teacher to the students.

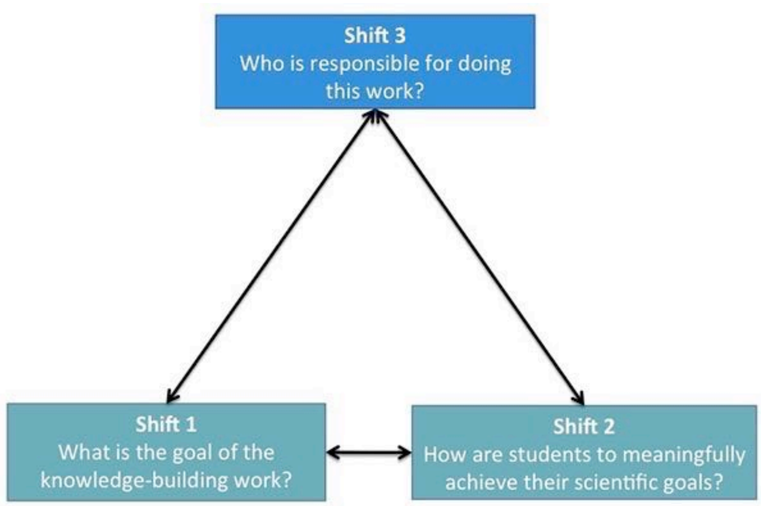

Figure 1.1. Goals of NGSS reforms.

I argue that successful achievement of NGSS reforms involves integrated attention to each core shift. As described earlier, much of the intervention work to incorporate authentic science in classrooms has focused on the lower two boxes in Figure 1: the incorporation of disciplinary goals (Shift 1) and students' use of disciplinary norms and practices to achieve those goals (Shift 2). However, NGSS reforms place students as the agents responsible for accomplishing the knowledge-building goals. For students to meaningfully engage in this knowledge-building work, we should ensure that students understand the goal that they are working towards and why it is important. In addition, when considering how to accomplish this work, it is important that students are not simply following a set of rules as dictated by the teacher; rather, students' decisions in service of achieving the desired epistemic aim are guided by important epistemic considerations. In doing so, we could enhance the meaningfulness of students' knowledge-building work because we are explicitly attending to students' interpretation of the knowledge-building goal and what is needed to accomplish that goal. In addition, if we want students to understand how to meaningfully engage in scientific practices characterized by students understanding the norms and practices used to construct scientific knowledge, we need to give students the opportunity to engage in this work (Shift 3). I use double-headed arrows to illustrate the interrelationships between these three core shifts. I argue that joint attention to these three core shifts will facilitate the opportunity for students to meaningfully participate in the construction of explanatory knowledge with others.

Given the goals of NGSS reforms, the next section examines research to understand the extent to which these reform practices are happening in classrooms and the potential epistemological and pedagogical challenges that would need to be addressed to realize this reform vision.

2. Challenges with existing classroom practices

Although research has shown the benefits of a practices-centered approach, this vision of learning science-as-practice differs from existing classroom practices in many classrooms. The goal of school science often involves students reproducing knowledge and obtaining the "right answer" rather than students making sense of scientific concepts or phenomena (Banilower et al., 2013; Weiss, Pasley, Smith, Banilower, & Heck, 2003) or using data to support their claims (V. Sampson & Blanchard, 2012). Topics of inquiry often involve testing predictions or relationships between observable variables rather than developing, testing, or revising explanatory models (Carey & Smith, 1993; Chinn & Malhotra, 2002; McNeill & Knight, 2013; Windschitl, Thompson, & Braaten, 2008).

Students often use experiments to confirm knowledge already learned in class rather than using experiments to test or revise knowledge claims (Driver et al., 2000). As such, students do not perceive the need to further interpret or evaluate experimental conclusions (Carey & Smith, 1993; Driver et al., 2000) or corroborate authoritative sources of evidence before accounting for it in their models (Schwarz et al., 2009). In addition, students attribute "wrong results" to student failure rather than questioning the original question or methodology (Chinn & Malhotra, 2002). The prevalent use of textbooks to disseminate scientists' conclusions often black boxes the intellectual work done to construct that knowledge and reinforces unproblematic views of evidence and the scientific endeavor (Chinn & Malhotra, 2002; Osborne, 2010).

Students' decision-making and knowledge-building responsibilities are often limited in scope and have little consequence to students' learning. Although teachers might open investigations to some degree of inquiry, students often do not have a role in posing and investigating questions in service of building and revising explanatory models (Windschitl et al., 2008). As such, students do not necessarily perceive themselves as having the authority to investigate questions of interest to them and have little experience discerning what constitutes a good question or devising appropriate means for investigating questions.

Classroom discourse often involve students responding to teacher-initiated questions with known responses (Mehan, 1985) with little opportunity for students to construct knowledge with each other (Driver et al., 2000). The teacher is often the agent responsible for coordinating evidence to communicate information (Driver et al., 2000) and determining what counts as valid scientific knowledge (Sandoval, 2005) rather than letting students have the responsibility for evaluating each other's ideas (Banilower et al., 2013; Driver et al., 2000; Herrenkohl et al., 2011). Consequently, students have little role using the epistemologies of science to construct and evaluate scientific knowledge.

Reforms require teachers to adopt new roles involving skill sets and epistemologies that might be unfamiliar to them. Rather than being the locus of knowledge and authority, the teacher's role is to create opportunities and establish classroom norms to support students' role in constructing knowledge with each other (Duschl, 2007; Ford, 2008; Manz, 2014; Stroupe, 2014). Teachers play an important role for implementing reform practices, yet many teachers lack the subject matter content knowledge, pedagogical content knowledge, and experience with authentic science to design and support instruction that is responsive to students' developing explanations (Driver et al., 2000; Windschitl, 2003; Windschitl et al., 2008). Many teachers do not have access to high-quality professional development (Wilson, 2013) or practices-centered curriculum materials (Windschitl et al., 2008) to provide a vision for what this ambitious pedagogy and learning might look like in their classrooms. Even when teachers are motivated and buy into the goal of designing instruction around student sensemaking, it is challenging for teachers to make sense of and implement these reform practices without professional support (Alozie, Moje, & Krajcik, 2010; Lo, Krist, Reiser, & Novak, 2014; Windschitl, Thompson, Braaten, & Stroupe, 2012).

3. Research Questions

Given the classroom challenges related to implementing the goals of NGSS, this dissertation research explores two related research questions:

1. What successes and challenges emerge for students and teachers when students construct and evaluate explanatory models of phenomena with others?
2. How can we help teachers understand and enhance the meaningfulness of their students' engagement in the construction and evaluation of explanatory models?

By understanding how students and teachers interpret, take up, and modify these reform practices, we as a research community can identify pedagogical and epistemological challenges involved in learning science-as-practice and devise appropriate responses to realize our reform vision in K-12 classrooms.

In the next two sections, I examine previous efforts to incorporate aspects of authentic scientific practice in classrooms. Next, I synthesize work in the literature to propose a fruitful direction for promoting meaningful scientific practice that organizes classroom instruction around the development and use of explanatory models and cultivating communities of scientific practice that provide explicit opportunities for students to evaluate each other's ideas and work together to reach consensus.

4. Efforts to promote authentic scientific practice in classrooms

Efforts to promote authentic science classrooms have focused on enhancing students' *productive disciplinary engagement* in science classrooms, which Engle and Conant (2002) defined as combining “moment-by-moment, interactional aspects of student engagement with ideas of what constitutes productive discourse in a content domain" (p. 400). This engagement is productive in that students are using disciplinary norms and practices to make progress on constructing robust scientific knowledge with one another (e.g.,Ford & Forman, 2006).

Much research (e.g., Erduran, Simon, & Osborne, 2004; McNeill & Knight, 2013; McNeill, Lizotte, Krajcik, & Marx, 2006; von Aufschnaiter, Erduran, Osborne, & Simon, 2008) has focused on helping students attend to the structural aspects of scientific practice, such as the components needed to produce a written explanation or argument. For example, McNeill and colleagues (2009; 2008; 2006) have used the claim-evidence-reasoning (CER) framework to scaffold students’ use of evidence when constructing written explanations and arguments. In this framework, students state their claim, provide two pieces of evidence to support their claim, and write a statement connecting their evidence and claim (reasoning). Researchers such as Erduran et al. (2004) and Garcia-Mila, Gilabert, Erduran, and Felton (2013) have considered the presence of rebuttals as indicators of high-quality arguments because it demonstrates students’ ability to respond to alternative claims or arguments, an important feature of argumentation.

However, this attention to the components or steps needed to construct written explanations and arguments can lead to rote engagement in scientific practices by which students mimic aspects of scientific practice without understanding the underlying rationale for how and why these actions are important or helpful for achieving students’ scientific goals. For example, students using the CER framework could include two pieces of evidence without assessing the appropriateness of the evidence used to justify or persuade others of the validity of one’s argument because the teacher told them to do so.

In addition, teachers or students’ attention to the presence or absence of components might lead to less attention to the argument's ideas or the broader goals guiding the argument's development. For example, McNeill and Knight (2013) found that teachers participating in a professional development program designed to help teachers understand the structural and dialogical components of argument attended more to whether students' arguments contained the necessary components rather than students' use of evidence to persuade others or students' underlying ideas. Similarly, Jacobs, Lamb, Philipp, and Schappelle (2011) found that math teachers often use students' "correct" use of mathematical strategies as evidence of student understanding rather than considering evidence of whether students understood the mathematical principles underlying their use of the strategy to solve the problem. In both science and math examples, teachers are attentive to what students are doing rather than the underlying rationales for their decisions or evidence of conceptual understanding. Thus, this problem is not unique to science and cuts across disciplines.

4.1 Focus on epistemic aspects of scientific practice

McNeill and Knight (2013)'s findings reflect how teachers' attention to the structural aspects of the practice could hinder students' achievement of the broader goals for engaging in argumentation — the production of convincing, evidence-based arguments and the persuasion of others of the validity of one's claims. In contrast, Berland et al. (2016) argued that students need more than the ability to take the right steps in a process — students need to connect their knowledge-building goals with the epistemic considerations that should guide students' decisions in service of achieving those goals. For example, Berland and Reiser (2009) argued that students could enhance the persuasiveness of their arguments if they were more explicit about the nature of the evidence for their claim and explain why an external audience should be convinced of a given claim. Emphasizing the goal of persuading others, rather than having all the components of an argument, might compel students to think about important epistemic considerations, such as the appropriateness and sufficiency of the evidence when constructing persuasive arguments. Rather than serving as a list of components to include, these epistemic considerations provide meaning and purpose to the structural and dialogical aspects of argumentation in service of achieving students' scientific goals.

Berland et al. (2016) further argued that students' and teachers' implicit or explicit attention to the epistemic aspects of scientific practice could support students' meaningful engagement in scientific practices. The goal of persuading others and the epistemic considerations guiding students' use of evidence are *epistemic* in nature because they involve issues related to the construction of scientific knowledge (Kitchener, 2002; Sandoval, 2012) and the basis by which individuals decide what they know and how they know it (Stroupe, 2014). The goals provide purpose for students' knowledge-building work, while implicit or explicit attention to important epistemic considerations contributes to students' understanding of what they are doing and how their actions will help them achieve their scientific goals. Schwarz et al. (2009) made similar arguments by arguing for teachers to make explicit the *metamodeling knowledge*, or the purpose for engaging in aspects of the modeling practice in the context of modeling instruction (Schwarz & White, 2005). In doing so, students might better understand how their modeling decisions, such as their use of diagrams to make visible their ideas, could support students' efforts to make sense of phenomena and construct new knowledge rather than simply represent what they had already learned in class to the teacher.

In summary, foregrounding attention to the epistemic aspects of scientific practices, rather than the components or steps in a process, could be a useful means for supporting meaningful use of disciplinary norms and practices in classrooms. In doing so, we move beyond the surface-level decisions that students make, such as the inclusion of particular features in a diagrammatic model or the choice to include evidence to support a claim, to focusing on the meaning that students apply to their use of scientific practices and their knowledge-building decisions. Using evidence from students' decisions, such as what students include in their explanations or diagrammatic models or the questions that students pose in response to one another's ideas (c.f., Louca, Elby, Hammer, & Kagey, 2004; Sandoval, 2005), teachers could infer the epistemic considerations guiding students' decisions and use their insight to help students make progress in developing their explanatory models or construct more persuasive arguments.

4.2 Attending to students' and teachers' interpretation of reform practices.

As teacher educators and researchers, attention to the meaning that students and teachers apply to reform practices has implications for how students and teachers enact reform practices and whether they have the intended effect in the classroom. Students and teachers do not enact reform practices whole-cloth — they interpret and implement the goals, norms for behavior, and methods of new disciplinary practices through the lenses of their existing disciplinary beliefs, understandings, and experiences (Berland, 2011; Hogan & Corey, 2001; Spillane, Reiser, & Reimer, 2002; Wilson, Shulman, & Richert, 1987). For example, when Hogan and Corey (2001) attempted to involve students in the evaluation of one another's ideas, students interpreted the opportunity as an invitation to identify student weaknesses rather improve one another's work. In doing so, students used their existing beliefs to interpret the activity's purpose rather than the role that critique plays in the context of authentic scientific practice. To prevent students from perceiving the evaluation of each other's ideas as personal attacks, Herrenkohl and Guerra (1998) argued that students need to understand how and why this activity is useful and productive for improving the validity of one another's ideas. In addition, teachers could establish classroom norms and goals that dictate how students and teachers ought to interact with one another so that students build upon each other's ideas to reach consensus.

Teachers often modify curriculum materials (e.g., Keys & Bryan, 2001) or learned strategies (e.g., Windschitl et al., 2012) in ways that are consistent with their interpretation of reforms and what they believe will be effective in their own classrooms. Consequently, many classrooms exhibit a *composite culture*, which Hogan and Corey (2001) defined as a "mixture of ideals of professional science practice and pedagogical ideals as filtered through the realities of classroom life and scientific practice" (p. 216-17). As shown in McNeill and Knight (2013)'s study, the features of scientific practice that teachers attend to may not be the features of consequential importance in the context of authentic scientific practice in classrooms.

To help students and teachers understand the nature of classroom reforms and why they are important, Hogan and Corey (2001) argued that it was important to consider how what was being asked of students and teachers might differ from existing classroom practices and identify what actions might need to be taken to bring reform practices into the classroom. As the agents responsible for accomplish this knowledge-building work, Duschl (2007) argued that it was important to elicit and build upon students' existing understandings of these reform practices, such as argumentation. Keys and Bryan (2001) suggested that researchers collaborate with teachers to design and implement reform curriculum materials to help teachers develop an understanding of the intended reforms and how to realize the reform vision in their classrooms. Hammerness (2006) argued that it was important to elicit teachers' existing beliefs related to effective classroom teaching and learning and the role that students and teachers play in that work. In doing so, teacher educators might better understand how teachers might interpret new reform practices, develop appropriate strategies to help teachers realize the reform vision in their classrooms.

5. Approaches to supporting meaningful scientific practice

Recognizing that previous efforts to incorporate disciplinary norms and practices have fallen short of our goal for students using scientific practices in meaningful ways, how does a teacher accustomed to a didactic, content-driven instructional approach begin to make shifts towards teaching science-as-practice and facilitate the process of students figuring things out together without giving the answer away?

In this section, I examine three approaches that I explore in this dissertation research for promoting the shifts needed to promote learning science-as-practice in classrooms. The first goal of NGSS involves shifting the knowledge-building goals towards the construction of explanatory models. In response, this dissertation research examines the central role that modeling as a central and organizing practice could promote sensemaking in science classrooms. I argue that there is a dialectic relationship between the second and third goals of NGSS, as the means by which students learn how to meaningfully engage in the practices is through their legitimate participation in the construction and evaluation of scientific knowledge (Ford, 2008). As such, I begin with a discussion of how students can learn how to meaningfully engage in scientific practices through their legitimate participation in communities of scientific practice. Next, I argue for the use of activity structures, or ways of organizing classroom activity and classroom discourse (Polman, 2004), that create explicit opportunities for students to publicly share and evaluate each other's ideas. In doing so, teachers explicitly position the students as the agents responsible for constructing and evaluating scientific knowledge, while creating opportunities for students to develop their understanding of the epistemic criteria and disciplinary practices through their participation.

5.1 Modeling as a central practice

One of the goals of NGSS involves shifting the goals of school science from accumulating scientific knowledge towards the construction of explanatory knowledge. Rather than viewing scientific practices as eight distinct practices, Passmore, Gouvea, and Giere (2014) argued for "placing a model-based view of science at the center" to bring coherence to all eight practices in service of developing and using explanatory models of phenomena. Through using modeling as a focal, organizing practice, it allows teachers to accomplish the goal of constructing explanatory knowledge and bringing coherence to the eight scientific practices. When engaged in the modeling practice, students pose questions about phenomena (*asking questions*) and construct their initial ideas to explain how and why the phenomenon occurs as it does (*constructing explanations*). Students devise methods to test their initial ideas (*planning and carrying out investigations*) (Passmore & Svoboda, 2011). Students *analyze and interpret the data* and use the empirical findings to support or refute theoretical explanatory components and underlying processes that can explain their observations (Windschitl et al., 2008, p. 15). Students can then use their diagrammatic models to facilitate the communication of their ideas to others (*obtaining, evaluating, and communicating information*) (Latour, 1990). Students use criteria to assess the models' ability to explain the data and its consistency with other models (Passmore & Svoboda, 2011). Students use evidence and argument to reconcile competing claims to reach consensus (*engaging in argument from evidence*) (Driver et al., 2000; Herrenkohl et al., 2011; Lehrer & Schauble, 2006b; Passmore & Svoboda, 2011; Schwarz et al., 2009). Students test their model's ability to explain other situations and revise them to create a model that can explain a range of situations (Schwarz et al., 2009).

5.1.1 Existing classroom uses of models. Studies examining existing classroom uses of models suggest challenges related to the purpose for constructing models. Students and teachers often use models to *represent* something in the world or communicate information rather than to explain (Grosslight, Unger, Jay, & Smith, 1991; Lehrer & Schauble, 2006a; Schwarz et al., 2009; van Driel & Verloop, 1999) or make predictions about related phenomena (Schwarz et al., 2009). For example, many science classrooms construct physical, 3-D models that resemble objects of study, such as the parts of the cell or to show how the planets orbit the sun. Although these representations can help students and teachers depict phenomenon, students do not always use these representations to explain scientific phenomena. Passmore et al. (2014) identified potential confusion in teachers' and students' understanding about what constitutes a scientific model and why they construct them, "Models are not simply *of* phenomenon, they are tools to be *used for* some reasoning about that phenomenon" (p. 1180).

External representations do play an important role in mediating student sense-making. For example, students can externalize their *conceptual* or mental models in the form of diagrammatic *expressed models* (hereafter described as diagrammatic models) (Gobert & Buckley, 2000). Constructing diagrammatic models can help students make visible components and processes important for explaining abstract and complex phenomena (Harrison & Treagust, 2000; Schwarz et al., 2009) and explore the connections between ideas (Schwarz & White, 2003; Windschitl et al., 2008). Figure 1.2 shows an example of a diagrammatic model used to explain how and why students could detect an odor from a distance. In the diagram, the student used arrows to show how the random movement of the odor molecules (circles) through the air led to the detection of the odor from a distance.

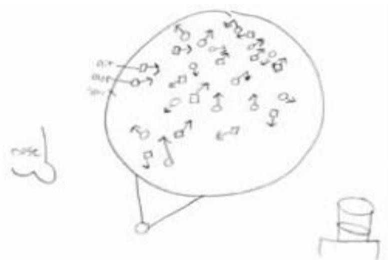

Figure 1.2. Diagrammatic model explaining how odor moves across the room. In this diagrammatic, expressed model, the student represented the relevant non-visible components, air (squares) and odor (circle) molecules, and processes, the molecule's random motion (arrows), to explain how and why students could detect the odor from a distance.

However, these diagrammatic representations could be used in less meaningful ways, as they could be used to depict rather than to explain scientific phenomena. Alternatively, these models could simply be tools to show the teacher what students know rather than used to mediate the co-construction of consensus knowledge. In addition, the focus of students' efforts could be on the generation of the diagrammatic model rather than development of students' underlying conceptual model. For example, Schwarz et al. (2009) found that students often include "details" or features, such as color, which have little connection to the underlying goal of explaining phenomena.

One reason for these less scientifically meaningful uses of modeling is that many teachers have not had previous experience, as students or adults, using models in scientifically meaningful ways to make sense of phenomena, (Davis et al., 2010; Windschitl, 2003; Windschitl et al., 2008). Consequently, teachers might not have an authentic understanding of what models are or how students could use them to make sense of scientific phenomena. In addition, there are few examples of model-based curricula to support a different perspective on modeling (Windschitl et al., 2008).

5.1.2 Promoting model-based reasoning in classrooms. This dissertation builds upon Schwarz et al. (2009)'s work to explore the meaning that students and teachers apply to modeling work. In particular, I am interested in studying the meaning that students apply to their use of diagrammatic models: What is the purpose for constructing diagrammatic models? Do students use diagrammatic models to communicate their ideas to others or mediate sensemaking? In what follows, I briefly review research promoting authentic engagement in modeling to identify areas where researchers were successful in promoting more explanatory uses of models and areas that require additional support.

Davis et al. (2010) found that pre-service teachers were more comfortable using models to explain and represent phenomena rather than using models to make predictions about new phenomena. Windschitl et al. (2008) found that pre-service teachers were more comfortable using observable, rather than non-visible, theoretical components and processes in their explanatory models, which is consistent with students and teachers' typical experience with science as investigating relationships between measurable variables rather than developing explanatory mechanisms.

Schwarz et al. (2009) studied elementary and middle school students' use of curriculum materials that made explicit the *metamodeling knowledge*, or the epistemic understandings that guide and provide purpose for students' engagement in aspects of the modeling practice (Schwarz & White, 2005), and students' use of diagrammatic models to mediate student sensemaking. With this support, they found that students' models became more explanatory in nature over time, with increasing consideration of non-visible explanatory mechanisms. In addition, older students recognized the utility of using multiple models to explain complex phenomena and other related situations. These findings suggest that teachers' explicit use of metamodeling knowledge could support students' meaningful engagement in modeling because students understand how their use of models could be useful for explaining phenomena.

Researchers found that students and teachers had difficulty developing investigations to test their ideas (Windschitl et al., 2008) and using their findings to revise their models (Schwarz et al., 2009). One potential explanation is that students have little experience posing and investigating questions of their own choosing (Lehrer, Schauble, & Lucas, 2008; Windschitl et al., 2008) or using experiments to test the validity of their own ideas (Carey & Smith, 1993; Driver et al., 2000). Consequently, students have little experience interpreting and using evidence, particularly quantitative evidence, to justify or revise their claims (Sandoval & Millwood, 2005). These challenges point to broader challenges involved in how students use evidence in service of developing students' explanatory models.

5.2 Participating in communities of scientific practice

Researchers have argued that the norms and practices of science are unique to the discipline and cannot be learned simply by exposing students to language, culture, tools, and epistemologies of science or watching others engage in this work. Driver et al. (2000) argued that learning the practices of science involves "inducting learners into the particular ways of representing the world used by scientists and socializing them into adopting the conceptual tools of that culture" (p. 298). Duschl and Osborne (2002) made similar arguments that this learning involves students' "*immersion* into the language, culture, and tools of scientific activity" (p. 45). Ford and Forman (2006) argued that students develop understanding of the practices used to construct knowledge and the epistemic criteria governing that work through their iterative participation in the construction and evaluation of scientific knowledge.

Similar to these researchers, I take a situated perspective that students learn how to meaningfully engage in scientific practices through their participation in *communities of practice*, which Lave and Wenger (1991) defined as "an activity system in which participants share understandings concerning what they are doing and what that means in their lives and for their communities" (p. 98). Novices gain develop expertise through their legitimate participation in the knowledge-building work and interactions with knowledgeable others who themselves have been inducted into these "ways of knowing" and can model and make visible the cognitive processes guiding their decisions (Collins, Brown, & Newman, 1989; Lave & Wenger, 1991). Thus, students learn how to use disciplinary norms, tools, and practices in increasingly meaningful and sophisticated ways through their use and interactions with others in the context of scientific practice rather than through peripheral observation. For example, Ford (2012) studied students' efforts to develop and receive feedback on methods to investigate the relationship between ramp steepness and object's speed. He found that without the teacher's intervention and feedback, the students' proposed methods would not generate sufficient evidence to adequately support the desired claims. Later when students had the opportunity to evaluate each other's findings and conclusions, the students were more attentive to each other's data collection methods and how they might affect the validity of the students' conclusions. These findings suggest that the epistemic considerations guiding the teachers' feedback likely influenced the issues that students attended to when evaluating each other's ideas.

5.3 Explicit opportunities for students to construct and evaluate each other's ideas.

To address the third goal of shifting the responsibility for constructing and evaluating knowledge from the teacher to the students, this dissertation research explores activity structures in which students ask clarifying questions, critique one another's ideas, and reconcile each other's ideas in service of constructing a class consensus model. Manz (2015) argued that requiring students to respond to and defend their arguments amidst critique destabilizes students' own understanding and prompts students to rethink what they know and how they know it. As a result, students are likely to deepen or potentially revise their own understanding.

Ford (2012) cautioned that if the knowledge-building goal only involved students getting the right explanation, it is easy for the teacher to persist in their traditional evaluative role. In contrast, explicit support for students' role in constructing and evaluating knowledge could accomplish all three goals of NGSS: the development of robust, explanatory knowledge, enhancing the students' knowledge-building role, and developing understandings of the norms and practices used to construct scientific knowledge.

5.3.1 Development of epistemic considerations to evaluate students' ideas. For students to have a legitimate role in evaluating each other's ideas, students need a principled way to evaluate and reconcile one another's ideas to reach consensus. When Ford (2012) provided students the opportunity to construct and provide feedback on each other's proposed methods for investigating the relationship between ramp steepness and object's speed, the students played a minimal role in evaluating students' ideas and were audibly frustrated when Ford and the lead teacher critiqued the "scientific" nature of students' proposed methods, "So everything we did so far is wrong?" (p. 224). One potential explanation for students' frustration is that students were given the opportunity to devise their own methods, yet did not have access to the epistemic criteria used by the teachers to assess the "scientific" nature of the methods. This lack of access might also explain why students did not participate in the evaluation of each other's ideas.

Ford (2012)'s findings point to the need to help students develop a meaningful understanding of the epistemic considerations that should guide the construction and evaluation of students' models. I use Berland et al. (2016) assigned students audience roles that embraced the epistemic issues involved in assessing the coordination of claims with evidence. Assignment of these roles resulted in students adopting a more active role in coordinating theories with evidence and evaluating students' ideas than students in a classroom where the teacher did not assign audience roles. Despite some limitations, including constraints preventing students from adopting multiple audience roles at a given time, the study suggests how students' explicit attention to these important epistemic issues could be useful for helping students construct and evaluate evidence-based claims.

Interesting research by Ryu and Sandoval (2012) considered how explicit attention to students' interpretation of knowledge-building goals and the co-construction of understanding for why these goals were important and the steps needed to achieve those goals could improve students' engagement in scientific practices. From these discussions, the students and teacher co-constructed four epistemic criteria: 1) causal structure, the presence of a causal explanation for a phenomenon; 2) causal coherence, the extent to which aspects of an explanation make sense together; 3) the citation of evidence; and 4) the justification for the evidence. Ryu and Sandoval (2012) concluded that teacher's efforts to co-construct these epistemic criteria and why they were important enhanced the quality of students' written arguments.

5.3.2 Argumentation: Means for students to reconcile their ideas. Once students understand the goal for evaluating each other's ideas and the epistemic considerations that should guide the evaluation of students' ideas, how do we facilitate students' engagement in argumentation to evaluate and reconcile competing ideas to reach consensus? In this section, I discuss two sets of challenges: 1) the epistemic challenges involved in students' use of evidence to justify, defend, and persuade others of the validity of their ideas and 2) the pedagogical challenges involved in supporting students' engagement in productive discourse to mediate argumentation.

Challenges: Students' use of evidence. Students often have difficulty explaining the appropriateness of evidence (Bell, 2000; Driver et al., 2000; McNeill et al., 2006) or determining whether they have sufficient evidence to support the desired claim (Sandoval & Millwood, 2005). In response, Berland and Reiser (2009) suggested prompting students to consider why an external audience ought to believe and be convinced of a particular claim. In doing so, students might consider issues related to the sufficiency or appropriateness of the evidence and decide whether they might need alternative evidence to persuade others of the validity of one's claims.

When persuading others of the validity of one's claims, Driver et al. (2000) found that students typically affirm evidence that they believe to be true despite the presence of evidence for the contrary (Zeidler, 1997), and are not likely to revise their beliefs in response to counter evidence (Chinn & Brewer, 1998). This is particularly true when students perceive the goal of argumentation as "winning" an argument rather than developing a consensus explanation of the phenomenon (Berland & Reiser, 2009; Garcia-Mila et al., 2013). In response, Herrenkohl et al. (2011) argued that casting epistemic doubt on all theories could prevent students from automatically favoring one theory over another and promote objective consideration of a theory's evidentiary support before assessing its validity. Sandoval (2005) argued that removing absolute certainty from knowledge helps focus students' attention on the use of epistemic criteria to evaluate students' knowledge.

Challenges: Organizing productive discourse. The construction of consensus knowledge is mediated by students' engagement in productive, accountable talk (Michaels et al., 2008), yet supporting students' efforts to engage in such discourse can be challenging (Alozie et al., 2010; Osborne, Erduran, & Simon, 2004). Manz (2014) argued that teachers need a good question to elicit a range of viable student ideas that could be resolved through argument, yet

McNeill and Knight (2013) found that identifying problematic, contentious, phenomenon-driven questions can be challenging for teachers.

Alozie et al. (2010) studied teachers' use of prompting and guiding questions designed to promote productive scientific discourse in curriculum materials. Without additional professional support, they found that teachers often reverted to more traditional teacher-initiated discourse patterns (e.g., IRE). One explanation is that many teachers have little experience engaging in the normative discourse practices used to mediate the construction of knowledge (Duschl & Osborne, 2002). As such, McNeill and Pimentel (2010) argued that teachers themselves first need to learn how to meaningfully respond to and critique each other's ideas before they can model and support these practices in their students. A second explanation is that teachers often lack the pedagogical skills needed to organize students' engagement in argumentative discourse within the classroom (Driver et al., 2000) or the epistemological framework in which to interpret how to use these prompts to facilitate students' efforts to explain scientific phenomena (Alozie et al., 2010; Windschitl et al., 2012).

In response to the challenges involved in supporting the productive talk during model-based instruction, Windschitl et al. (2012) identified three discourse tools to help teachers anticipate resources that students might draw upon to make sense of phenomena and guide the planning of classroom discussions. However, these discourse tools can be up to 4-5 pages in length, reflecting the complex task involved in supporting model-based discussions in classrooms. Although these tools could be helpful for developing teachers' vision for what instruction could look like and conceptualizing potential pathways for discussion, these tools might be less helpful for guiding teachers' in-the-moment responses to students' ideas without making explicit the underlying principles or epistemic issues guiding these discourse moves. In response, this dissertation research seeks to identify a core set of epistemic questions to guide teachers' decisions in service of develop students' explanatory models.

5.4 Summary of approach

Although research indicate that students' meaningful participation in modeling is not common, growing research suggests that they can do so if given the opportunity and adequate support (Driver et al., 2000; Duschl, 2007; Ryu & Sandoval, 2012). To promote shifts in classroom practice to be more aligned with the goals of NGSS, I have argued for cultivating communities of scientific practice in classrooms where students have explicit opportunities to iteratively construct and evaluate each other's explanatory models. Such activity structures can promote student agency because it foregrounds students' decision-making roles while creating opportunities for students to use disciplinary norms, practices, and tools to construct reliable scientific knowledge with others. Through their legitimate participation in the iterative construction and evaluation of explanatory models, students understand the justification for their ideas, because they have had to defend their ideas to others, and develop an understanding of the practices and epistemic considerations that guide the construction of explanatory models. However, more work is needed to understand how to facilitate students learning science-as-practice through their meaningful participation in such an activity structure (Ford, 2008) — particularly in the context of students' engagement in modeling. Thus, this dissertation research seeks to fill this gap to consider how supporting this activity structure could enhance the students' knowledge-building role and the meaningfulness of students' participation in the development and use of explanatory models.

At the same time, this literature review has identified potential epistemological and pedagogical challenges involved in this endeavor. Students and teachers do not have experience using models in meaningful ways. Organizing classroom discussions and activities in service of developing students' explanatory models can be challenging for teachers and students alike. Although diagrammatic models have the potential to help students attend to theoretical, non-visible explanatory components and processes (Schwarz et al., 2009), they are often used in less meaningful ways to represent phenomena rather than to explain or mediate students' sensemaking with others. These findings raise the issue of how we can help teachers support students' use of diagrammatic models in service of explaining rather than simply depicting scientific phenomena.

Chapter 2: Dissertation Overview

The dissertation involves two related goals that are addressed in a different study. The first goal involves understanding the successes and challenges involved in supporting students' meaningful participation in the construction and evaluation of explanatory models with others. Building on these findings, the second goal involves developing ways to address these challenges and promote shifts in classroom practice to be more aligned with the goals of NGSS.

1. Study 1: Analyzing the successes and challenges involved in supporting students' participation in the construction and critique of explanatory models

Study 1 investigated Research Question 1, "What successes and challenges emerge for students and teachers when students construct and evaluate explanatory models of phenomena with others?" I studied three classrooms that used NGSS-aligned curriculum materials designed to support students' role in the construction and evaluation of explanatory models with others.

1.1 Analytical Lenses

To identify the successes and challenges involved in supporting ambitious scientific practices, we need a principled way to understand what is working well and what is not — and why. As such, I frame the epistemic issues posed by each NGSS shift in the form of questions that teachers or researchers could apply to a given classroom enactment to understand the extent to which students' engagement in modeling is meaningful: 1) *Epistemic aim: What is the goal of the knowledge-building work?* 2) *Epistemic considerations: What ideas or questions are guiding students' decisions?* and 3) *Epistemic agency: Who is responsible for doing this work?* I refer to these epistemic questions as *analytical lenses*, because they provide teachers and researchers with a window through which to analyze the extent to which students are participating and meaningfully engaged in the construction of knowledge with one another. By studying students' actions and stated rationales, I could infer the epistemic aim or epistemic considerations could be guiding their decisions to reach consensus (Louca et al., 2004). In addition, I could examine the role that students played in posing ideas and evaluating each other's ideas to understand how the knowledge-building responsibilities were distributed between the students and teacher.

In Chapter 3, I present my argument for why I chose these analytical lenses and how each lens could be useful for identifying the epistemic and pedagogical challenges involved in supporting students' role in evaluating each other's explanatory models to reach consensus (RQ1). Although other researchers have previously advocated for consideration of these epistemic issues, this dissertation will argue for *integrated* attention to the issues posed by each analytical lens to support students' meaningful engagement in scientific practices.

1.2 Study Design

I studied three teachers with different levels of experience with modeling-centered instructional materials with the hypothesis that teachers with less experience might be less equipped with strategies to support students' meaningful use of disciplinary norms and practices to construct and evaluate each other's explanatory ideas. By understanding how students and teachers interpret, take up, and modify these reform practices in the context of their use in practice, I hoped to 1) identify epistemological and pedagogical challenges involved in students' and teachers' attempts to meaningfully use disciplinary norms and practices to construct and evaluate explanatory models with others and 2) understand the effects of differential student access to opportunities to engage in the knowledge-building work.

Chapter 4 explains further the methods used to investigate Research Question 1, while Chapter 5 explains the analytical methods used to operationalize the analytical framework presented in Chapter 3. Chapter 6 explains the observed successes and challenges involved in supporting students' role and meaningful participation in the construction and evaluation of students' scientific models. Chapter 7 discusses the significance of these findings in the literature.

2. Study 2: Learning to Notice: Assessing and enhancing the meaningfulness students' engagement in scientific practices

In Study 1, I used the three analytical lenses to investigate the successes and challenges that emerge when students and teachers attempt to use ambitious scientific practices and pedagogy to construct and evaluate scientific knowledge. The goal of Study 2 was to build on this work to consider how a teacher could use the issues posed by the analytical lenses to analyze her own classroom practice and use her interpretations to inform her decision-making to enhance her students' opportunities to participate and use scientific practices in increasingly meaningful ways. In other words, Study 2 explored the usefulness of the analytical lenses in the context of classroom instruction and investigates Research Question 2, "How can we help teachers understand and enhance the meaningfulness of their students' engagement in the construction and evaluation of explanatory models?"

2.1 Study Context

To investigate Research Question 2, I conducted a case study of a teacher named Kami. During Study 1, I found that Kami, rather than her students, played a greater role in synthesizing and evaluating students' ideas. When reflecting on her students' learning, she reported frustrations with persuading students of the meaningfulness of their scientific work and challenges with encouraging her students to participate in the construction of explanatory knowledge. Thus, there were differences between the teacher's expectations and actual opportunities for students to participate in the knowledge-building work.

This study differs from previous professional development studies in important ways. Some studies explain that the lack of meaningful engagement in scientific practices involves teachers' lack of subject matter content knowledge needed to help students develop deep conceptual understandings of scientific phenomenon or experience with authentic science to have authentic epistemologies of science (e.g.,Windschitl, 2003). However, Kami had expert content knowledge and an authentic understanding of the scientific endeavor due to her background as a professional scientist. Other studies have suggested that a barrier to changing one's practice is the lack of buy-in of teachers into the reforms. However, Kami did understand the value of these reform efforts and was eager to reflect, invite others to observe her classroom, and consider ways to improve her classroom practice. Kami's challenges with supporting ambitious scientific practices and pedagogy are supported by research demonstrating that teachers, even when they are motivated and buy into the goal of designing instruction around student sensemaking, still find it challenging to implement reform practices without professional support (Alozie et al., 2010; Lo et al., 2014; Windschitl et al., 2012).

2.2 Study Design

To promote change in Kami's classroom practices, my approach involved revising *what* Kami noticed in the classroom so that she could attend to the elements of classroom practice that were relevant for supporting her students' engagement in meaningful scientific practice. For example, did her students understand the rationale for why their scientific work was worthwhile for their own learning? I used teacher noticing as a lever of change because teachers act on what they notice (Jacobs et al., 2011). Thus, if we want to teachers to better support students' meaningful use of scientific practices, we should ensure that they are noticing the components of scientific practice that are important for promoting these shifts.

My professional development approach involved using the analytical lenses as a framework for understanding the teacher's considerations and commitments guiding her decisions, helping Kami reflect on her instructional practice, and using her interpretations to inform her classroom decisions. I explain in more detail the model for teacher learning and the professional learning approach used to promote shifts in Kami's classroom practice in Chapter 8. I used the same analytical methods used in Study 1 to track changes in classroom practices over the course of the intervention. I detail these shifts in classroom practices in Chapter 9.

I conclude the dissertation with a discussion of the findings across the two empirical studies to consider how the findings from the two studies could contribute to our field's understanding of how we can help teachers use ambitious pedagogy to promote shifts in classroom scientific practices.

Chapter 3: Framework for analyzing students' meaningful engagement in scientific practices

In the previous chapter, I argued that there are three core shifts involved in implementing NGSS in classrooms: 1) shifting the goal of student's knowledge-building work from learning scientific facts towards constructing explanatory knowledge; 2) ensuring that students are using scientific practices in meaningful, rather than rote, ways to achieve their scientific goals; and 3) shifting who is responsible for doing this work from the teacher to the students. These shifts move beyond examining what students do or say to examining the underlying rationales for students' knowledge-building decisions. However, these shifts in classroom practice involve ambitious pedagogy, epistemologies, and roles that might be unfamiliar and challenging for students and teachers.

To help teachers learn new pedagogical practices, Grossman et al. (2009) argued that educators need to break down complex practices into its components and help teachers understand how and why each component contributes to the overall activity. As such, promoting practices-centered pedagogy and learning in classrooms involves the teacher and students understanding what constitutes meaningful engagement in scientific practices and why these components have consequence on students' learning. In this chapter, I propose a framework composed of three analytical lenses that embrace the epistemic issues posed by these core shifts in NGSS. Using these analytical lenses, teachers can analyze the extent to which students' use of scientific practices is scientifically and personally meaningful and use their interpretations to inform their decision making. In what follows, I first provide an overview of the analytical lenses before discussing each in more detail.

1. Overview of Framework

1.1 Epistemic aim: What is the goal of the knowledge-building work?

The first analytical lens examines the *epistemic aim* guiding the students' and teacher's decisions or activities. Chinn et al. (2011) defined epistemic aim as the goal for acquiring some type of knowledge or understanding (p. 142). For example, when students are sharing and evaluation of each other's explanatory models, what is the reason for doing this activity? Are students simply sharing their ideas, or is the activity designed to help students reach consensus and develop a more robust understanding about a phenomenon? Furthermore, this lens also examines the *epistemic value* of the epistemic aim or an understanding of how and why this knowledge is worth pursuing from the perspective of the discipline and the students (Chinn et al., 2011). When evaluating epistemic aims, this analytical lens examines the extent to which the knowledge-building goal involves obtaining scientific knowledge that students could use to explain and make predictions about scientific phenomena, rather than acquire discrete scientific facts, as this epistemic aim is more epistemically valuable because students recognize how and why this knowledge is useful from the perspective of the discipline and students.

1.2 Epistemic considerations: What ideas or questions are guiding students' decisions?

The first analytical lens examines the goal and purpose for engaging in the knowledge-building work. However, how do students use their vision for what they're trying to do to guide their moment-to-moment decisions? The second goal of NGSS involves students using disciplinary norms and practices in meaningful ways so that they understand what they are doing and how their actions will help them achieve their scientific goals. In response, the second analytical lens moves beyond examining what students do to inferring the epistemic considerations guiding their scientific decisions (Berland et al., 2016).

1.3 Epistemic agency: Who is responsible for doing this work?

The first two goals of NGSS refer to the need for students to meaningfully engage in knowledge-building work that is valued and guided by disciplinary norms and practices. However, this work cannot happen without students having the opportunity to construct and evaluate scientific knowledge. Thus, the third analytical lens examines the extent to which students have *epistemic agency*, or a role in making decisions related to the construction and evaluation of scientific knowledge. For example, how are the knowledge construction and evaluation responsibilities distributed between the students and teacher? Are students' ideas taken up and used to shape the classroom knowledge?

1.4 Summary

Using a similar representation to Figure 1.1 (see Chapter 1, Section 1.4) that illustrated the interrelationships between the goals of NGSS, Figure 3.1 illustrates the interrelationships between the analytical lenses of this framework and how they could be used to support students' meaningful engagement in scientific practices. If students are to adopt a more active knowledge-building role, it is important for students to be given the opportunity to make decisions related to constructing scientific knowledge and evaluate the extent to which they have achieved their scientific goals. For this work to be meaningful for students, students need to understand the purpose and epistemic considerations that should guide their scientific decisions.

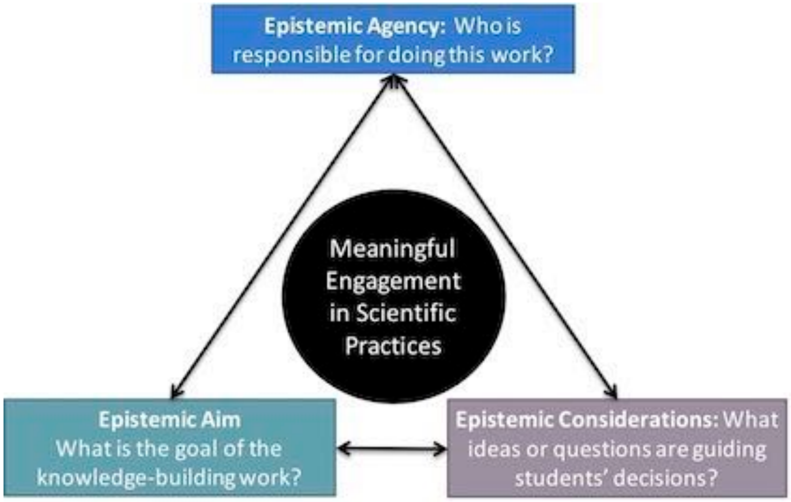

Figure 3.1. Framework for analyzing students' meaningful engagement in scientific practices

In what follows, I explain in detail the issues posed by each analytical lens and how students' and teachers' synergistic attention to these issues could enhance the meaningfulness of students' engagement in scientific practices.

2. Epistemic aim: What is the goal of the knowledge-building work?

2.1 Role of epistemic aim in scientific practice

When studying the meaning that students apply to their engagement in scientific practices, it is important to analyze the students' and teachers' interpretation of the epistemic aim guiding students' knowledge-building work and why this work is epistemically valuable from the perspective of the discipline and students. Students' interpretation of the epistemic aim influences their understanding of what is needed to accomplish that goal, the adopted student roles, and the norms governing students' participation in the knowledge-building work (Berland & Hammer, 2012; Ryu & Sandoval, 2012). For example, researchers found that students' goal for engaging in argumentation influenced their willingness to consider the relevance of competing ideas or revise their own ideas in light of alternative ideas or evidence. Garcia-Mila et al. (2013) found that students whose goal was to win an argument used data to justify their ideas, yet did not consider the limitations of their own claims. Berland and Reiser (2011) found that students with similar goals rarely revised their ideas in light of challenges or questions. In contrast, Garcia-Mila et al. (2013) found that students who had a *deliberative* goal to reach consensus with others showed evidence of including rebuttals in their arguments, as the epistemic aim prompted students to respond to each other's ideas and critiques and recognize potential limitations in their own arguments. Thus, the students' interpretation of the epistemic aim guiding their engagement in argumentation influenced students' use of evidence and the extent to which students were compelled to work together to reach consensus.

Hammer, Elby, Scherr, and Redish (2005) argued that the epistemic aims guiding students' knowledge-building work are dynamic and responsive to changes in the situated context of students' scientific activity. Students receive contextual cues from the teacher about what ideas are important and valued (Lidar, Lundqvist, & Ostman, 2006). Berland and Hammer (2012) argued that these contextual cues influence students' *framing*, or sense of what is going on at a particular moment (Goffman, 1974), and more specifically their *epistemological framing*, which accounts for students' perception of the epistemic aim and what is needed to accomplish that work. As such, students' perceived epistemic aims might differ from the students' (or teacher's) stated goals or beliefs about the scientific endeavor (Chinn et al., 2011). For example, a teacher might ask students to propose their own explanations for a phenomenon without worrying about whether it was the "right answer." However, if the teacher affirmed or revoiced particular student responses, students might interpret the affirmed responses as the "correct" answer and converge on particular ideas regardless of their original ideas or interpretation of the evidence. Berland and Hammer (2012) would refer to this lack of alignment between the teacher and students' frames or interpretation of what they were up to in a situation as a *discordant* *discussion*. Because students' epistemic aims are dynamic and can differ from the students' or teacher's stated goals, it is important from an analytical perspective to use contextual cues and evidence from students' and teachers' actions to infer the epistemic aims guiding the students' and teachers' decisions (Louca et al., 2004; Sandoval, 2005).

2.2 Meaningfulness of epistemic aim

I extend Berland et al. (2016)'s construct of meaningfulness to assess the epistemic value of a particular epistemic aim from the perspective of the discipline and the students. In what follows, I explain what it means to have a scientifically and personally meaningful epistemic aim.

2.2.1 Scientifically meaningful. For an epistemic aim to be *scientifically* meaningful, students need to understand why this knowledge is worth engaging from the perspective of the discipline. The goal of science is not to accumulate discrete pieces of knowledge by reading sections in a textbook; rather, a central goal of the scientific endeavor involves developing explanatory knowledge (Berland et al., 2016; Lehrer & Schauble, 2006b; Passmore & Svoboda, 2011; Schwarz et al., 2009). Although both goals are epistemic in that they involve acquiring knowledge, the construction of explanatory knowledge is more epistemically valuable than the accumulation of discrete facts because of its usefulness for explaining and making predictions about new scientific phenomena. Another indicator of a scientifically meaningful epistemic aim is that it involves a "big idea," in which students learn fundamental ideas and processes that are relevant to students' lives (Windschitl et al., 2012, p. 889). Taken together, scientifically meaningful epistemic aims involve the development of scientific knowledge that has fundamental disciplinary importance and can be used to explain a range of scientific phenomena.

2.2.2 Personally meaningful. Reforms call for *students* to be the agents responsible for using scientific practices to construct, evaluate, and revise scientific knowledge. As such, I attempted to understand the extent to which students find the epistemically aim to be *personally meaningful* to them, meaning that students recognize its worthiness for their own learning. When assessing characteristics of a personally meaningful epistemic aim, Engle and Conant (2002) argued that the goal of students' knowledge-building work should compel students to investigate the problem and sustain student engagement over time.

Accounting for students' funds of knowledge. Accounting for students' interests and *funds of knowledge* (Moll & Greenberg, 1990) could enhance the epistemic value of the epistemic aim because students recognize how their funds of knowledge could have consequential, rather than peripheral, effects for achieving the desired goals. For example, students might construct a rap song to describe differences in how tectonic plates move at different plate boundaries. However, students' use of their funds of knowledge plays a peripheral knowledge-building role, as leveraging students' interest does not play a direct role in facilitating students' understanding for how or why plate movement leads to various phenomena, such as earthquakes.

In contrast, Lee (2001)'s cultural modeling work shows productive and consequential uses of students' funds of knowledge in service of achieving important epistemic aims. For example, Lee (2001) documented the challenges that some African American students encountered with interpreting metaphors in canonical literary texts due to students not having the social or cultural knowledge through which to understand the symbolism often referenced in these texts. To scaffold students' ability to achieve this goal, students first interpreted metaphors using familiar vernacular texts before applying these learned strategies to interpret, with scaffolding, metaphors found in canonical texts. In this way, leveraging students' funds of knowledge could enhance the accessibility of the knowledge-building work by removing barriers preventing students' from achieving and potentially recognizing the value of the work for their own learning.

Complex epistemic aims. Researchers argue that epistemic aims should be sufficiently complex such that their solutions are not straightforward and could elicit multiple viable ideas for students to reconcile using argument and evidence (Engle & Conant, 2002; Lehrer et al., 2008; Manz, 2014; Windschitl et al., 2012). For example, a teacher could ask students to plot and explain the location of earthquakes around the world. Through analysis of these patterns, students might conclude that earthquakes occur along plate boundaries. Teachers could then show students a map showing that mountains only form along certain plate boundaries and not others. This new information creates a new problem for students to figure out, prompting students to revise their existing models to account for new evidence. In addition, explaining complex phenomena lends authenticity to efforts for students to work together because the task requires varied perspectives and ideas to solve the problem (Manz, 2014). In addition, achieving complex epistemic aims with others compels students to consider authentic epistemologies, such as considering the justification for their claims, because they need to persuade others of their ideas' validity.

3. Epistemic considerations: What ideas or questions are guiding students' decisions?

3.1 Role of epistemic considerations in scientific practice

The first analytical lens examines the students' interpretation for what they are trying to accomplish and the underlying rationale for pursuing the desired epistemic aim. The second analytical lens examines the epistemic considerations that might implicitly or explicitly guide students' decisions for achieving the desired epistemic aim.

3.1.1 Illustrative example: Condensation on cold coke can. In the following example, I provide examples of the epistemic questions that could guide the development of students' models explaining how and why water droplets formed on the outside of a cold coke can.

Small group model construction. *What type of account am I constructing?* Since the epistemic aim involves explaining, rather than describing the phenomenon, students ought to construct a step-by-step account that explains how and why the water droplets formed on the otherwise dry, yet cold, coke can. *What knowledge could students draw upon to help them explain the current situation?* Students might identify other situations involving similar observations, such as the early morning formation of dew on grass. In doing so, students might identify cool temperatures as a relevant factor for explaining both situations. *How can the students test the validity of this idea?* Students might test their idea by investigating whether water droplets also form on room temperature coke cans. *What have I figured out?* Although the absence of water droplets on the room temperature cans suggested that cool temperatures are an important causal factor, students have yet to figure out the mechanism by which the water droplets formed on the cold coke can or the source of the water. Thus, students assess what they have figured out to identify next steps.

Where does the water come from? When considering the source of the water, one student might believe that the water came from inside the can. *How could I persuade my classmate that the water could not come from inside the can?* However, the other group members recognize that the can is sealed, thus preventing liquid from entering or exiting the can. Students use this evidence refute the proposed idea. Another student claims that the water could come from the air and justifies his argument by noting that the absence of water vapor would be very dry air. *How could the water from the air form on the cold can?* To test the validity of this claim, students consider a plausible mechanism for the formation of the water droplets. Using students' prior understanding for how matter changes phase, students might consider how the cooler temperatures lead to the condensation of the water vapor into liquid droplets.

Whole-class consensus building. *How could I explain my ideas so that students will understand and be convinced that my ideas are correct?* To reach consensus, students might consider how others might interpret and evaluate the validity and persuasiveness of their accounts. As such, students might articulate the evidence used to justify their claims and explain how their models could explain all the observations in the phenomenon. *How do my ideas compare to others' ideas?* Students might compare their ideas and assess the competing ideas' ability to explain the phenomenon. For example, one student might think the water droplets originated from inside the can. In response, a student might identify evidence, such as citing differences in the color of the water droplets and soda, to support the argument that the air is the source of water and rebut the competing argument.

In summary, this example illustrates how students' implicit consideration of the justification used to support one's ideas and the extent to which one's audience understands is convinced of one's claims could be useful for guiding the development of robust scientific knowledge.

3.2 Epistemic criteria

Researchers have argued that teachers need a language to talk about the epistemic criteria that should guide students' scientific work (Berland & Reiser, 2011; Herrenkohl et al., 2011; Sandoval, 2005). In particular, researchers have found that explicit attention to the epistemic criteria can improve the quality of students' scientific work. McNeill and Krajcik (2008) found that teachers explaining the underlying rationales for the components in students' written explanations helped improve the quality of students' explanations. To help students construct more persuasive arguments, Berland and Reiser (2009) argued that students should be explicit and clear about what the evidence is, explain how the evidence support the claim, and explain why the reader or audience should believe the desired claim.

Ryu and Sandoval (2012) found that students' explicit attention to epistemic criteria contributed to pre- to post-test improvements in students' use of causal claims and evidence. In particular, Ryu and Sandoval (2012) suggested that involving students in discussions about epistemic criteria can contribute to their understanding for why these issues were worth attending to and how they would help students achieving their epistemic aims.

The previously described research suggests that teachers' attention to students' interpretations for what is needed to achieve the desired epistemic aims could have a positive impact on students' learning. However, the use of these epistemic criteria should be meaningful and used in the context of authentic scientific practice. For example, Pluta, Chinn, and Duncan (2011) gave students pairs of diagrammatic models that differed on a particular epistemic criterion, such as whether a model had a more detailed mechanism, and asked students to explain which model they preferred and why. Using their responses, students derived a list of six criteria describing "good" scientific models. Although the generated criteria suggested that students had a more sophisticated understanding of models than was shown in previous studies (e.g., Grosslight et al., 1991), it was unclear whether these students understood the significance for how or why these criteria were helpful or whether they could use them in the context of developing models in other situations. In other words, it is not enough for students to be able to make a list of normative epistemic criteria; rather, meaningful understanding of these criteria involves students knowing how to appropriately use these epistemic criteria in the context of their scientific work.

3.3 Motivating study of epistemologies in practice

To understand the meaning applied to students' scientific decisions and prevent rote use of scientific practices, Berland et al. (2016) argued for studying students' *epistemologies in practice (EiP)*, which refer to the broad set of epistemic knowledge that implicitly guide students' decision-making and actions in the context of constructing, evaluating, and revising scientific models. These EiPs refer to the reasoning that students apply in the context of scientific practice, rather than being inert beliefs about knowledge (Sandoval, 2012, 2014). Berland et al. (2016) used the term *epistemic considerations* to refer to the epistemic issues that guide students' explanation of scientific phenomena, such as the desire to justify one's ideas or persuade others of the validity of one's ideas.

The field has previously used a number of constructs to refer to students' ideas about knowing and knowledge, such as *epistemic commitments* or *epistemic beliefs* (Chinn et al., 2011). However, the literature's use of these terms suggests that students' beliefs about knowledge are stable and consistently applied across situations. In contrast, Berland et al. (2016) join researchers that have argued that students' stances on particular epistemic considerations are context-dependent and might differ from their stated beliefs about scientific knowledge (Chinn et al., 2011; Louca et al., 2004; Sandoval, 2005; Sandoval & Morrison, 2003). To explain this lack of coherence, Hammer et al. (2005) argued that these epistemic considerations are units of knowledge that are "activated" when students perceive them to be helpful and relevant for achieving an epistemic aim. As such, activation of these pieces of knowledge is neither coherent nor stable, but dependent on cues received from the students' situated context (diSessa, 1993). For example, a student might believe that evidence is important for justifying claims in science, yet not do so because he is short on time. Thus, the absence of evidence on an assignment does not necessarily mean that the student does not believe that evidence is unimportant — it simply means that the student chose not to do so based on the circumstances of the current situation.

3.4 Berland et al. (2016) epistemic considerations

Grounded in empirical studies of students' engagement in modeling (Schwarz, Reiser, Acher, Kenyon, & Fortus, 2012; Schwarz et al., 2009), Berland et al. (2016) identified four epistemic considerations (ECs) that they argued are helpful for guiding students' construction, defense, evaluation, and revision of explanatory models.

When suggesting that a student or teacher might "attend to" or "consider" issues related to an EC, I am not claiming that there was a noticeable point in students' or teachers' decision-making when these issues arose and participants made a conscious decision or that they explicitly considered the question posed by the EC. Similarly, B. L. Sherin and Star (2011) argued that when making claims about what teachers attend to in the classroom, these claims refer to the topic or the emergent features of what is noticed or discussed rather than the "underlying noticing machinery" that gave rise to those decisions (p. 76). Taken together, I use the questions posed by Berland et al. (2016)'s ECs as a means to reference the types of epistemic issues that might be guiding students' decisions as evidenced by their actions or stated rationales.

3.4.1 Nature of Account: What type of answer should our account of the phenomenon provide? The *nature of account* consideration considers whether students' accounts should be descriptive or explanatory. If students interpret the task as *describing* the phenomenon, students' actions and rationales might reflect the desire to show or describe what happened. In contrast, if participants interpret the goal as creating an *explanatory* account, they might identify the phenomenon's components, relationships, and processes to explain how and why the phenomenon occurred (Russ, Scherr, Hammer, & Mikeska, 2008). For example, students' attempts to devise a mechanism to explain how cold temperatures led to the formation of water droplets would be an example of implicit attention to issues related to the *nature of account* consideration. Because the students desired to create an explanatory account, they moved beyond describing the formation of water droplets to trying to explain how and why they formed.

3.4.2 Generality: How does our account of the phenomenon relate to other scientific phenomena and ideas? The *generality* consideration prompts students to identify knowledge from other situations that could be relevant and useful for explaining the target situation. For example, the students might identify parallels between the formation of dew on grass and the formation of water droplets on the can. Leveraging this related situation would be implicit evidence of attention to issues related to the *generality* consideration. This EC is often mediated by beliefs about whether knowledge is specific and contextual or general and universal (Chinn et al., 2011). Individuals guided by the former might explain each situation separately, whereas individuals guided by the latter might identify commonalities across different situations or use general principles to explain the target situation.

3.4.3 Justification: How do we justify the ideas in our account of the phenomenon? The *justification* consideration prompts students to think about the nature of the justification used to support or refute one's ideas. One aspect of this consideration involves examining the source of the support, which could range from personal opinions, authoritative sources (e.g., textbooks or the teacher), and normative sources, such as empirical data. The second aspect involves examining how students might use this support to justify or refute one's claims. In doing so, students might consider the appropriateness and sufficiency of the evidence for persuading others of the validity of one's claim. Thus, students' interpretations for what they are trying to accomplish influences how they use, or do not use, evidence to support their claims.

3.4.4 Audience: Who will use our account of the phenomenon and how? The *audience* consideration examines the extent to which students attend to how an external audience might engage with or use the model's ideas. If students recognize the value in sharing their explanatory ideas with their peers, students might consider how they could clearly communicate or persuade others about the validity of their claims (e.g., Passmore & Svoboda, 2011; Schwarz et al., 2009). In doing so, they might anticipate and account for any potentially confusing ideas and their audience's prior conceptions or potential objections. For example, students might incorporate a key or written text in their diagrammatic models to help the audience understand and correctly interpret their ideas. Alternatively, if students perceive the teacher as their target audience, students might focus on communicating what they know because the teacher likely already knows the "correct answer" and does not need to be convinced about the validity of one's ideas (Cornelius & Herrenkohl, 2004).

3.5 Link to other frameworks

Other researchers have identified similar epistemic issues or criteria. For example, Windschitl et al. (2008) argued that students should account for the processes, properties, or structures that could explain the phenomena; conduct investigations to test those ideas; consider how the evidence could be used to support or revise those ideas; consider alternative explanations for the evidence; and anticipate any weaknesses in their argument. V. D. Sampson and Clark (2006) synthesized the field's understanding of what epistemic criteria should guide the evaluation of students' arguments. First, students should examine the nature (explanatory vs. descriptive) and quality of knowledge claim. Second, students should examine how (or if) the claim is justified and assess the evidence and reasoning used to support the claim. Third, students should examine the extent to which a claim is able to account for all available evidence from the phenomenon. Fourth, students should examine how (or if) the argument accounts for potential alternative explanations or interpretations of the data or consider weaknesses in the argument. Fifth, students should assess the validity of the methods used to collect and interpret the evidence used to support the claims.

The overlap between the epistemic issues identified by others and Berland et al. (2016)'s ECs provides additional support that these epistemic issues are important for supporting students' engagement in modeling. However, Berland et al. (2016)'s ECs are distinct in that they attend to what guides students' decision-making rather than focusing on what students should do or the criteria used to evaluate students' explanations or arguments. For example, rather than looking for the presence of evidence and a statement linking the evidence to the desired claim, the issues posed by the *justification* consideration prompt students to consider the appropriate ways for using evidence to justify their ideas. Thus, there is greater attention to the underlying questions or rationales guiding students' use of evidence for achieving one's scientific goals rather than serving as an additional checklist of things to include in a scientific explanation.

3.6 Summary

The epistemic considerations identified by this analytical lens are aligned with disciplinary norms and criteria, yet focus on how these epistemic issues guide students' decisions rather than being isolated, stated beliefs about scientific knowledge. By examining evidence of what epistemic considerations might be guiding students' decisions, teachers could infer the meaning that students apply to their decisions and use their interpretations to help students develop their explanatory models.

4. Epistemic agency: Who is responsible for doing this work?

Thus far, I have argued that having the class engage in scientifically meaningful aims, such as explaining scientific phenomena, and attending to important epistemic issues to guide the development of scientific knowledge are important. However, meaningful scientific work cannot occur if students do not have the opportunity to make decisions related to the construction and evaluation of scientific knowledge. For example, a teacher might present her own explanation of the coke can phenomenon (see Section 3.1.1). Even if the teacher could explain the evidence used to justify her model or explain how the model's ideas were similar to those found in other contexts, this type of learning reinforces the teacher’s role as the traditional source of knowledge and authority in the classroom. Consequently, students might not challenge or consider competing accounts for the teacher’s explanation. In addition, students might not have a robust understanding of the evidentiary basis for the account because they were not involved in generating the evidence used to support those claims or reconciling competing ideas to generate the final account.

The third analytical lens examines the extent to which students have *epistemic agency* or responsibility for defining, addressing, and resolving problems that will shape and advance the knowledge of the classroom community (Engle & Conant, 2002; Stroupe, 2014). In other words, this analytical lens examines the distribution of knowledge-building responsibilities between the students and teachers. Engle and Conant (2002) argued that students’ knowledge-building responsibilities involve defining, addressing, and resolving disciplinary problems (p. 404). In doing so, students pose and investigate questions valued by them and the discipline, collect and interpret the significance of their findings, and evaluate whether the derived conclusions address the posed questions. In doing so, students recognize the value and usefulness of their own ideas for achieving their scientific goals (Russ, 2014) and recognize themselves as legitimate participants in these communities of scientific practice.

Students' construct deeper, more robust conceptual understandings when they construct knowledge with one another (Driver et al., 2000; Engle & Conant, 2002; Osborne, 2010). In doing so, students develop an understanding of the justification for their claims (Herrenkohl et al., 2011), how and why their claims are better able to explain the phenomenon compared to raised alternatives (McNeill & Krajcik, 2008; Sandoval & Millwood, 2005), and how they can use this knowledge to explain other situations (Schwarz et al., 2009).

Students' legitimate use of scientific practices is important for helping students develop authentic epistemologies of science and use disciplinary norms and practices in appropriate ways to construct and evaluate scientific knowledge (e.g.,Chinn & Malhotra, 2002; Driver et al., 2000; Duschl & Osborne, 2002; Lave & Wenger, 1991). For example, when students pose and investigate questions of their own choosing, Lehrer et al. (2008) argued that students learn important disciplinary considerations related to how to propose a good question, develop measures and methods to investigate aspects of the phenomenon that are important for answering one's questions, and derive appropriate conclusions from the data. Through students' participation in the iterative process of constructing and evaluating knowledge, students develop expertise to determine what counts as valid and reliable knowledge scientific knowledge (Ford, 2008; Lave & Wenger, 1991). Sandoval (2005) argued that students are not likely to develop understandings about how to choose appropriate evidence or coordinate evidence needed to support their claims unless they have been given the opportunity to do so in the context of scientific practice. Thus, developing a grasp of practice involves students' legitimate participation in these communities of science practice (Lave & Wenger, 1991).

When examining the extent to which students have epistemic agency in the classroom, I consider three sub-questions that provide unique, but complementary, insight into understanding the students' knowledge-building role: 1) Who is doing the work? 2) Who has the authority? and 3) How are students' ideas used during instruction?

4.1 Who is doing the work?

4.1.1 Analyzing students' participation status. Goffman (1981) identified two types of conversations that occur in a classroom: *dominant* communications, which involves *ratified participants* who are supposed to be in conversation, and *subordinate communication*, which involve *bystanders* interfering with or seeking to participate in the dominant interactions. Goffman (1981) argued that a student's *participation status*, or role that a student or teacher plays in relation to others, influences whether they can participate in the dominant conversations that shape the knowledge of the classroom community. The ability to access the conversational floor and contribute to classroom discussions is socially-negotiated with others in the classroom (Engle, Langer-Osuna, & McKinney de Royston, 2014).

The sub-question, "Who's doing the work?" examines the extent to which the students are the ratified participants involved in the dominant conversations that contribute to the classroom knowledge, characterized by students initiating and responding to each other's ideas in the context of these knowledge-building discussions. However, this sub-question examines not only students' participation in classroom discussions, but also the substance of the conversation to understand how students' participation shapes the consensus knowledge of the classroom. In other words, this sub-question examines the extent to which the *students* are the agents responsible for making scientific decisions guided by important epistemic issues.

For example, a student presenting their model to the class might use evidence to justify his ideas. In response, the teacher asks the presenter several questions to explain the justification used to support the claim or to defend why his model was a better explanation than an alternative model. A student from the class might ask a clarifying question about a feature in the student's model. When applying this sub-question to this example, the teacher was the primary individual responsible for evaluating the presenter's ideas because she asked the presenter to defend the validity of the presented claims rather than only seeking to understand the students' ideas. All discussed epistemic issues are important, as you cannot meaningfully evaluate someone's ideas without understanding them. However, the teacher's efforts to evaluate the students' ideas are more likely to shape the consensus knowledge of the classroom than the students' clarifying question alone. Thus, the sub-question, "Who is doing the work?" involves identifying how the students and teacher share the knowledge-building responsibilities and the extent to which the *students'* decisions and actions contribute to shaping the classroom community's knowledge.

4.1.2 Use of questioning to enhance students' knowledge-building responsibilities. To enhance the students' role in constructing knowledge, van Zee and Minstrell (1997) argued for teachers to continually "throw" knowledge-building responsibilities back to the students. Research suggests that teachers' and students' use of questioning could create additional opportunities for students to engage in the knowledge-building work. For example, van Zee and Minstrell (1997) found that teachers' use of neutral, open-ended questions, rather than evaluative questions, helped students elaborate upon and better explain their ideas to others. McNeill and Pimentel (2010) found that using open questions helped students make connections to their prior ideas and enhanced students' ability to justify their claims. Martin and Hand (2009) found that students' ability to participate in argumentation with others was enhanced when teachers provided students with "meta-questions" (e.g., What are my questions? What can I now claim?

What evidence do I have to back up my claim? Do you agree or disagree with the claim?) to reflect on their learning.

4.2 Who has the authority?

This sub-question examines the extent to which students have *epistemic authority*, or the power to assess the validity of each other's ideas (Sandoval, 2005), and how this power is shared by the students and teacher. Candela (1999) argued that many classrooms exhibit *classroom asymmetry*, in which certain individuals have more power than others. In many classrooms, students turn to traditional, institutional positions of authority, such as the teacher or textbooks, to validate the "correctness" of their ideas (Driver et al., 2000). However, the source of epistemic authority is not always dependent on one's institutional status alone; rather it is socially-negotiated with others. Candela (1999) showed examples of students defending a position not accepted by the teacher and openly questioning whether a teacher's response was correct. Rather than simply trying to usurp the teacher's authority or be disruptive, Candela (1999) argued that these students did not blindly accept the teacher's authority and attempted to contribute in substantive ways to the knowledge-building work. In a study of how students develop power and influence over other students' ideas, Engle et al. (2014) found that students can develop and wield their power and influence through *socially-negotiated influence*, which is based on students' social capital or status in the classroom, or *socially-negotiated authority*, which is based on the students' credibility as a source of helpful ideas for achieving the students' goals. Cornelius and Herrenkohl (2004) argued that students exercise power and authority by gaining support or agreement for ideas by persuading others why their views are correct.

To promote the redistribution of epistemic authority from the teacher to the students, Sandoval (2005) argued for helping students understand the epistemic criteria that determines what counts as valid scientific knowledge. In doing so, students can make their own judgments about the validity of each other's knowledge (Cornelius & Herrenkohl, 2004; Ford & Forman, 2006). In addition, this re-distribution enhances student agency because students recognize that their ideas have as much authority or validity compared to knowledge from more authoritative sources, such as the teacher (Cornelius & Herrenkohl, 2004). In addition, Sandoval (2005) argued that removing absolute certainty from knowledge encourages students to focus more on using epistemic criteria to evaluate knowledge rather than relying on the institutional status of the individual alone. In summary, this sub-question examines *who* is responsible for determining what counts as scientific knowledge in the classroom and how that authority is socially-negotiated.

4.3 How are students' ideas used during instruction?

The first two sub-questions examined the extent to which *students* are involved in using epistemic issues to construct and evaluate scientific knowledge. In many classrooms, students have little role in posing and investigating their own questions (Windschitl et al., 2008) or using evidence to test and revise their own ideas (Carey & Smith, 1993; Driver et al., 2000). As such, students do not perceive their ideas to be worthy because they do not contribute to the knowledge of the classroom community. The third sub-question focuses on how students' ideas, questions, and methods for testing students' ideas play a role in shaping the trajectory of the knowledge-building work. For example, does the teacher simply elicit students' ideas or will students' ideas have actual consequence on students' learning?

Students construct new knowledge and understanding by building upon existing knowledge (Bransford, Brown, & Cocking, 2000). Research has shown that teachers' elicitation and use of students' ideas to inform instructional decisions contributes to students developing deeper conceptual understanding (e.g.,Fennema et al., 1996). McNeill and Krajcik (2008) found that students constructed better explanations of phenomena when teachers made efforts to connect to students' everyday knowledge. When teachers account for students' prior knowledge, students recognize that they can use their existing *funds of knowledge* (Moll & Greenberg, 1990) in productive ways to achieve one's scientific goals (Russ, 2014). Furthermore, Cornelius and Herrenkohl (2004) found that using students' ideas in the construction of knowledge was important for students feeling ownership over their ideas and helping them recognize that their ideas are just as valuable as the teacher's ideas and can make valuable contributions to the classroom knowledge.

For students' participation to be meaningful, researchers argue that achievement of the epistemic aim should require students to attend to, value, and build upon one another's ideas. To do so, Brown and Campione (1996) argued for creating tasks that leveraged the diversity of ideas and expertise found in the classroom in service of solving important disciplinary problems. In doing so, it promotes a focus on the collective knowledge-building endeavor and the role that each student can play in accomplishing the collective epistemic aim (W.-M. Roth & Lee, 2007). Berland and Reiser (2011) argued for creating tasks and activity structures that required students to build upon, question, and challenge each other's ideas to reach consensus.

In summary, this sub-question examines whose investigative or explanatory ideas are taken up during classroom instruction. The answer to this question has implications for students' ability to construct robust understandings and perceive themselves as valued and legitimate sources of scientific knowledge.

4.4 Illustrative example to show analytical utility of sub-questions

In this dissertation research, I examine activity structures in which students publicly share and evaluate one another's explanatory models to reach consensus. In this section, I present an example to illustrate how consideration of each sub-question could contribute to our understanding of the students' knowledge-building role. In this example, a teacher might ask students to individually construct explanatory models of a phenomenon. Rather than have a student present her ideas to the whole-class, the teacher presents an example from the curriculum materials for the students to evaluate using epistemic criteria. Students then ask the teacher questions to clarify their understanding of the model's ideas and evaluate the justification used to support the presented ideas. The teacher concludes the question and answer period by validating the correctness of the presented model and asking students to copy the model into their notebooks.

Who is doing the work? The students and teacher are using epistemic criteria to explain scientific phenomena and evaluate the presented ideas.

Who has the authority? Although the students are involved in evaluating the account's validity, the assessor of the validity of the knowledge was the teacher.

How are students' ideas used during instruction? The teacher provided the students the opportunity to construct their own models, yet the teacher did not put forward the students' ideas for evaluation. Although there might be similarities between the presented model and the students' own models, it was the teacher's model ideas that became part of the classroom knowledge.

Thus, these three sub-questions provide ways to examine the different aspects of students' participation in the knowledge-building work and provide concrete ways in which teachers could enhance the students' position as epistemic agents, such as letting students present their own models to the class for evaluation or letting the students be the ultimate arbiters of the model's validity.

4.5 Comparison to other frameworks

Stroupe (2014) identified two dimensions of analysis to explore the construct of epistemic agency within the context of ambitious instruction. The first dimension involves *who knows*, which examines "the unit of knowing" or the individuals responsible for constructing knowledge, with attention to whose ideas are made public and acted upon in the classroom. While Stroupe aggregated students' ideas and decisions into a single category, I teased apart *whose* explanatory ideas were taken up and discussed from other epistemic work that students did with respect to those ideas. For example, students could be involved in evaluating ideas raised by the teacher without posing their own explanatory ideas or methods for investigating the phenomenon. This distinction is important when supporting shifts in classroom instruction when we are trying to support the students' participation in the development of explanatory models, which privileges students testing and revising their own initial model ideas rather than those of others (e.g.,Windschitl et al., 2008; Windschitl et al., 2012).

The second dimension involves who is the *cognitive authority*, which considered whose knowledge has the ability to become expert knowledge (Addelson, 1983 in Stroupe, 2014) and contribute to the knowledge of their learning community. Engle and Conant (2002) used a similar construct, *disciplinary authority*, to refer to the extent to which students could contribute knowledge with responsibility for defining, addressing, and resolving problems in the classroom. I accounted for the status of students' ideas for becoming part of the community's knowledge through the sub-question, "How are students' ideas used during instruction?" However, I take the perspective of researchers (e.g.,Berland & Hammer, 2012; Ford, 2008; Ford & Forman, 2006; Sandoval, 2005) that use the construct of *epistemic authority* to refer to the ability to determine what counts as scientific knowledge and use it as one indicator of the extent to which students have epistemic agency, which refers to the broader role and responsibilities that students have in the knowledge-building work.

4.6 Summary

In this framework, the analytical lens of epistemic agency captures the extent to which students are the individuals responsible for making decisions related to the development of explanatory models. The desired response to each sub-question should be the students, as we want the *students* to pose and investigate questions that are of interest to them, propose initial ideas to explain the phenomenon, develop means to test and revise their ideas, use epistemic criteria to evaluate the validity of one another's ideas, and reconcile each other's ideas to reach some consensus understanding. Thus, each sub-question reveals a different, yet complementary aspect of the students' knowledge-building role.

5. Framework Summary

In this chapter, I proposed a framework composed of three analytical lenses that teachers and researchers could use to examine the extent to which students' engagement in modeling is both scientifically and personally meaningful to them (summarized in Table 3.1). At the center of this endeavor is enhancing the students' role in making decisions related to the development of explanatory models. To ensure that this work is meaningful, it is important for students and teachers to attend to the purpose for engaging in the knowledge-building work and the epistemic considerations guiding students' decisions. This framework builds upon the work of others, yet provides a new way of thinking about how integrated attention to these epistemic aspects of scientific practice could be helpful for ensuring that students understand what they are doing and how their decisions will help them achieve their scientific goals.

I used this framework in two ways that are aligned with the research questions. First, the framework could provide lenses through which teachers and researchers could identify the successes and challenges involved in supporting students' meaningful participation in modeling. Second, this framework could be used as lenses through which teachers could use their interpretations to make decisions to enhance the meaningfulness of students' engagement in scientific practices and promote shifts in classroom practice. Study 2 embraces both goals by exploring how a teacher, Kami, used the issues posed by these analytical lenses to reflect on and make decisions that enhanced the meaningfulness of her students' engagement in scientific practices. In doing so, these analytical lenses could be used as tools to refine teachers' *professional vision*, or the "socially organized ways of seeing and understanding events that are answerable to the distinctive interests of a particular social group" (Goodwin, 1994, p. 606), so that teachers could attend to aspects of classroom practice that are consequential for supporting students' engagement in scientific practices.

Table 3.1
Framework for analyzing meaningful engagement in scientific practices

Analytical Lenses	**Subcomponents for each analytical lens**
1. Epistemic Aim: What is the goal of the knowledge-building work?	a) Are students attempting to make sense of scientific phenomena or learn discrete scientific facts? b) **Why should the students' care?** Why is this goal worthwhile or important from the perspective of the discipline and students? c) Do students understand the purpose and epistemic value of the scientific practices used to achieve the desired epistemic aim?
2. Epistemic considerations: What ideas or questions are guiding students' decisions?	a) ***Nature of Account***: What type of answer should our account of the phenomenon provide? 1) *Descriptive*: To what degree does the account *show* or *describe* what happened or will happen? 2) *Explanatory*: To what degree does the account explain how and why the phenomenon occurred? b) ***Generality***: How does our account of the phenomenon relate to other scientific phenomena and ideas? c) ***Justification***: How do we justify the ideas in our account of the phenomenon? d) ***Audience***: Who will use our account of the phenomenon and how? 1) *Clarity of communication*: How can we clearly communicate our ideas so that others can understand them? 2) *Persuasiveness of argument*: How can we convince others of the validity of our idea and/or to revise their idea(s)?
3. Epistemic agency: Who is responsible for doing this work?	a) **Who is doing the work?** 1) Do students have opportunities to engage in knowledge-building work together? 2) To what extent do the students and teacher share the knowledge-building responsibilities? 3) Do students' decisions and actions contribute to and shape the classroom community's knowledge? 4) Is the teacher *supporting* students' efforts to construct knowledge? b) **Who has the authority?** 1) Do students understand the epistemic criteria used to evaluate what counts as scientific knowledge? 2) Who makes the final decision about whether a model is "correct"? c) **How are students' ideas used during instruction?** 1) Whose ideas and questions are taken up during whole-class discussions? 2) Do students' ideas and questions shape the consensus knowledge of the classroom?

Chapter 4: Study 1 Methods

Study 1 investigated Research Question 1, "What successes and challenges emerge for students and teachers when students construct and evaluate explanatory models of phenomena with others?" To do so, it was important to observe classrooms in which the students and teachers engaged in ambitious scientific practices and pedagogy as a part of their instructional practice. During the 2011-12 academic year, I observed three sixth-grade classrooms located in the suburbs surrounding a large Midwestern city that used a comprehensive, practices-centered curriculum, *Investigating and Questioning our World through Science and Technology* (IQWST) (Krajcik, Reiser, Sutherland, & Fortus, 2013).

In Section 1, I explain the process for selecting the study participants. In Section 2, I explain the curriculum context of the observed lesson and explain how and why it is useful for answering Research Question 1. In Section 3, I explain the lesson sequence as articulated in the curriculum materials to understand what resources teachers could have used to interpret the goals for each component of the lesson and support students' opportunities to construct and evaluate explanatory models of phenomena with others. In Section 4, I explain the design features present in this lesson that support ambitious pedagogy and explain why it was a rich context for investigating the meaningfulness of students' engagement in scientific practices. In Section 5, I explain what data I collected to investigate Research Question 1.

1. Participants

1.1 Participant Selection

I recruited teachers with varying levels of experience with a practices-centered curriculum with the hypothesis that I would observe differences in teachers' understanding of how to organize and support classroom instruction and discourse to mediate students' meaningful participation in the construction and evaluation of each other's models. In doing so, I could investigate the successes and challenges of trying to support model-based instruction in a variety of classroom contexts. Although many experienced teachers have skills that could be useful for supporting meaningful engagement in modeling, prior research has argued that teachers often have little experience with authentic uses of models either as students themselves or as classroom teachers (Davis et al., 2010; Windschitl, 2003; Windschitl et al., 2008). In addition, there are pedagogical and epistemological challenges involved in supporting model-based pedagogy in classrooms (e.g.,Alozie et al., 2010; Osborne et al., 2004; Schwarz et al., 2009; Windschitl et al., 2008). Thus, the number of years of teaching experiences might not be a reliable indicator of teachers' expertise with practice-centered instruction compared to the number of years spent trying to use such an approach as part of one's classroom practice.

The studied teachers were participants in a broader study, *Supporting Scientific Practices in Elementary and Middle School Classrooms*, a longitudinal study seeking to characterize and support students' meaningful engagement in scientific practices. I divided the sixth-grade teachers into three bands based on their experience teaching IQWST: four novice teachers were using the full curriculum for the first time, two intermediate-level teachers had been teaching IQWST for three years, while the most experienced teacher had taught IQWST for six years. Since there were multiple novice and intermediate teachers, I selected teachers based on 1) the teacher's willingness to be interviewed and videotaped and 2) the teacher's teaching schedule to facilitate data collection from three different school sites. See Table 4.1 for information about the study teachers' experience with IQWST and school demographic information.

1.2 Teacher and School Information

Table 4.1
Study 1 Teachers and School Demographics

	Experience [a]		School Information	
Teacher	**IQWST**	**Total**	**Type**	**Demographics [b]**
John	1	23	Public 6-8	Students: 861, White (85%), African American (1%), Hispanic (5%), Asian (6%), Multiracial (4%); FRL[c] (7%)
Kami	3	5	Parochial K-8	Students: 474; White (98.2%), Hispanic (0.7%), Asian (0.7%), African American (0.4%); FRL (0%)
Laura	6	17	Public K-8	Students: 855; White (55%), Hispanic (10%), African American (2%), Asian (27%), Multiracial (6%), FRL (18.9%)

[a] Years of experience as of the 2011-12 academic year; [b] National Center for Education Statistics, 2013-14; [c] Free and reduced priced lunch

Novice. Although John had the most number of years teaching, he was a "novice" in terms of his experience using a practices-centered instructional approach. John had some experience using model-based instruction before the study, having taught the sixth-grade physics IQWST unit as part of his district's evaluation of the IQWST materials. However, it was John's first year teaching the chemistry unit, which was the focus of this dissertation work.

Intermediate. Kami had professional experience developing and using models in the context of her prior career as a professional biochemist. She used a more traditional instructional approach in the two years before her school's adoption of IQWST (Kami Interview, 5/3/12). At the time of the study, Kami had taught IQWST for three years and was the school's science department chair.

Expert. Laura was the most experienced IQWST teacher in this study. IQWST researchers have observed her classroom in prior studies and have used videos from her classroom in professional development workshops as exemplary examples of students' meaningful use of scientific practices. In addition, Laura had been leading PD activities for new IQWST teachers.

2. Lesson Context

2.1 Curriculum context

The IQWST curriculum was designed with the expectations that all students could engage in meaningful practices with scaffolded support from the curriculum materials and the teacher. In the sixth grade, students completed up to four curriculum units. Each unit began with students experiencing an anchoring phenomenon that addressed an important disciplinary core idea and model, such as understanding the particle nature of matter or how light allows us to see objects. In doing so, students' knowledge-building work was in service of explaining scientific phenomena rather than obtaining scientific facts.

The unit context for this study is sixth-grade chemistry unit, *How can I smell things from a distance?: Particle nature of matter and phase changes* (Krajcik, Merritt, Shwartz, Sutherland, & van de Kerkhof, 2013), the second of four units in the curriculum sequence. The unit has sixteen lessons — each taking place over several days. In total, the teachers used twelve to sixteen weeks to complete the unit. I chose this unit for three reasons. First, it featured a lesson using the target activity structure in which students publicly shared and received feedback from their peers. Second, this was the first unit in which I could observe all three teachers due to logistical issues with obtaining consent in John's school. Third, each teacher had the opportunity to establish classroom norms and practices for sensemaking during the first curriculum unit. In doing so, it minimized potential confounding issues related to teachers working with new students for the first time.

2.2 Unit context

In the chemistry unit, students developed a particle model of matter by explaining how and why students could detect an odor from a distance. In this target model of matter, odors were distinct particles that moved in random directions away from the odor source. Students detected the smell after the odor molecules reached the nose receptors. This phenomenon was a rich context for investigating the meaningfulness of students' use of scientific practices for two main reasons. First, the particle nature of matter is a fundamental process or "big idea" that is important for explaining a range of scientific phenomena. Windschitl et al. (2012) found that ambitious instruction did not occur unless the phenomena involved "big ideas" and teachers understanding how and why these ideas were important. Second, the phenomenon's explanation is not straightforward. Research has shown that students have varied ideas about the nature of matter and the idea that matter is made up of particles with empty space between them is not an intuitive topic for students to grasp (Smith, Wiser, Anderson, & Krajcik, 2006). Thus, the phenomenon could elicit multiple viable ideas for students to reconcile using argument and evidence (Engle & Conant, 2002; Lehrer et al., 2008; Manz, 2014; Windschitl et al., 2012) and created an authentic need for students to work together to explain the phenomenon (Manz, 2014).

Students engaged in a sequence of investigations to test and revise their models and provide evidence to support one or more components of the overall explanatory model. To challenge students' existing understandings about matter and prompt students to consider the particle nature of gases and matter in general, students developed a single model that could explain contrasting behaviors of air, such as students' ability to add or remove air from a closed container of constant volume. Because all gases share certain characteristics and properties, students reasoned analogically about the structural and behavioral properties of odors by studying air as a representative and easily accessible gas (Gentner, 1983). I could examine students' attempts to use existing knowledge and evidence from the phenomena to theorize about what might be happening at the non-visible level, bring coherence to contrasting gaseous behaviors, and obtain evidence to support a general model of matter. The unit culminated in students using their models to explain other related phenomena.

3. Lesson 4 Sequence

The focus lesson of Study 1 took place over two to three 40 to 50-minute class periods and involved investigating the question, "How can I model the things gases do?" More specifically, teachers asked students to develop a model that could explain two behaviors of gases: the ability to add or remove air from a sealed flask. The particle nature of air was an important component of this explanatory model. When the teacher added some air to the flask, the space between the particles provided the space for the additional air particles to enter the flask. When the teacher removed some air, the remaining air particles continued to move inside the increased empty space inside the flask and occupied the space of its container. In both cases, the volume of the gas, or the amount of space that the gas takes up inside the container, remained the same.

Students did not have to have a coherent particle model by the end of the focus lesson; instead, students were expected to reach some consensus understanding and use evidence from subsequent lessons to test and revise their ideas. In what follows, I explain the designed lesson sequence (summarized in Table 4.2 and illustrated in Figure 4.1) and the resources that teachers could use when planning and enacting the lesson. All quotations are from the curriculum materials (Krajcik, Merritt, Shwartz, Sutherland, & van de Kerkhof, 2013).

Table 4.2
Summary of Lesson 4 Sequence

Step	**Purpose**
1. Situating air investigations	1. Explicitly discuss the relevance of using air as a representative gas to investigate and explain the anchoring, odor phenomenon 2. Students review existing knowledge about gases and findings from prior investigations that could be relevant for explaining the current situation.
2. Students construct initial air models	1. Students document their ideas about the nature of gases. 2. Students create knowledge product that they could use to explain contrasting behaviors of gases.
3. Class discusses students' initial air models	1. Students use model to explain and defend their ideas. 2. Students reconcile competing ideas to develop a consensus model of air.
4. Students observe contrasting behaviors of air	Use contrasting behaviors of air to challenge students' existing ideas about air and provide evidence for the particle nature of matter.
5. Students construct models of contrasting behaviors of air.	Students consider how their air models might change to account for contrasting behaviors of air.
6. Class discusses students' models of contrasting behaviors of air	1. Students use model to explain and defend their ideas. 2. Students reconcile competing ideas to develop a consensus model that could explain both situations. 3. Students revise their initial air models to account for the ideas of others.

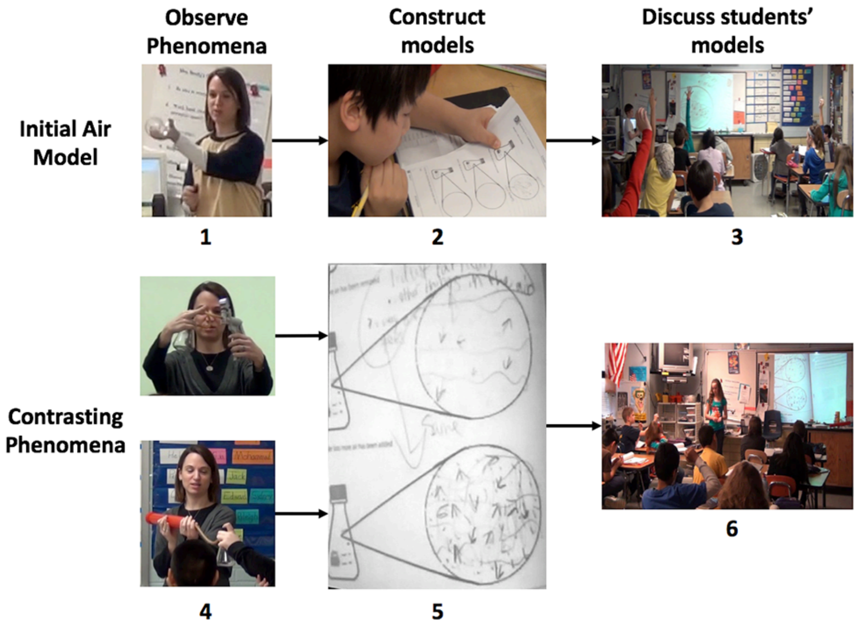

Figure 4.1. Lesson 4 sequence. The numbers correspond to the steps in Table 4.2.

3.1 Situating air investigations

The teacher reminded the students that they had figured out that odors were gases. Since all gases share typical characteristics, students could use air as a representative gas to study characteristics of all gases and by extension odors. This connection was important for communicating the epistemic value of the air investigations for investigating the anchoring odor phenomenon. Next, the class reviewed properties of air and gases in general and the evidence used to support those ideas. For example, students figured out that air was matter after detecting differences in the mass and volume of a basketball after they added air. This step culminated with the teacher filling the flask with air by moving it through the air and sealing it with a stopper.

3.2 Students construct initial air models

Teachers asked students to focus on one tiny spot of air inside the flask and use what they knew about gases to represent what they thought the air looked like inside the flask. To help students attend to the non-visible characteristics of air, teachers asked students to imagine that they had access to a "special instrument" that could allow them to see things that were not visible with the naked eye. The goal of creating initial air models was to document students' initial ideas about the nature of air and create a baseline model that students could use to explain the contrasting air behaviors. In doing so, students learned that models contained ideas that students could use to explain a range of phenomena.

3.3 Class discusses students' initial air models.

The students then publicly shared their air models with the class with the goal of 1) *clarifying* and *exploring* students' ideas and 2) evaluating the extent to which students' models accounted for existing knowledge about gases. The curriculum materials provided prompts to help teachers explore students' ideas (e.g., "How did you represent air in your model?" and "How does your model account for what you have already learned about air (gases)?", pp. 4) and facilitate discussions between students (e.g., "What is similar between yours and (a classmate's) model?" and "How are your models different?", pp. 4). To guide the discussion, the curriculum provided six "Evaluation Criteria for Models" (Krajcik, Merritt, et al., 2013, pp. 3, Lesson 4):

1. Accuracy: How does the model accurately represent the phenomenon?
2. Consistency: How does the model account for all of the evidence?
3. Usefulness: Can the model be used to illustrate, explain, and predict new phenomena?
4. Clarity of Communication: How is the model organized and labeled?
5. Simplicity: How does the model ONLY include necessary information?
6. Key ideas: How does the model include key parts and relationships?

In addition, the curriculum materials provided a list of common student conceptions (see Figure 4.2) to help teachers understand the range of ideas that students might use to construct their air models. For example, students might construct a *continuous* model (see Figure 4.2a), in which the entire flask was filled with air with no empty space.

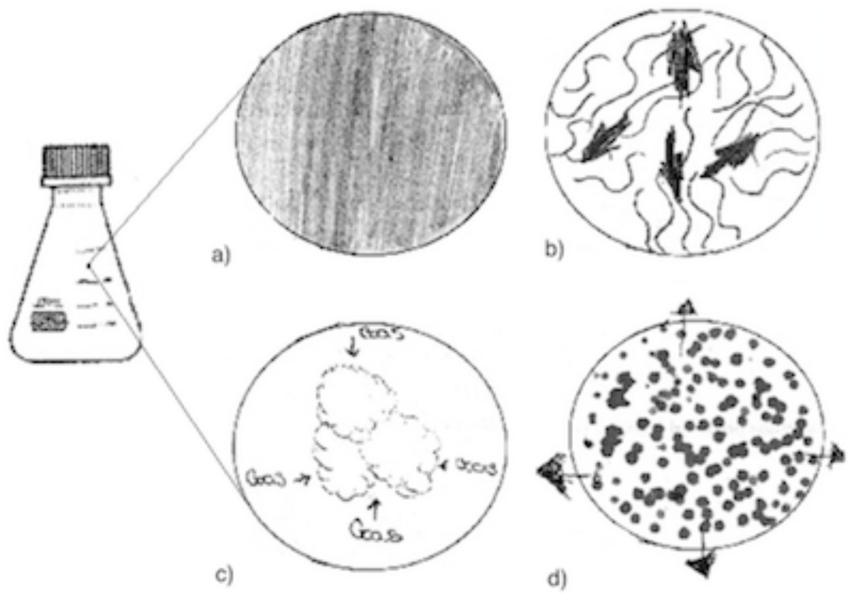

Figure 4.2. Common student conceptions of air: a) continuous model, b) linear streams of air, c) "clouds" of gas, and d) particles (Adapted from Krajcik, Merritt, et al., 2013).

The curriculum materials cautioned teachers not to assume the meaning of students' ideas based on what was observed in students' models. For example, if students had circles or dots that suggested a particle-like model (see Figure 4.2d) or even used terms like particle or molecule, teachers were cautioned not to assume that students had a coherent particle model. Instead, teachers were encouraged to probe students' ideas about the nature of the space between two entities.

> **If Ss [student(s)] draw particles** (i.e. dots, circles, triangles, etc.), focus Ss attention to the dots and the space between the dots. Possible prompts to help Ss clarify their ideas:
> • What does this represent? (while pointing to dots/circles/other particle representation)
> • What is between the dots? (Point to any 2 dots and ask, "What's between this one and this one?"
> **If Ss draw shade, lines, etc.,** ask Ss what each represents. (Original emphasis, Krajcik, Merritt, et al., 2013, pp. 3, Lesson 4)

Teachers should not expect students to have the "correct" answer after discussing each other's air models; rather, students should use evidence from the contrasting behaviors of air to develop and support this idea over time. Thus, the purpose of these prompts was to help students *clarify* and *articulate* their ideas rather than convince students about the particle nature of matter.

3.4 Students construct contrasting behaviors of air models

To demonstrate the contrasting behaviors of air, the teacher used a hand-evacuating pump to remove some air and an air pump to add some air to the flask (see Figure 4.1). Because there were no visible changes to the inside of the flask, teachers were encouraged to provide evidence that changes were occurring. For example, the curriculum materials asked students to observe changes in the pressure gauge or hear air leaving the flask (Krajcik, Merritt, et al., 2013, pp. 7, Lesson 4). Although the curriculum materials did not provide guidance for how to persuade students that the teacher added air into the flask, each teacher used the air pump to add excess air to the flask to "pop off" the stopper.

3.5 Students construct models of contrasting behaviors of air.

Students constructed two diagrammatic models showing how the air inside the flask might have changed after the teacher added or removed some air from the flask. The curriculum materials provided prompts to guide students' thinking as they constructed their models.

> What do you think is happening inside the flask when some air is removed? What do you think the air is doing in the flask? Is it staying in one place? Is it moving around? If so, how is it moving? Is it moving in any particular manner (in circles, in a line, randomly)? (Krajcik, Merritt, et al., 2013, pp. 7, Lesson 4)

In addition, teachers were encouraged to help students evaluate whether their initial air models could explain the contrasting behaviors of air, "In particular, can their model account for air in the flask AND air being removed from the flask?" (Krajcik, Merritt, et al., 2013, pp. 8, Lesson 4).

3.6 Class discusses students' models of contrasting behaviors of air

Students shared their models with the class to evaluate the extent to which students' models could account for the phenomena and existing knowledge about gases. The curriculum materials suggested prompts that teachers could use to evaluate students' models (e.g., "How does you model account for removing some of the air AND that gases take the shape of their container?", pp. 10) and facilitate conversations among students (e.g., "Do some models do a better job of taking into account the removal of air? How?", pp. 10). As before, these discussions were opportunities for teachers to prompt students to consider the existence of "empty space" in the air (e.g., "What is in the part of flask where there is no air?" and "Can the spaces in your drawing be absolutely nothing? Explain your answer," pp. 9). After the discussion, teachers asked students to consider revisions to their initial air models, "Based on the discussion, can your current model be used to explain some air being removed from the flask?" (pp. 10). In the next lesson, students would use their revised air model to explain another set of contrasting behaviors of air, the ability to compress and expand gases.

4. Features to support ambitious pedagogy

The focus lesson had three design features that promoted students' meaningful participation in modeling. The first feature involved students *observing a phenomenon* to ensure that scientific knowledge was constructed in the context of explaining a phenomenon rather than collecting scientific facts. The second feature involved creating opportunities for students to make sense of each of the three situations and *construct their own model* by express their ideas using words or diagrams in their own workbooks. In doing so, students might feel that they have ideas to contribute to the whole-class discussion, as they have had the opportunity to make connections with existing knowledge or identify connections for themselves across phenomena, and benefit from hearing other students' ideas. The third feature involved *students discussing their models with others*. During these discussions, students used evidence and argument to defend their ideas and reconcile competing ideas to reach consensus. Because the problem was not straightforward, there was a legitimate need for students to work together to reach consensus.

This lesson involved students engaging in demanding scientific practices to develop a robust understanding of the particle nature of matter. Textbooks usually tell students that there are three states of matter (solids, liquids, and gases) and that matter is in the form of particles. However, students often do not understand how and why it makes sense for matter to be in the form of particles or the explanatory significance of this model. For example, when students learn that liquids and gases take up the space of the container, students intuitively think that this means that the container is completely filled with that substance. However, the idea that there is empty space between the air was counterintuitive to many students (Krajcik, Merritt, et al., 2013; Smith et al., 2006).

During this unit and lesson, students work through the evidence from the investigations and contrasting behaviors of air to systemically construct and defend their models of matter. The goal of this work is not simply to get the "right answer," but involves students understanding how their ideas fit together and the evidence to support those ideas. Thus, this lesson was a rich opportunity to observe students engaging in ambitious scientific practices and study the successes and challenges involved in supporting students' position as epistemic agents in the classroom.

5. Study 1 Data Collection

I used two types of data to investigate Research Question 1: 1) video and audio recordings from the classroom enactments and 2) post-unit student and teacher interviews.

5.1 Classroom Observations

Using a wide-angled video camera, I captured classroom video from the back of each classroom to capture how the teacher and students interacted with one another. In addition to the video camera's microphone, I used an external audio recorder to capture audio from the front of the classroom to ensure accurate transcription of the classroom discourse. I transcribed all audible discourse verbatim. I used conversation analysis conventions (Jefferson, 2004) to identify areas of overlapped talk ([overlapped talk]); latched speech with was no audible pause between turns of talk, or changes in speaker (=); and talk that was difficult to transcribe verbatim (*best estimate of text*).

I focused my analysis on the whole-class modeling discussions, as I was interested in studying the distribution of knowledge-building responsibilities between the teacher and the students. As such, I attended to the extent to which the students, rather than the teacher, had the opportunity to pose questions and comment on each other's ideas. As students defended and evaluated each other's ideas, I could analyze the epistemic aims and considerations guiding their decisions to reach consensus.

Due to challenges with observing classrooms enacting the same lesson on the same day, it was necessary to observe two different classes in John and Laura's classrooms. Table 4.3 shows the total number of observed class periods and the number of enrolled students in each observed class. For example, John enacted this lesson over three class periods. I observed a class with 27 students on the first day and a class with 15 students on the second and third days.

Table 4.3
Lesson 4 classroom observations

Teacher	Observed Class Periods [a]	Number of Students [b]
John	3	27 (Day 1), 15 (Days 2-3)
Kami	2	14
Laura	2	25 (Day 1), 23 (Day 2)

[a] Class periods were 40-50 minutes in length; [b] I observed two different class periods for John and Laura's enactment of the focus lesson and note how many students were in the observed classes.

Using the six key steps of the lesson sequence as written in the curriculum materials, I identified ways in which the lesson differed from the planned sequence. By identifying *what* was different between the classrooms, I could begin to think about differences in teachers' interpretation of the goals for each feature of the lesson and how these decisions could have influenced students' opportunities to meaningfully use scientific practices to construct and evaluate scientific knowledge. For example, John co-constructed an explanation of the contrasting behaviors of air with his students, rather than providing students with the opportunity to first make sense of the phenomena before sharing their ideas with the class for feedback. Thus, there was no explicit Step 6 in John's classroom, while the task of representing students' ideas occurred after the class had reached consensus. I explain these classroom differences in Chapter 6 before examining the data through the three analytical lenses.

5.2 Interviews

To triangulate my observations, I conducted semi-structured interviews with each teacher at the end of the chemistry unit[1] to discuss their interpretations of the purpose, epistemic criteria, and reflections on students' use of diagrammatic models (See Appendix A for interview

[1] I observed four further lessons in this unit that are not part of this study: two lessons that involved students applying the air model to explain two further situations, the consensus conversation involving their "final" models of the anchoring phenomenon, and one lesson in which students used their final odor models to explain another related phenomenon involving the particle nature of matter.

protocol). I wanted to understand from the teacher's perspective the meaning that students and teachers applied to the modeling practice and the successes and challenges involved in supporting students' engagement in modeling. In addition, students completed embedded assessments during which students drew diagrammatic expressed models and answered questions related to the issues posed by Berland et al. (2016)'s ECs (see Appendix B). I interviewed two students from each class about their models, the interpretation of the purpose for constructing diagrammatic models and whether students viewed them as being helpful for their own learning (see Appendix C for protocol).

Chapter 5: Analytical Methods

In this chapter, I present the analytical methods used to investigate Research Question 1, which involved identifying the successes and challenges involved in supporting and enhancing students' meaningful participation in the development and evaluation of each other's explanatory models. I used these analytical methods to analyze data from both studies. In Study 1, I used these methods to examine the goal for using the contrasting air phenomena and sharing and evaluating each other's models, the epistemic considerations guiding that work, and the opportunities that students had to shape the consensus knowledge of the classroom. In Study 2, I used these methods to identify issues and analyze changes in Kami's classroom practice over time.

I divided this chapter into five parts. In Section 1, I discuss the methods used to identify instances in which students are constructing and evaluating scientific models of phenomena, organize the classroom discourse to understand the meaning applied to students' and teachers' decisions, and create profiles to document my interpretations of classroom events and interviews. In Section 2, I present an overview of the methods for each analytical lens before doing a deeper dive into each analytical lens in Sections 3-5. Using the same data set, I used each analytical lens to gain different perspectives on the successes and challenges involved in supporting students' engagement in scientific practices. In the discussion, I will argue how integrated attention to these analytical lenses could be a fruitful approach to helping students make progress in the scientific work and develop ways to make learning more meaningful for students.

1. Organizing data for analysis

In this section, I provide an overview of the methods used to process the data before I examined the meaning applied to students' and teachers' knowledge-building work using the three analytical lenses. In Section 1.1, I explain how I chunked the classroom transcripts to identify model-related activities and further chunked them into episodes. Because I was interested in the distribution of knowledge-building responsibilities between the students and teachers, I needed a way to understand instances in which students were initiating and responding to ideas. In Section 1.2, I explain how I organized the classroom transcript into interactional units to provide a structure for understanding these issues. To understand students' interpretation of the epistemic aim and considerations that should guide their work and the roles that they should adopt, it was important to identify instances in which the teacher framed these expectations for the students. In Section 1.3, I explain how I identified and analyzed teacher's framing of the activity. In Section 1.4, I explain how I created profiles to document my interpretations of the meaning applied to students' and teachers' decisions.

1.1 Segmenting modeling work

I identified instances when the class engaged in *modeling work* in which students: 1) experienced the phenomenon, 2) proposed their initial model ideas to explain their observations, 3) expressed their ideas diagrammatically, 4) shared and discussed their model ideas with others, 5) evaluated the validity of each other's ideas, 6) reconciled competing ideas to reach consensus, and 7) revised their models to account for ideas of others. The purpose of identifying such modeling talk is to distinguish between conversation related to classroom logistics, such as discussing homework assignments or scheduling tests, or other talk that are unrelated to constructing knowledge in the classroom.

I further categorized modeling activity based on *participant structure* to account for whether it occurred *individually*, in *small groups*, or as a *whole-class* (Phillips, 1972). The teacher's instructions preceding the modeling activity received the same participant structure code as the activity. For example, when the teacher communicated to the class expectations for how students were to evaluate each other's models in small groups, I coded the directions as *small group modeling*, as these directions framed students' small group discussions. I further divided the transcripts into episodes, or units of activity around a question or idea. I identified various episodes based on the various phases of the lesson sequence (see Chapter 4, Section 3) and separated discussions around each student's model. Please see Appendix D for an example of how I chunked the transcript from Laura's classroom.

1.2 Organizing transcript into interactional units.

To understand who initiated and responded to each other's ideas, I organized the classroom discourse into *interactional units*. Each interactional unit was composed of 1) a single *topic-initiating comment or question* (hereafter referred to as *topic-initiating statements*) that prompted conversation around an idea or question (Erickson, 1984) and 2) the back-and-forth talk in response to a given topic-initiating statement.

A new topic-initiating statement involved the students or teacher sharing a new idea for the class to consider or posing a question or comment to elicit a response from others. After identifying a topic-initiating statement, I would identify the back and forth talk that directly resulted from the topic-initiating statement. I identified each turn of talk when there was change in the speaker. If a follow-up question changed the topic of the conversation, I identified the beginning of a new interactional unit. In the following excerpt, Micah considered the relevance of the mechanism by which air and clouds moved outside for explaining how the air molecules moved inside the flask.

Turn	Type	Interactional Units
1	S-T	MICAH: Air moves... Because outside, how do the clouds move? Air is pushing the clouds, like... When there's wind, the, it's air moving=
2	T-S	T: =Well, what causes wind? Do you know?
3	T-S	S: No.
4	T-S	ISAIAH: The atmosphere!
5	T-S	T: Also, how much wind is inside this flask right now?
6	T-S	Ss: None. Nothing.
7	S-T	MICAH: But there's still air.
8	S-T	T: I know, but realize we're dealing with what's inside the…
9	S-T	T: I know what you're saying. Alright? But, we're dealing with what's inside this sealed flask. It's got a rubber stopper on the top. Ok?

(John Observation, 12/12/11)

I identified four topic-initiating statements in this excerpt.

1. **Turn 1, Student-initiated**: Micah was thinking about what could cause the air molecules inside the flask to move. He then considered another context in which air moved and considered how moving air caused clouds to move.
2. **Turn 2, Teacher-initiated**: John interrupted Micah to ask him what causes wind. This question marked a shift in the trajectory of the conversation. Turns 5, 8, and 9 revealed John's underlying goal of dismissing the relevance of wind as the cause of air movement inside the flask.
3. **Turn 5, Teacher-initiated**: Related to this goal, John asked Micah about how much wind was inside the flask to discount the relevance of Micah's idea for the target situation.
4. **Turn 7, Student-initiated**: Micah attempted to defend the relevance of the related situation by citing that both involve air.

I indented all back and forth talk to show how the topic-initiating statements influenced the classroom discourse. For example, John's question in turn 2 elicited student responses in turns 3 and 4. Organizing the transcript into interactional units helped to keep track of what topics were discussed, who initiated and responded to those ideas, and how issues were resolved in interaction with one another.

Coding types of interaction. After organizing the transcript into interactional units, I characterized the type of interaction evident in each turn of talk: Who was speaking? Was it in response to a student or teacher-initiated statement? Each turn of talk received an *interaction type* code (initiator-responder) that identified whether the student (S) or teacher (T) initiated or responded to a topic-initiating statement. For example, I coded turns 2-6 as T-S interactions because the teacher asked a question that elicited student responses. I coded turn 1 as an S-T interaction because Micah initiated a statement that the teacher responded to in the form of another question. This turn-by-turn coding accounted for multiple types of interaction that could occur within a given interactional unit. For example, the teacher (S-T) and another student (S-S) could respond to a student-initiated question. Thus, interactional units became a way to organize the discourse to identify whether the students or teacher initiated the discourse, while the interaction types characterized who responded to these statements.

The target activity structure involved students publicly presenting their ideas to the class and receiving feedback from their student peers and the teacher. To understand the role that students played in evaluating students' ideas, it was important to assess the extent to which students posed questions and commented on the presented ideas. Thus, I created a student presenter code, SP, to determine the extent to which the student's peers (S-SP) or teacher (T-SP) asked questions or commented on the student presenter's ideas. I used the SP-X code to refer to the discourse in which the student presenter initially explained their ideas to the entire class (X), which included the students and teacher. I coded instances when the student or teacher's initiated statements did not receive a response as S-0 or T-0 respectively, where the 0 indicates the absence of a response. In situations where there were two adults, such as the teacher and an aide, talking to one another, I coded the interaction as T-T. In all, there were 10 interaction types that I grouped based on whether the teacher (T-S, T-SP, T-0, T-T) or student (S-T, S-S, SP-X, SP-S, SP-T, and S-0) initiated the topic-initiating statement.

I used coded examples to train an undergraduate research assistant on how to identify a topic-initiating statement, organize discourse into interactional units, and code each type of interaction. She then used training cases to practice organizing discourse into interactional units and coding each turn of talk. We then discussed any questions and resolved any differences. After the coder was comfortable with the coding scheme, we independently coded more than 20% of the data for each teacher. For each teacher, I assessed the percentage of agreement for each turn of talk.

1.3 Identifying teacher's framing

To understand the meaning that students applied to their knowledge-building decisions and their adopted knowledge-building roles, I examined teacher statements preceding an activity that informed students' epistemological framing, or understanding of "what they are up to" at any moment and the norms governing their knowledge-building work (Berland & Hammer, 2012). Because students' epistemological framing is dynamic and could differ from expectations verbalized at the beginning of the lesson (Berland & Hammer, 2012; Hammer et al., 2005), I also examined teachers' efforts to reinforce or modify this framing as the activity unfolded. This framing also could include instances in which the student and teacher negotiating these expectations to reach consensus on the expected goals and norms governing their knowledge-building work.

To examine the extent to which the teacher sought to enhance the meaning that students applied to their modeling work, I examined how this framing aligned with issues posed by the three analytical lenses.

1. Epistemic aim: What are the students going to be doing? Why is this work important or worthwhile to do? What is the expected product of students' work?
2. Epistemic agency: What are the students' or teacher's expected knowledge-building roles? Why is their participation important? In what ways is the teacher supporting students' knowledge-building role?
3. Epistemic considerations: What epistemic issues should be guiding students' work, either individually or with others?

For example, Kami framed the whole-class sharing of students' initial models explaining the odor phenomenon in the following way:

> So now, when scientists get up in front of other scientists and share their models, okay, one of the reasons they do that is to get what we call feedback from other scientists. […] Other scientists, your colleagues in this room, are now going to take a look at these models, and we're gonna make sure we understand them. And then, we're gonna be sure that the models show everything we know about odors, okay? (Kami Observation, 1/17/12)

I analyzed the extent to which the teacher attended to issues related to each analytical lens. The epistemic aim guiding students' enactment would involve students sharing, evaluating, and providing feedback on the presented ideas. She ascribed implicit value to this work by noting similarities between the students and scientists' work. In addition, she referred to the other students as "colleagues" and "scientists," which implied that the student would be the agents responsible for providing feedback on the students' ideas. Kami further articulated the epistemic considerations that should guide the audience's evaluation of the presented ideas: their ability to understand the presented ideas and its consistency with existing knowledge about gases.

1.4 Create a profile

I applied analyses for each analytical lens to the same data to identify the successes and challenges involved in supporting students' engagement in modeling. To understand how these issues influenced students' knowledge-building work, I created memos that chronologically documented my interpretation of how issues related to each analytical lens influenced students' engagement in modeling. I then aggregated the findings to construct activity-specific and classroom-level profiles for each lesson. These profiles provided a more holistic picture of what was happening and could reveal differences between the teacher's framing and the classroom enactment and identify shifts in the perceived epistemic aims, norms, and knowledge-building roles. Through comparing classroom enactment of the same lesson, I could identify how the presence or absence of classroom supports could influence what was observed in the classroom. When multiple curriculum lessons occurred on a single day, I created separate profiles for each lesson. Appendix E shows an example of a profile of the transcript constructed of a model discussion in Laura's classroom.

2. Overview of Analyses

When studying the meaning that students and teachers apply to their decisions in the context of modeling and argumentation, Louca et al. (2004) found that students' *professed epistemologies*, or their stated beliefs about knowledge and learning, might differ from their *enacted epistemologies,* or the views on knowledge that guide students' actions. Sandoval (2005) argued that these differences could be due to contextual, non-epistemological reasons. For example, students might not justify their claims due to a lack of interest in the topic rather than due to underlying beliefs about evidence. Because the proposed activity structure provided students the opportunities to state and defend their decisions in response to questions and comments, I used evidence from students' actions and stated rationales to analyze the perceived epistemic aims and epistemic considerations guiding students' and teachers' decisions and actions. From observing the enactment, I could track who was initiating ideas to understand students' position as epistemic agents and how students' ideas contributed to shaping the knowledge of the classroom.

In this section, I provide an overview of the methods used to analyze the meaningfulness of students' engagement in scientific practices before doing a more in-depth explanation of the methods used to identify the successes and challenges involved in supporting students' engagement in scientific practices and how these issues could help teachers reflect on and inform their decision-making.

2.1 Epistemic aim: What is the goal of the knowledge-building work?

To examine the meaningfulness of the epistemic aim guiding students' knowledge-building work, I first examined the epistemic aim that was guiding students' work to understand the students' goals and to analyze the extent to which students' knowledge-building work was guided by the goal of collecting scientific facts or developing disciplinary knowledge through explaining phenomena. The second phase sought to identify instances in which the teacher attempted to ascribe meaning to students' knowledge-building work, by explaining how and why students' work was worthwhile for students' learning.

Table 5.1
Overview of analytical methods for epistemic aim lens

Question	**Analysis**	**Rationale**
Phase 1: What is the epistemic aim guiding students' work?	Examine teacher's statements about what students are going to be doing, learning, or explaining.	Identify the epistemic aim guiding students' knowledge-building work. Understand how students used modeling to mediate student sensemaking
	Classify epistemic aims into three categories: 1. Phenomenon-based (observe, predict, and plan investigations) 2. Content-based 3. Model-based (construction, sharing, and revision)	Understand the extent to which students' knowledge-building work was driven by learning facts or explaining a phenomenon.
Phase 2: How did the teacher ascribe meaning to students' work?	Identify instances in which the teacher discussed issues related to the following questions: 1. What are we trying to figure out? 2. Why is this work worthwhile?	Identify and analyze teacher's attempts to explain why students' work was worthwhile from the perspective of the discipline and students

2.2 Epistemic considerations: What ECs guided the development and evaluation of students' models?

This analytical lens investigated the epistemic considerations that might have guided the development and use of students' explanatory models (see Table 5.2 for overview). Using the topics of conversation and students' rationales when explaining, defending, commenting on, or evaluating students' models, I coded students' statements when they showed evidence of considering issues related to Berland et al (2016)'s epistemic considerations. I calculated the proportion of modeling talk in which students attended to each EC to understand what issues guided students' and teachers' scientific work and how these issues helped students make progress in developing valid, explanatory accounts of phenomena. Using this relative attention profile for each classroom, I then considered the implications of these classroom differences on students' scientific work.

Table 5.2
Overview of analytical methods for epistemic considerations lens

Question	Analysis	Rationale
What epistemic considerations guided the development and evaluation of students' models?	Calculate proportion of classroom talk in which students and the teacher implicitly or explicitly considered issues related to Berland et al (2016)'s ECs. 1. *Nature of Account*: What type of answer should our account of the phenomenon provide? 2. *Audience*: Who will use our account of the phenomenon and how? 3. *Justification*: How do we justify our account of the phenomenon? 4. *Generality*: How does our account of the phenomenon relate to other scientific phenomena and ideas?	Understand what epistemic issues might have guided the students' and teacher's modeling decisions
Which epistemic considerations were most influential in guiding students' and teacher's knowledge-building work?	Calculate relative attention profiles: Rank which ECs most highly attended to in each classroom.	Identify and explain observed classroom differences on students' knowledge-building work.

2.3 Epistemic Agency: How are students' ideas used during instruction?

The third analytical lens analyzed the extent to which students and their ideas had a role in defining, addressing, and resolving problems that shaped and advanced the knowledge of the classroom community (Engle & Conant, 2002; Stroupe, 2014). I organized the analysis around the three sub-questions (see Table 5.3 for overview).

2.3.1 Who's doing the work? The first analysis investigated the question, "How are the knowledge-building responsibilities distributed between the students and teacher?" To answer this question, I first analyzed the patterns of interaction in the classroom to examine the extent to which students were initiating and responding to each other's ideas. Next, I examined the epistemic considerations guiding student and teacher-initiated talk to examine the extent to which the students, rather than the teacher, were making decisions in service of developing convincing, evidence-based, explanatory models of phenomena. Since each teacher voiced the desire for their students to participate in the knowledge-building work, I examined the supports present that enhanced the students' knowledge-building role. For example, did the teacher articulate how their role would be distinct from the students' role and supportive of students' knowledge-building work? Did the teacher create opportunities for students to engage in discussions with other students?

2.3.2 Who had the authority? This question examined who had the responsibility for evaluating and assessing the validity and relevance of students' ideas for achieving the desired epistemic aim. In addition, this analysis examined whether students had the authority to assess whether they had achieved the desired epistemic aim or whether further work was warranted.

2.3.3 How were students' ideas used during instruction? This question examined the extent to which students' ideas and questions shaped classroom knowledge-building work. I then examined whether there were implicit or explicit criteria that influenced which ideas were discussed.

Table 5.3
Overview of analytical methods for epistemic agency lens

Question	**Analysis**	**Rationale**
How were the knowledge-building responsibilities distributed between the students and teacher?	Analyzed patterns of interaction in classroom. • Compared proportion of student and teacher-initiated discourse • Examined proportion of student-student (S-S) interactions	Understand extent to which students initiated and responded to each other's ideas. Understand whether the students or teacher directed students' knowledge-building work
	Compare student and teacher relative attention profiles	Understand extent to which students, rather than the teacher, were making decisions in service of developing convincing, evidence-based, explanatory models of phenomena.
	Examined classroom supports and norms that positioned and reinforced the students as the agents responsible for constructing and evaluating knowledge	
Who had the authority?	Identified who assessed the validity or relevance of student ideas (students, teacher, or another authoritative source) Identified who assessed the class' progress towards achieving the epistemic aim	Understand distribution of responsibility for who determines "what counts" as scientific knowledge in the classroom.
How were students' ideas used during instruction?	Examined the extent to which students' ideas were discussed, motivated investigations, and shaped the class consensus knowledge. What criteria, if any, guided what student ideas were discussed?	Assessed the extent to which students' ideas contribute to shaping the knowledge of the classroom community Analyzed the openness of the space for students to explain the phenomena on their own. Understand how teacher's planned trajectory for achieving epistemic aim might influence what ideas were discussed.

3. Epistemic Aim: What is the goal of students' knowledge-building work?

The first analytical lens examined the epistemic aim(s) guiding students' knowledge-building work. I used the construct of epistemic aim to include not only the content knowledge that the students would be learning, but also the practices used to construct that knowledge. This decision was important for distinguishing rote and meaningful uses of scientific practices. For example, when students share their models with the class, there should be an underlying epistemic aim guiding students' discussions so that students understand what they are trying to accomplish and how they would use each other's ideas to achieve their knowledge-building goals. Thus, the practice of sharing students' models had meaning when coupled with a content goal and an understanding of how engagement in the practice would help them achieve that goal.

In a phenomenon-driven, model-based instructional approach, students engage in a series of investigations to explain the anchoring phenomenon and develop aspects of the broader explanatory model. For example, students investigate contrasting behaviors of air to obtain evidence and develop ideas about the particle nature of matter. In preparation, students might review principles, information for which students have evidence (Krajcik, Merritt, et al., 2013), or do a reading to provide students with background information. By teasing apart the various epistemic aims used to achieve the broader goals of explaining phenomena, we have a way to understand how teachers bring coherence to the overall endeavor of developing the explanatory model. In addition, I could analyze whether certain epistemic aims were more meaningful to students than others or whether there were differences in whether students were responsible for achieving particular types of epistemic aims. For example, students might be responsible for making observations of the phenomena, but the teacher might be the agent responsible for manipulating the equipment or informing the methods used to investigate the phenomenon.

In what follows, I explain the four phases used to identify and analyze the meaningfulness of the epistemic aim from the perspective of the discipline and students.

3.1 Phase 1: What is the epistemic aim guiding students' work?

3.1.1 Identifying epistemic aim. I examined three data sources to identify the epistemic aim guiding students' knowledge-building work: the framing of the modeling work during classroom discussions, interviews, and the curriculum materials. To identify the epistemic aims guiding students' modeling work, I examined the teacher's framing before and during the activity for answers to the following questions: 1) What are the students going to be doing or learning? and 2) What are the students going to be figuring out or explaining? I coded sentences from the classroom discourse that referenced these issues under the umbrella code of *epistemic aim*. Using the same questions, I examined the curriculum materials (Krajcik, Merritt, et al., 2013) to understand what guidance teacher might have received about the intended purpose for each activity and how those activities would be used to achieve the broader epistemic aims.

In addition to using the classroom discourse and curriculum materials for evidence of the epistemic aim, I used teacher and student interviews to understand their interpretation of the epistemic aim guiding the activities (e.g., "What was the purpose of doing [activity]?") and their views on how students could use models to mediate their knowledge-building work (e.g., "How are models used in your classroom?" "What was the purpose of students constructing models during [activity]?" see Appendix A). Students interviews focused on their interpretation of the purpose for constructing their models, "What was the reason for constructing this model?" (see Appendix C). I triangulated these findings with classroom observations and the intended epistemic aims as stated in the curriculum materials.

3.1.2 Identifying type of epistemic aim. Once I identified the epistemic aim(s), I categorized them into three groups: 1) *phenomenon-based* epistemic aims, which involved students observing, making predictions, or investigating phenomena without explicit direction to explain the observations or findings; 2) *content-based* epistemic aims, which involved acquiring or reviewing disciplinary knowledge without using it to explain a phenomena; and 3) *model-based* epistemic aims, which involved constructing, sharing, evaluating, and revising explanatory models. I identified three types of *model-based* epistemic aims: model construction, sharing, and revision. In what follows, I explain the indicators for each type (see Table 5.4 for summary).

Table 5.4
Types of model-based epistemic aims

Type	Indicators
Model construction	• Students asked to construct a model to describe or explain a phenomenon • Models used to show others what they know • Use existing model to explain another situation
Model sharing	• *Neutral*: Students report out students' ideas or identify commonalities/differences between models without evaluating the validity of discussed ideas. • *Evaluative*: Students evaluate students' ideas using criteria, evidence, or the model's consistency with existing knowledge • *Consensus building*: Students reconcile competing ideas using argument and evidence to construct common knowledge product.
Model revision	• Students revise their existing models to account for new or existing information.

Model construction. *Model construction* epistemic aims involved students constructing a model, either diagrammatically, orally, or in writing, to represent or explain a phenomenon. In Lesson 4, students constructed diagrammatic models to 1) describe what air looked like inside a flask and 2) use or revise their air models to explain teacher's ability to add or remove some air from the flask. I coded the following sentences as *model construction* because students were constructing their air models. To help students attend to air's non-visible features, Kami asked her students to pretend that they had access to a "really strong" microscope.

> And what you're gonna do is, pretend you're magnifying this little bit of air in the flask and draw in this circle what you think the air looks like, but think slowly, ok? Think carefully and then draw your model. (Kami Observation, 2/1/12)

Model sharing. *Model sharing* epistemic aims involved students sharing their models with others, either to the whole-class or small groups. The curriculum materials intended for students to discuss each other's models (Krajcik, Merritt, et al., 2013), yet provided little guidance about the purpose or guidelines for organizing such discussions (see Chapter 4, Sections 3.3 and 3.6). Thus, I analyzed the reasons provided for why students shared their models with others. I identified three types of *model sharing* epistemic aims: *neutral*, *evaluative*, and *consensus building*.

Neutral. I coded model sharing epistemic aims as *neutral* if students shared their ideas without evaluating the validity of the shared ideas or reconciling different ideas to reach consensus. Students might ask clarifying questions to understand each other's ideas. For example, Kami's students shared and listened to each other's ideas without commenting on the validity of the presented ideas, "And then we're going to take a look at these models and see what they tell us about air. Ok? Alright?" (Kami Observation, 2/2/12). In other cases, the teacher might ask students to share their models without providing an underlying reason, "Now that you have your new [air] model, again, take a couple of minutes, take a couple minutes to share with your table mates and that's about as far as we are going to get today, guys" (John Observation, 12/12/11).

Evaluative. I coded model sharing epistemic aims as *evaluative* when students attempted to assess students' ideas without a goal for why they were evaluating one another's ideas, such as reaching consensus. For example, John explained that students would use epistemic criteria to evaluate one another's ideas without stating a goal to frame their model evaluation work, "This is evaluate — using these criteria and what we've done as a class — thinking about the evidence and challenging people to think things in different ways" (John Observation, 12/12/11). Thus, there was a focus on what students would be doing without understanding why.

Consensus-building. I coded model sharing epistemic aims as *consensus-building* when students shared and reconciled competing ideas in service of reaching some consensus understanding. The *consensus building* code superseded the *evaluative* code. For example, Kami asked students to share their models with the goal of developing a group consensus model.

> How you, as a group, want to put together a consensus model, ok, for your group. All the things that your models have in common, you want to be sure that's in there. And, if there are things that are different among your four models, talk about it and figure out which of those things do belong in the models and which of the things don't belong. (Kami Observation, 3/1/13)

Additional indicators of a consensus building epistemic aim included students identifying areas of agreement to include in the group consensus model and reconcile identified differences.

Model revision. *Model revision* epistemic aims involved students modifying their existing models to account for new ideas or the ideas of others. For example, Kami's students recognized that their models needed to account for movement, "So, take a look at your model. If your model does not show movement, you should add that in. Revise your model" (Kami Observation, 2/2/12). Thus, the epistemic aim did not involve constructing a brand-new model, but involved making minor revisions to an existing model.

3.2 Phase 2: How did the teacher ascribe meaning to students' work?

After identifying and classifying the epistemic aim guiding students' knowledge-building work, I examined the teacher's efforts to ascribe meaning to the epistemic aim by explaining how and why this work was worthwhile from the perspective of the discipline and the students. Using the teacher's framing before and during the activity, I examined instances in which the teacher addressed issues related to the following questions: 1) What are we trying to figure out? and 2) Why is this work worthwhile? I also coded teacher interviews for evidence that teachers explained the rationales for the enacted activities and their attempts, if any, to make the learning more meaningful for students.

In what follows, I explain how each question contributed to the meaning applied to the knowledge-building work. Table 5.5 summarizes the rationales and coding rules for each question.

Table 5.5
Teacher's efforts to ascribe meaning to students' modeling work

Question	**Rationale**	**Indicators**
1) What are we trying to figure out?	Teacher reminds students about the purpose for their knowledge-building work.	Teacher asks students to recall the goal or question driving their knowledge-building work
2) Why is this work worthwhile?	Helps students understand how and why this work is valued by the discipline and useful for students' learning	Teacher asks students to reflect on and articulate their interpretation of why their work is worthwhile Teacher explains how students' actions or findings will help students achieve their broader epistemic aims

3.2.1 What are we trying to figure out? This analysis identified instances in which the teacher posed a question to elicit students' ideas or remind students about the purpose or question driving their knowledge-building work, "Alright, who remembers what question we're trying to answer? What question are we trying to answer?" (Kami Observation, 2/6/13).

3.2.2 Why is this work worthwhile? The previous question examined the purpose of students' knowledge-building work. The second question involved teacher's attempts to inform or elicit students' understanding of the reasons for why this work is worthwhile from the perspective of the discipline and students. For example, students conducted experiments to determine whether odors had mass and volume. Kami reminded her students why these investigations were worthwhile, "If we can figure out how to do an experiment to prove that odor has mass and odor has volume, then we'll have proof, right? We'll know odor is matter" (Kami Observation, 2/4/13). In other cases, the teacher might ask students to consider their interpretation of the epistemic value of the epistemic aim, "Why do we care that odor has mass and volume?"

4. Epistemic considerations: What ECs guided the development and evaluation of students' models?

4.1 Overview

This analytical lens examined the epistemic considerations guiding students' and teacher's decisions when developing and evaluating each other's models. I operationalized Berland et al. (2016)'s *Epistemologies in Practice* Framework to identify indicators of students' or teacher's implicit attention to issues related to each epistemic consideration. When suggesting that a student or teacher "attended to" or "considered" issues related to an EC, I am claiming that the discussed topics or stated rationales were consistent with potential responses to an EC rather than making claims about the underlying cognition that might have led to students' actions (B. L. Sherin & Star, 2011) or that students explicitly considered the question posed by the EC.

I coded each sentence within a conversational turn when students discussed topics related to one or more EC(s). This coding did not account for scientific accuracy. For example, I coded discourse as considering issues related to the *justification* consideration why students showed evidence of trying to use empirical evidence to support a claim, regardless of whether students interpreted the evidence correctly. Thus, the goal of this analysis was to understand the underlying issues or rationales guiding students' decisions rather than the scientific accuracy of the statement. I did not code statements that were unrelated to the development of students' explanatory models, such as discussing testing deadlines or classroom management. When the teacher might have asked students to restate their ideas or questions (e.g., "I'm sorry, I missed it. What was your question? And then what did you say?"), I coded the most audible statement or the statement that led to a response.

After coding the classroom discourse, I examined what ECs the students and teacher attended to the most in each classroom and considered the implications of these differences on students' knowledge-building work. In what follows, I explain the coding rules for each epistemic consideration.

4.2 Nature of Account: What type of answer should our account of the phenomenon provide?

The epistemic aim of the lesson sequence involved students investigating phenomena to develop model ideas related to the particle nature of matter. I examined whether students achieved this content goal in the context of explaining the phenomena or whether students sought to learn the "correct" model idea or answer without considering the explanatory significance of the idea. In other words, did students understand the explanatory significance of empty space for explaining students' ability to add/remove air or compress/expand air? To do so, I operationalized Berland et al. (2016)'s *nature of account* consideration to code the extent to which students' statements were *descriptive* or *explanatory*.

4.2.1 Descriptive. *Descriptive* statements involved the students and teacher showing or describing what happened in the phenomenon without considering how and why it occurred. For example, many of students' air models included a description of the components that they believed made up air, "These are like the things that make up air. Like all of the different gases in the air and all the gases together make up the air" (John Observation, 12/12/11). Other descriptive statements could involve observations that the popper came off when the teacher added excess air to the flask without explaining how and why the popper came off.

4.2.2 Explanatory. I coded sentences as *explanatory* when the students or teacher considered aspects of cause and effect or identified parts, relationships between those parts, and processes that could lead to a phenomenon (Russ et al., 2008). For example, a student, Dean, claimed that space between the air was necessary for explaining air's ability to move inside the flask, "This space in-between is the little space that has the molecules are able to move around in" (John Observation, 12/12/11). Thus, the student accounted for a model feature that could account for observations in the phenomenon. In what follows, I explain additional indicators of an explanatory account.

Explanatory processes. Students might identify general processes that could give rise to a model component or idea. For example, a student could describe processes involved in photosynthesis and cellular respiration to justify the presence of oxygen and carbon dioxide in the air, "Plant and trees give off oxygen and so oxygen is actually what we breathe in and carbon dioxide is what we breathe out" (Laura Observation, 1/27/12). Other examples could include students naming the process of *condensation* to explain the formation of water droplets outside a cold coke can.

Relationships between model components and ideas. Student should consider the relationship between model ideas or the implications of one idea on another known idea (Passmore & Svoboda, 2011). For example, students might think that the flask was filled with air with no empty space between them. However, students might consider this idea's coherence with a known principle that odors and air move in all directions. Thus, considering the relationship between model components and ideas could be one way to assess the validity and coherence of an explanatory model.

Considers ideas at multiple levels or time scales. Wilensky and Resnick (1999) argued that observed phenomena emerge from interactions at multiple levels of the phenomenon. For example, water droplets form due to the aggregate effect of millions of microscopic water molecules slowing down and moving closer together near the cold coke can. Thus, one indicator could involve students examining interactions at multiple levels of a phenomena to explain the observed phenomenon.

Identifies mediating factors. More sophisticated accounts might consider how external factors, such as temperature, might affect the explanatory model. For example, students might note how increasing the temperature leads to faster molecular movement and quicker detection of the odor.

4.2.3 Coding students' accounts. Because students' accounts could involve descriptive and explanatory statements, I examined students' accounts at the model level to determine whether students sought to *describe* or *explain* phenomena. In addition, I created two additional codes to account for differences in the extent to which students developed or justified the concept of "empty space" in their models in the context of explaining phenomena.

Correct answer. It was possible for the students or teacher to identify an explanatory model component, such as the presence of empty space in the air, without considering the relevance of the idea for explaining the phenomenon. For example, John summarized a student's model ideas, "Alright, so you're saying that the molecules could actually move around, the particles could move around, there's empty space, and the different dots represent the different things that make up air" (John Observation, 12/12/11). Thus, the concept of empty space was described as one of many model components without explicating its relevance for explaining air's ability to move within the flask or the teacher's ability to add or remove air from the flask. I coded these accounts as attending to the *correct answer,* as the underlying goal guiding the development of the account was to have all the correct model components without considering the explanatory significance of the ideas or the model's coherence for explaining the phenomenon.

Mechanistic. I created a fourth code, *mechanistic*, to describe students' efforts to generate an internally consistent model without considering the model's ability to explain the phenomenon. For example, when constructing a model explaining a teacher's ability to add air into the flask, the students might justify the presence of empty space by considering its consistency with existing model ideas, such as the need for space for the air molecules to move, without considering the idea's relevance for explaining the contrasting behaviors of air. To make this account more *explanatory,* students could explain how empty space was important for explaining the teacher's ability to add air to the flask by providing a place for additional air molecules. Thus, I used *mechanistic* as a hybrid code to describe instances in which students or the teacher leveraged mechanistic reasoning without connecting these ideas to explaining phenomena.

4.3 Audience: Who will use our account of the phenomenon and how?

This analysis examined the extent to which students' decisions were guided by the desire for an external audience to understand or be convinced of the presented claim's validity. Did students anticipate potentially confusing ideas and take steps to communicate their ideas so that their classmates understand them? Did students use sufficient evidence or consider the persuasiveness of their evidence to support the validity of their claims? At the same time, this analysis examined the audience's perspective to assess the extent to which they understood or were convinced by the present claims. Evidence for these assessments came from analyzing the topics of questions or comments, in which the students or teacher sought to clarify or elicit further justification to support the presented ideas.

Table 5.6
Audience consideration coding

Code	**Indicators**
No external audience	Student explains ideas verbatim without considering how others might understand or be convinced of one's claims.
Audience-clarity	Student considers how to communicate ideas so that others can understand them. • Includes features (e.g., key, labels, or written text) in expressed model to facilitate communication of ideas. • Anticipates potentially confusing ideas • Uses examples to explain ideas in a different way Audience considers extent to which understands presented ideas. • Asks questions to clarify understanding • Checks interpretation of presented claims
Audience-persuasion	Student considers how to persuade others of the validity of one's idea. • Considers how proposed idea(s) could better explain the phenomenon than competing ideas • Responds to critiques Audience considers extent to which convinced of claim's validity. • Evaluates persuasiveness of claims compared to competing claims • Requests further evidence to justify claims

I teased apart instances when participants considered the clarity of the communication of one's ideas to others (*audience-clarity*) from efforts to persuade others or assess the persuasiveness of a claim's validity (*audience-persuasion)* because they involve different goals related to how an external audience might use a student's ideas (see Table 5.6). Berland and Reiser (2011) made similar distinctions when analyzing instances of *information seeking dialogue*, in which students sought to clarify their understanding of students' ideas without attempting to evaluate or critique the presented claims, and *persuasive dialogue*, in which students focused on defending the presented claims. In what follows, I explain the coding for the *audience* consideration (see Table 5.6 for summary).

4.3.1 Audience-clarity. I coded sentences as *audience-clarity* if the students' or teacher's decisions showed evidence of the desire to communicate one's ideas to others. For example, students might use diagrammatic models as a tool to mediate the communication of one's ideas to others. In doing so, students might use labels or a key to help their audience understand the referents for various features. In addition, students might explicitly ask their audience whether they understood the presented ideas ("Does that make sense?"). As audience members, I examined three ways in which participants might have attended to issues related to *audience-clarity*.

Clarifying understanding of ideas. The audience might ask clarifying questions or restate ideas to check their interpretation of the presented ideas. In the example below, John asked questions to clarify his understanding of the arrow's referents and Craig's ideas about air movement.

Turn	Type	Interactional Units
1	T-SP	T: And the arrows represent...
2	T-SP	CRAIG: Where the air is moving.
3	T-SP	T: So you're saying that the air particles actually move around.
4	T-SP	CRAIG: Yeah.
5	T-SP	T: Ok.
6	T-SP	CRAIG: Yeah, in the flask.

(John Observation, 12/12/11)

Evaluating consistency between expressed and conceptual models. Another indicator involved the audience evaluating the consistency between the verbal explanations and students expressed models. For example, Rob shared his diagrammatic model (see Figure 5.1) explaining how students could detect odors from a distance. Kami asked a question to clarify the nature of the “white space” in his model, a strategy articulated in the target lesson to prompt students to begin thinking about the existence of “empty space” in the air.

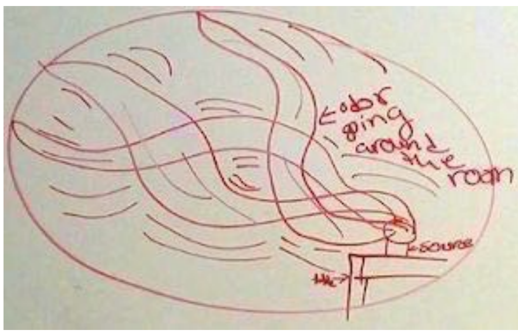

Figure 5.1. Rob’s diagrammatic model explaining how and why could detect odor.

Turn	Type	Interactional Units
1	T-S	T: This part of the model right here [white space in model]? What is that?
2	T-S	ROB: Like it [odor] goes everywhere. I just didn’t draw it.
3	T-S	T: Oh, so this actually should be like solid.
4	T-S	T: More like a cloud or more like lines?
5	T-S	ROB: Both.
6	T-S	T: Cloud and lines.
7	T-S	T: So, it should fill-up the whole space [is what you want to say?
8	T-S	ROB: [Mm-hmm.
9	T-S	T: So, there’s not really any space here. [fills in model] This should fill up like all the space. So, it’s sort of like a cloud. Right, Rob?
10	T-S	ROB: Mm-hmm.

(Kami Observation, 1/17/12)

After learning that Rob intended for the odor to “go everywhere” without any empty space between the air, Kami considered ways to revise the diagrammatic model to reflect his ideas, such as using “clouds and lines” to fill any white space in the model. Thus, Kami did not evaluate Rob's idea or attempt to persuade him of the existence of empty space; rather her intent was to understand Rob's ideas and assess the alignment between Rob's conceptual and expressed models.

Help others understand someone else's ideas. Lastly, students or teacher's moves could help others understand someone's ideas. For example, a student recognized that other students misinterpreted someone else's idea and sought to present her interpretation of the student's ideas, "I know what you mean. Like he means […]" (Laura Observation, 1/27/12).

4.3.2 Audience-persuasion. I coded sentences as *audience-persuasion* if there was implicit or explicit evidence that the students' or teacher's decisions were guided desire to persuade others, account for potential critiques, or assess the persuasiveness of a claim's validity guided students' or teacher's decisions. For example, I coded the following example as *audience-persuasion* because Laura wanted to convince her students that the hand-evacuating pump removed some air from the flask.

Turn	Type	Interactional Units
1	T-S	T: If I go like this [activate hand-evacuating pump], do you see how this [tubing] is getting thinner, sort of?
2	T-S	S: Yeah.
		[…]
3	T-S	T: But if you look at the reader [gauge] here, can you tell that some air, and you can hear it? You can see it's not going flat? Would you agree with me that some air is being removed from it?
4	T-S	Ss: Yes.

(Laura Observation, 1/31/12)

Because there were no visible changes inside the flask, Laura helped her students notice indirect empirical evidence that air was leaving the flask. For example, Laura convinced students that she removed air from the tube, as it got "thinner" when a student placed his finger at the end of the tubing (turns 1-2). After connecting the tubing to the flask, Laura asked students to observe changes in the gauge, hear the audible noises from the pump, and notice how the tube was "not going flat" (turn 3) to show that air was now passing through the tube and out of the flask. Throughout, Laura demonstrated attention to the appropriateness and sufficiency of the evidence used to justify the desired claim. In addition, Laura checked whether her students were convinced, "Would you agree with me that some air is being removed from it?" (turn 3). In doing so, she provided her audience the opportunity to state their views and assess whether she had achieved her goal of persuading them. However, the provision of evidence alone does not always mean that students had the intent to persuade others. It was Laura's use of multiple sources of evidence together with an explanation of the significance of those findings that signified her desire to persuade her audience. In other words, her use of evidence was to address potential alternative ideas and persuade others of the validity of the desired claim.

As an audience member, students might evaluate the persuasiveness of the presented ideas and consider what might be needed to convince them of the claim's validity. For example, one of John's student claimed that she was not convinced that there was "empty space" between the air and expressed her need for further evidence to support the claim, "I don't know. I might change my mind. I need evidence" (John Observation, 12/14/11).

4.4 Justification: How do we justify our account of the phenomenon?

I coded sentences as *justification* if the students or teacher demonstrated implicit or explicit desire to justify their ideas. I was interested in analyzing 1) the source or reasoning used to support participants' claims and 2) the extent to which students attempted to justify how and why the evidence was appropriate and/or sufficient for supporting the desired claim. Evidence was *appropriate* if it could be used to justify the desired claim, while *sufficient* evidence involved having enough evidence to convince others of the validity of the claim (Sandoval & Millwood, 2005). For each instance in which I coded sentences for the *justification* consideration, I coded the type of evidence used to support the desired claim: empirical, everyday experiences, authoritative, and opinion (see Table 5.7).

Table 5.7
Sources of evidence

Type	Indicators
Empirical	• Data that all individuals could observe, interpret, and use to test claims in the classroom setting.
Everyday experiences	• Experiences from outside the classroom that students might share • Students could not test claims in the classroom setting.
Authoritative	• Source has institutional authority (e.g., teacher or textbooks)
Opinion	• Does not leverage external source of support

4.5 Generality: How does our account of the phenomenon relate to other scientific phenomena and ideas?

One indicator of students' or teacher's implicit attention to issues related to the *generality* consideration involved the students or teacher discussing the relevance of knowledge from other situations to explain the target situation or using the target situation to explain other related situations. To justify their argument, the students or teacher could articulate the related components and processes that are analogous in both situations (Gentner, 1983). I coded the example discussed in Section 1.3 as *generality* because Micah and the teacher were discussing the relevance of the mechanism by which air and clouds. If there was no evidence of the students or teacher considering issues related to the *generality* consideration, I did not assume that participants believed that specific answers were better than general ones.

A second indicator involved the students or teacher discussing the relevance of general principles for explaining the target phenomenon or evaluating a model's consistency with existing knowledge. In the IQWST context, principles are statements about the world for which students have evidence (Krajcik, Merritt, et al., 2013). These principles become increasingly general as students use and revise them to account for other situations. Examples of principles include “molecules in the gaseous state move and take up the space of their container,” “hot fluids/gases rise, while cold fluids/gases sink,” or “molecules move faster and farther apart when temperature rises.”

Figure 5.2. Eric’s model showing air's location after some air removed.

For example, a student, Eric, claimed that after removing some air from the flask, the remaining air would remain at the bottom of the flask (see Figure 5.2). In response, another student argued that the air would fill the flask, “Since air takes up the space of the container, it would circulate all the way around the container no matter how much there is in there” (Laura Observation, 1/27/12). In this exchange, the student considered a general characteristic of gases, its ability to take up the space of a container, to justify her argument.

4.6 Calculate relative attention to each EC

For each classroom, I developed a *relative attention profile* that ranked which ECs were most highly attended (1-most to 5-least) in each classroom. To do so, I calculated the proportion of the whole-class model discourse in which students and teachers discussed topics related to each EC. I used word count as an indicator of time spent discussing topics to account for differences in the duration of conversational turns, turn-taking frequency, and time allocated to whole-class discussion of students' models. The relative attention profile was useful for understanding which ECs most frequently guided students and teachers' knowledge-building work, as evidenced by the higher proportion of coded talk for an EC.

4.7 Explain relative attention patterns

To explain the observed relative attention patterns, I examined the teacher's framing to understand what guidance teachers provided about what epistemic considerations should guide students' work. For example, when evaluating students' odor models, Kami noted that students should consider their ability to understand the model's ideas (*audience-clarity*) and the model's consistency with existing knowledge about odors (*generality*).

> Other scientists, your colleagues in this room, are now going to take a look at these models, and we're gonna make sure we understand them. And then, we're gonna be sure that the models show everything we know about odors. OK? (Kami Observation, 1/17/12)

In addition, I examined how the desired epistemic aim might have influenced students' decisions. For example, if the students' goal involved reaching consensus, there might be more attention to *audience-persuasion* and *justification* compared to instances in which the epistemic aim involved sharing their ideas with others.

4.8 Reliability Coding

I used classroom discourse examples from each teacher in Study 1 to train a graduate student on how to use the coding scheme to code for students and teachers' attention to Berland et al. (2016)'s ECs. I assessed reliability for the ECs used in the classroom level analyses: *audience-clarity*, *audience-persuasion*, *justification*, *generality*, and *nature of account*. My unit analysis was the interactional unit. For each interactional unit, I determined whether there was agreement about the presence or absence of a given code. We independently coded more than 20% of the data for each teacher for Lesson 4. There were 29 total interactional units coded from Laura's classroom and 44 interactional units from John's classroom. There were two rounds of coding for each teacher. After the first round, we discussed our coding and areas of disagreement. We then commenced a second round of coding after the discussion. For John's classroom, there was 83% agreement after the first round and 94% after the second round. For Laura's classroom, there was 90% agreement after the first round and 95% after the second round.

5. Epistemic agency: How do students' ideas and questions influence the knowledge-building work?

The third analytical lens analyzed the extent to which students and their ideas had a role in defining, addressing, and resolving problems that shaped and advanced the knowledge of the classroom community (Engle & Conant, 2002; Stroupe, 2014). Given the explanatory significance of the particle nature of matter and research documenting the non-intuitive nature of this concept for students (Smith et al., 2006), it was important for students to have the opportunity to use evidence to reconcile competing ideas about the nature of matter with others to develop a robust understandings of this concept (e.g., Driver et al., 2000; Engle & Conant, 2002; Osborne, 2010).

To examine the extent to which the students are the agents responsible for constructing, evaluating, and revising scientific knowledge in the classroom, I first examined how the knowledge-building responsibilities were distributed between the student and teacher. Second, I examined the classroom supports that were present that enhanced or hindered students' opportunities to engage in the knowledge-building work with others. Third, I examined the extent to which students' ideas contributed to shaping the consensus knowledge of the classroom. I used these three phases to organize the investigation of the three questions from the framework: 1) Who is doing the work? 2) Who has the authority?, and 3) How are students' ideas used during instruction?

5.1 Phase 1: Who's doing the work? and Who has the authority?

The purpose of Phase 1 was to characterize the nature of students' knowledge-building roles and assess students' opportunities to shape the consensus knowledge of the classroom. First, I examined the observed patterns of interaction to analyze the extent to which students initiated and responded to one another's ideas. Next, I constructed relative attention profiles for students and teachers to analyze the distribution of responsibilities for constructing convincing, evidence-based models of phenomena. Although teachers might invite students to participate in the process of constructing and evaluating students' ideas, the third analysis examined whether the students had the epistemic authority to validate student ideas or whether the teacher continued to hold this traditional role in the classroom.

5.1.1 Analyze patterns of interaction. I wanted to develop a measure of *conversational dominance* (Erickson, 1984) to assess the extent to which the students, rather than the teacher, initiated and responded to each other's ideas in the classroom. To analyze the patterns of interaction in the classroom, I calculated the proportion of whole-class modeling discourse coded for each *interaction type.* I used word count to account for differences in the duration of conversational turns, turn-taking frequency, and multiple types of interaction within an interactional unit. By comparing these percentages, I had one measure to understand how the knowledge-building responsibilities were distributed between the teacher and students. For example, who were the primary individuals commenting on and evaluating the presented ideas

(S-SP vs. T-SP)? Could students initiate and respond to one another's ideas (S-S) or did the teacher mediate students' knowledge-building work (T-S or S-T)? In addition, I examined the type of questioning that was used to develop students' accounts. For example, *teacher-directed* accounts might involve sequences of teacher-initiated *closed* questions that involved a limited number of responses, rather than more *open* questions, which would allow the students to express their opinions and reasoning for their choices (c.f.,McNeill & Pimentel, 2010). I coded the observed patterns of interaction as *student* or *teacher-directed* (See Table 5.10 for summary of coding rules).

Table 5.8
Analyzing patterns of interaction

Patterns of interaction	Indicators
Student-directed	• Students were the primary individuals responsible for commenting on the presented ideas (S-SP > T-SP) • Students initiated and responded to one another's ideas (S-S) • Teacher uses open-questioning to allow students the opportunity to explain their ideas.
Teacher-directed	• Teacher was the primary individual responsible for commenting on presented ideas (T-SP > S-SP) • IRE-like discourse patterns • Teachers' questions scaffold the development or evaluation of student's account (T-S > S-S)

Analyze relative attention to ECs in interaction. In addition to examining the patterns of interaction, I constructed relative attention profiles for teachers and students to analyze the distribution of responsibility for constructing convincing, evidence accounts of phenomena. Similar to the procedure described in Section 4.6, I examined what proportion of student- and teacher-initiated discourse showed evidence of considering issues related to Berland et al. (2016)'s ECs. Through this lens, I could interpret whether students' attention to a given EC was done on the students' own volition, as evidenced by its presence during student-initiated interactional units, or whether it was in response to a teacher's question or comment (T-SP, T-S). For example, did a student presenter justify his ideas while explaining his model to the class (SP-X) or was it in response to a student (S-SP) or teacher (T-SP) initiated request? Although both cases involved the student presenter considering the justification for his claims, the former case involved the student anticipating the need to justify one's ideas to convince others of the validity of one's ideas, whereas the second case involved responding to a critique or question.

Next, I divided these numbers by the total word count to indicate the students' and teacher's relative contribution to the overall classroom findings. Once I calculated these percentages, I ranked which ECs were most highly attended to (1-most to 5-least) when teachers and students initiated interaction with others and interpret the students' and teachers' knowledge-building role. To analyze the distribution of responsibility in the classroom, I could compare the students' and teachers' relative attention profiles to examine whether the teacher or students discussed more topics related to a given EC. I provide more detailed instructions for how I interpreted these findings in Chapter 6.

5.1.3 Who had the authority? The observed patterns of interaction and the distribution of knowledge-building responsibilities are two measures that contribute to our understanding who has the epistemic authority, or power to assess the validity of one's claims, in the classroom. However, teachers might invite students to pose and respond to one another's questions, yet the students still turn to their teacher or another authoritative source to validate their conclusions. The purpose of this analysis was to understand the ultimate source of epistemic authority in the classroom, as evidenced by whether 1) the students were responsible for evaluating the evidence used to support students' claims (S-SP > T-SP); 2) the students turned to one another to validate student ideas (S-S > S-T); and 3) the students had the opportunity to assess the class' progress towards achieving the epistemic aim. Using the assessment of the three questions, judgments were then made about whether the ultimate source of authority was the *students*, *teacher*, or *other authoritative source* (e.g., textbook or website). For example, Kami asked her students whether air movement should be reflected in their models.

Turn	Type	Interactional Unit
1	T-S	T: So, should we have movement in the models?
2	T-S	S: Uh, huh.
3	T-S	T: We really should, right?

(Kami Observation, 2/2/12)

One of her students responded affirmatively. However, rather than asking him to justify his answer or consider whether other students also agreed with his statement, Kami immediately validated the idea, "We really should, right?" In doing so, the teacher did not rely on the student's judgement alone to justify the inclusion of movement in the model and served as the source of epistemic authority to validate the presented idea. In many ways, this discourse move resembled an IRE discourse pattern (T-S), in which the teacher posed a question of known answer, elicited a student reply, and evaluated the student's response.

5.2 Phase 2: What supports are present to enhance students' knowledge-building role?

The first analysis examined how the knowledge-building responsibilities were distributed between the students and teacher as evidenced by the patterns of interaction in the classroom and differences in the students' and teachers' relative attention profiles. In Phase 2, I explored the presence or absence of classroom supports that could enhance the students' role in shaping the knowledge of the classroom. I use the term "shape" here intentionally, as the class might be discussing students' ideas, yet the responsibility for assessing the validity of the presented ideas and reaching consensus belonged to those who commented on and evaluated the presented ideas.

I examined four types of supports. First, I examined the extent to which the teacher specified and valued students' knowledge-building role. Second, I examined the extent to which students had access to the conversational floor and could explain their ideas when desired. Third, I examined whether teachers adopted neutral evaluative stances to allow students the opportunity to evaluate student ideas on their own. Fourth, I examined instances in which the students had the opportunity to make sense of the phenomena before discussing and defending their ideas with the class. I summarize these supports in Table 5.9.

Table 5.9
Teacher supports for enhancing students' knowledge-building role

Support	Indicator(s)
1. Teachers specifies and values students' knowledge-building role.	• Students were clear about what they were supposed to do and how their decisions would help them achieve the desired epistemic aim • Teacher was clear about what they would be doing and how his or her actions were supportive of students' knowledge-building role.
2. Students had access to the conversational floor	• All students had the opportunity to initiate and complete conversational turns when desired. • Intended audience responded to initiated statement. • Students understood the criteria (if any) that determine whose ideas would be discussed. • Encouraged students to voice opinions without fear of being wrong or criticized
3. Teacher maintains neutral evaluative stance	• Teacher adopted neutral, evaluative stance to allow students the opportunity to evaluate presented ideas. • Teacher revoiced rather than reformulates student ideas.
4. Teacher provides students with opportunity to make sense of phenomena before whole-class discussion.	• Students given time to explain the phenomenon, coordinate claims with evidence, and represent their ideas diagrammatically.

5.2.1 Teachers specifies and values students' knowledge-building role. One type of classroom support involved teacher attempts to articulate the students' role when framing the task at the beginning or during the activity. These explicit expectations were important because it helped students understand who was responsible for doing the work, what they were supposed to do, and how their participation would be helpful and important for achieving the desired epistemic aim. For example, Laura specified the students' audience role when framing the whole-class discussion of students' models, "And, your job is going to be to ask personal questions that would help us, because we want to come up with a consensus. We want to try to figure out really what does air look like" (Laura Observation, 1/27/12). In this framing, Laura specified what the students were going to be doing ("your job is going to be to ask personal questions"), the desired epistemic aim ("We want to try to figure out really what does air look like"), and explained how the students' actions would help them accomplish the desired epistemic aim. In doing so, it played the onus of responsibility on the students for engaging in the knowledge-building work. In addition, I examined teachers' attempts to clarify, reinforce, value, or revise these stated student roles during the classroom enactment. For example, Laura included statements, such as "Does it help to ask people questions?" (Laura Observation, 1/27/12), to remind students that asking questions would enhance students' learning.

5.2.2 Students had access to the conversational floor. For students to have a substantive knowledge-building role, students required equitable *access to the conversational floor* so the they could initiate and complete turns of talk when desired (Engle et al., 2014). In addition to examining the proportion of student and teacher-initiated interactional units, I used the transcribed transcripts to determine the number of students who participated in the whole-class discussion. As part of this analysis, I analyzed the turn-taking norms that determined how students were granted access to the conversational floor. For example, did the teacher call on students or was this responsibility given to the students? What rules, if any, determined which models were presented or discussed in the classroom? To characterize the extent to which students had the opportunity to share their ideas when desired, I identified instances in which students were *denied access* to the conversational floor, such as students' persistent attempts to get called on by the teacher ("She never calls on me!"), and instances in which there were *shifts in access* to the conversational floor. For example, Nathaniel was in the middle of explaining his ideas. However, when Jackie wanted to ask a question, John granted her access to the conversational floor.

Turn	Type	Interactional Units
1	S-T	JACKIE: Oh, I have a question.
2	S-S	NATHANIEL: What? I didn't even finish.
3	S-T	T: Go ahead.

(John Observation, 12/12/11)

Related to giving students access to the conversational floor involved the presence of supports that encouraged students to participate without fear of being wrong or personally criticized (c.f., Herrenkohl & Guerra, 1998; Hogan & Corey, 2001). For example, the teacher might communicate that he or she is interested in what the students are thinking rather than whether their answer is correct, "If you're not sure, that's ok. You're just gonna try to put your ideas down in a model" (Kami Observation, 2/7/12).

5.2.3 Teacher maintains neutral evaluative stance. In the context of this activity structure, the teacher might play a role in facilitating students' ability to evaluate the presented ideas and reach consensus. Thus, a third support for enhancing students' opportunities to shape the consensus knowledge in the classroom involved the teacher adopting a neutral stance during the whole-class modeling discussions, in which the teacher allows students to decide for themselves whether a given claim is valid. O'Connor and Michaels (1993) documented discourse moves that teachers use when facilitating class discussions. Teachers might *revoice* a student's idea to get further input or lend authority to a student's idea (p. 327). In doing so, the teacher maintains a neutral evaluative stance that allows students the opportunity to build on or comment on each other's ideas. Alternatively, teachers might *reformulate* a student's idea, whereby "the teacher [could] take a student contribution and recast it within a wider frame or [could] slightly alter it to accent a different aspect of the lesson topic than the one intended by the student" (p. 328). In doing so, the teacher does not simply restate the student's idea; rather, she alters it to achieve a goal. When reformulating student ideas, the teacher's stance is no longer neutral and is playing a role in shaping the knowledge of the classroom community. Thus, this analysis examined the teacher's knowledge-building role to understand whether they adopted a neutral evaluative stance, characterized by teachers revoicing students' ideas, and allowing students to evaluate the presented ideas, or whether the teacher adopted a more active role in shaping the knowledge of the classroom.

van Zee and Minstrell (1997) provided examples of strategies that teachers could employ to position students as knowledgeable participants in construction of knowledge and frame instruction around student ideas. van Zee and Minstrell (1997) argued for teachers asking neutral statements and questions to help students articulate, think through, and understand their own ideas and the ideas of others. van Zee and Minstrell (1997) argued for teachers to continually "throw" knowledge-building responsibilities back to the students and to continuously prompt students to reflect on the state of their understanding and how it might have changed during the conversation.

5.2.4 Teacher provides students with opportunity to make sense of phenomena before whole-class discussion. A fourth support for enhancing students' opportunities to shape the consensus knowledge of the classroom involved giving students time to make sense of the phenomenon before discussing students' ideas as a class. In doing so, students might be better able to defend their ideas or consider how their ideas align with those of others if they had the opportunity to coordinate claims with evidence before the whole-class discussion.

5.3 Phase 3: How were students' ideas used during instruction?

Throughout this endeavor, students were the intended agents responsible for constructing knowledge in the classroom. Once students' ideas were made public, this analysis examined the extent to which students' ideas or questions influenced the trajectory and knowledge of the classroom community. This focus on examining how students' ideas were used in the context of constructing knowledge was important, as it contributed to students' perception that they were legitimate participants in their classroom communities of scientific practice. For example, did students' and teachers' ideas receive equal attention during classroom discussions? Did students' questions motivate and guide subsequent investigations? This analysis was distinct from issues of epistemic authority, as it focused on the extent to which students' ideas, rather than ideas from authoritative sources, shaped the class consensus knowledge. To understand how students' ideas were used in the context of their knowledge-building work, I did three different analyses that examined 1) whose ideas could shape the consensus knowledge and 2) what factors influenced why particular ideas were discussed in the classroom?

5.3.1 Whose ideas could shape the consensus knowledge? The first analysis examined whose ideas were discussed and whether students' ideas, rather than those from authoritative sources, were given privileged access to be discussed during whole-class discussions. For example, rather than discussing students' final odor models, Kami had the students watch and discuss a computer-generated model, "I have a model that I want to show you that I think you're gonna really enjoy, ok? […] It was created by some scientists who were interested in this idea of odor moving through the air (Kami Observation, 2/8/12). In this example, the teacher had a choice of whether to discuss the students' ideas or the scientists' ideas and chose the scientists' ideas. Consequently, the scientists' ideas, rather than the students' ideas, contributed to the consensus knowledge of the classroom.

This analysis also examined whether students had the ability to shape the class consensus knowledge to ensure its consistency with the students' current understanding of the phenomenon. For example, a student, Nathan, proposed revisions to students' models to reflect their understanding that air and odors move. In response, the teacher granted Nathan access to the board, "Why don't you come up and put arrows then, since that was your [idea]" (Kami Observation, 2/2/12). In other cases, the teacher might not accommodate students' request. For example, the teacher compiled a list of characteristics of solids, liquids, and gases that purported to reflect the consensus knowledge of the classroom. However, Kami did not accommodate a student's request to revise one of the characteristics to account for student concerns.

Turn	**Type**	**Interactional Unit**
1	S-T	CHASE: Can you change the characteristic of gas ["can't see them"]?
2	S-T	T: If you want to say, "Can't see most of them or some of them," we can do that if you think that's true. I'm not sure that we can't see.

(Kami Observation, 2/13/13)

In summary, this analysis examined whose ideas are discussed in the classroom and whether students had the ability to contribute to and shape the consensus knowledge of the classroom.

5.3.2 What criteria, if any, guided what student ideas were discussed? In this analysis, I examined what factors might explain why particular ideas were taken up and discussed in the classroom. First, I examined how the content goal of developing a particle model of matter influenced what ideas were investigated and discussed. Second, I examined how the teacher's interpretation of the trajectory for achieving the desired epistemic aim influenced teacher's responses to students' ideas and teachers' decisions about the appropriateness and relevance of student ideas.

Influence of teacher's attention to content goal. The intended goal of the focus lesson was to use the contrasting behaviors of air to challenge students' existing knowledge about matter and begin the process of collecting evidence over the course of three lessons to support a particle model of matter. Thus, students were not expected to have a definitive particle model of matter by the conclusion of the focus lesson (Lesson 4) and were to have agency to use evidence from the lessons to test and revise their models. At the same time, the curriculum materials suggested that the teachers should prompt students to think about what might be between the air particles because the particle nature of matter is not an intuitive idea. Thus, there were several factors at play that could influence the degree of freedom that students had to develop this model idea, both within this activity and overall trajectory of the unit.

Within the focus lesson, I examined the extent to which opportunities to investigate and discuss student ideas were constrained by the content goal of students developing a particle model of matter. To do so, I identified all the model ideas raised during the discussion of students' air models, categorized them thematically, and tallied the number of model presentations that discussed an idea. I then calculated the percentage of *nature of account* discourse that involved discussing the content goal and more specifically the nature of what was between the air/odors. In addition, I identified which ideas were the topic of persuasive discourse, as ideas that were the topic of persuasion had explanatory significance for the students or teacher. Thus, I examined how attempts to persuade others about the particle nature of matter compared to other ideas.

Second, I examined whether the students or teacher were responsible for initiating and persuading others about the validity of ideas related to the particle model of matter. Since the particle nature of matter was not an intuitive idea, the curriculum materials suggested that teachers prompt students to think about what might be between the air particles. Thus, the degree of emphasis on the content goal might be affected depending on whether the teacher continued to press students to think about topics relate to the content goal or whether the students themselves recognize something in the phenomena that compelled them to consider this non-intuitive idea.

I coded discussions at the classroom level as *open-ended* if the students and teacher attempted to reconcile all relevant explanatory ideas and not necessary focus only on topics related to the content goal. In contrast, I coded discussions as *focused on content goal*, if the students and teacher mostly discussed issues related to the nature of the space between the air/odor at the expense of other ideas that the students raised. Table 5.14 summarizes the indicators for the two codes.

Table 5.10

Analyzing how teacher's attention to content goal influenced what ideas were discussed

Code	Indicators
Focused on content goal	• Significant proportion of explanatory ideas discussed what might be between the air/odor • Ideas related to what is between the air/odor topic of persuasive discourse • Teacher was the agent responsible for initiating or persuading others about ideas related to what might be between the air/odor
Open-ended	• Student ideas, other than those related to what might be between the air/odor, were discussed and the target of persuasive discourse. • Students were the agents responsible for initiating discussion about ideas related to what might be between the air/odor. • In response to teacher's prompting about the space between the air, students could state that there was "something" between the air without being persuaded to revise their model by the teacher.

Influence of teacher's trajectory for achieving epistemic aim. Using the scope and sequence found in the curriculum materials (See Chapter 4, Section 3), the teacher interprets the purpose for activities to plan his or her sequence of instruction for developing each component of the particle model of matter. In this analysis, I examined how the teacher's interpretation of the lesson's epistemic aim and the planned trajectory and timeline for achieving that goal might have influenced what ideas teachers deemed to be relevant for answering the target question. By trajectory, I mean the planned sequence of activities that were designed to develop key ideas in students' explanatory models and would provide students with the evidence to test and revise their models. By timeline, I mean that teachers appreciate the longitudinal scale of this work and how long it would take for students to develop ideas related to the explanatory model. The teacher's interpretations likely influenced the types of ideas that he or she expected students to raise and how he or she might attempt to use and build on those ideas to construct the overall explanatory model. Insight into teachers' interpretations of the lesson goals was revealed during interviews, as the teacher explained the rationales for activities or how they sought to build on prior learning.

Chapter 6: Successes and Challenges: Constructing and Evaluating Students' Models

In this chapter, I present the findings from investigating Research Question 1, which involved using the three analytical lenses to identify the successes and challenges involved in supporting students' participation in the construction and evaluation of students' explanatory models. I begin the chapter by examining what was different across the three classrooms to provide context for understanding what teachers decided to do when given a common set of instructional materials and guidelines. Identifying these classroom enactment differences could provide insight into the teachers' interpretation of the focus lesson's goals, how students were to achieve the desired goals, and the purpose for students presenting and evaluating one another's ideas. Next, I examined how teachers used the curriculum-provided instructional supports to analyze whether they were used in rote or meaningful ways to support students' engagement in scientific practices.

Using the classroom discourse, I used the three analytical lenses (epistemic aim, considerations, and agency) to identify the successes and challenges that emerged for teachers and students in the three classrooms and assess their implications on students' engagement in scientific practices. I am not trying to make claims that these illustrative challenges were reflective in general or that there were reliable differences between these classrooms. Future work will explore what challenges and successes were most common and the factors that led classrooms to experience one type of challenge compared to another. The goal of this work is to begin identifying what issues might arise in today's classrooms as they attempt to make shifts toward learning science-as-practice and how integrated attention to these epistemic issues could provide a more complete understanding of the meaning that students apply to their engagement in scientific practices.

1. Classroom enactment differences

To contextualize the successes and challenges involved in this lesson, I examined the ways in which each classroom enactment differed from the lesson sequence as written in the curriculum materials. By examining these classroom differences, together with how the teacher framed the various aspects of the lesson, I could begin to understand the teacher's interpretations of the lesson's goals and the extent to which they privileged students' opportunities to engage in the knowledge-building work with one another. In what follows, I describe the enactment differences (summarized in Table 6.1) and provide a modified lesson sequence flowchart after each classroom description. As a reminder, the numbers in the flow chart correspond with the numbered steps in Table 6.1.

Table 6.1
Summary of Lesson 4 enactment differences

Step	Laura	Kami	John
1. Situating air investigations	Yes	Yes	Yes
2. Students construct initial air models	Yes	Yes	Yes
3. Class discusses students' initial air models	Yes	Individually compared and contrasted students' models before whole-class discussion. Discussed at same time as contrasting behaviors of air models	Students evaluated each other's models in groups using epistemic criteria before whole-class discussion Teacher led debate to convince students about empty space between air particles.
4. Students observe contrasting behaviors of air	Yes	Yes	Yes
5. Students construct models of contrasting behaviors of air.	Yes	Yes	Teacher led discussion to use initial air models to explain each situation. At the end, students represented this consensus understanding individually in their workbooks.
6. Class discusses students' models of contrasting behaviors of air	Yes	Completed with initial air model	No

1.1 Laura

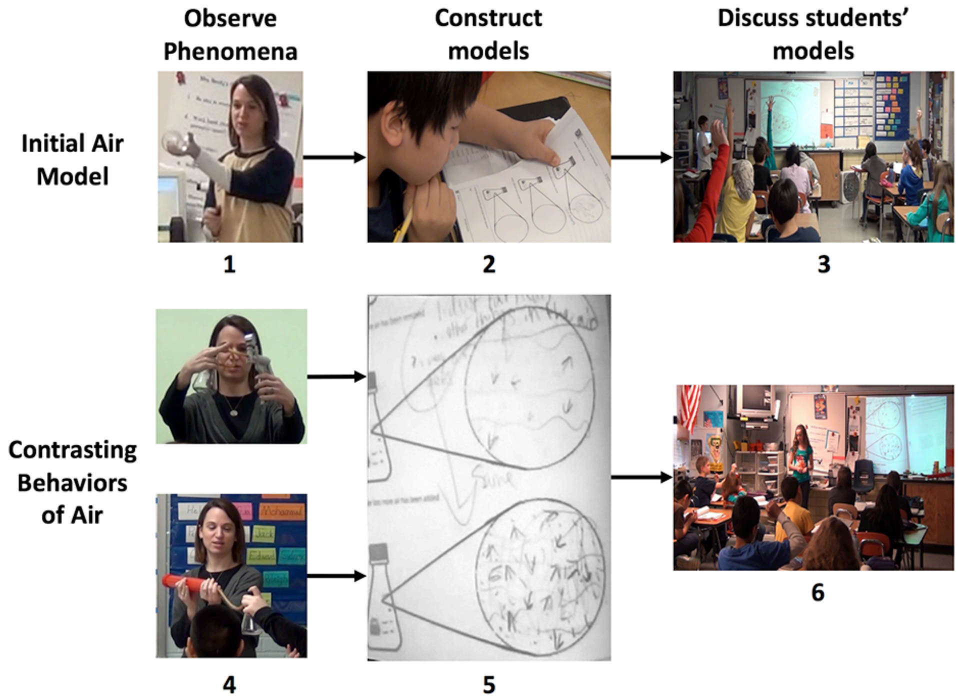

Figure 6.1. Laura's enactment of Lesson 4. The numbers reflect the steps in the lesson sequence as shown in Table 6.1.

In general, Laura followed the designed lesson sequence (Figure 6.1 is the same as 4.1). Students discussed each other's initial air models before observing and constructing models of the contrasting behaviors of air. During whole-class discussions about how students modified their initial air models to account for each gas behavior, students posed clarifying questions and commented on one another's models.

1.2 Kami

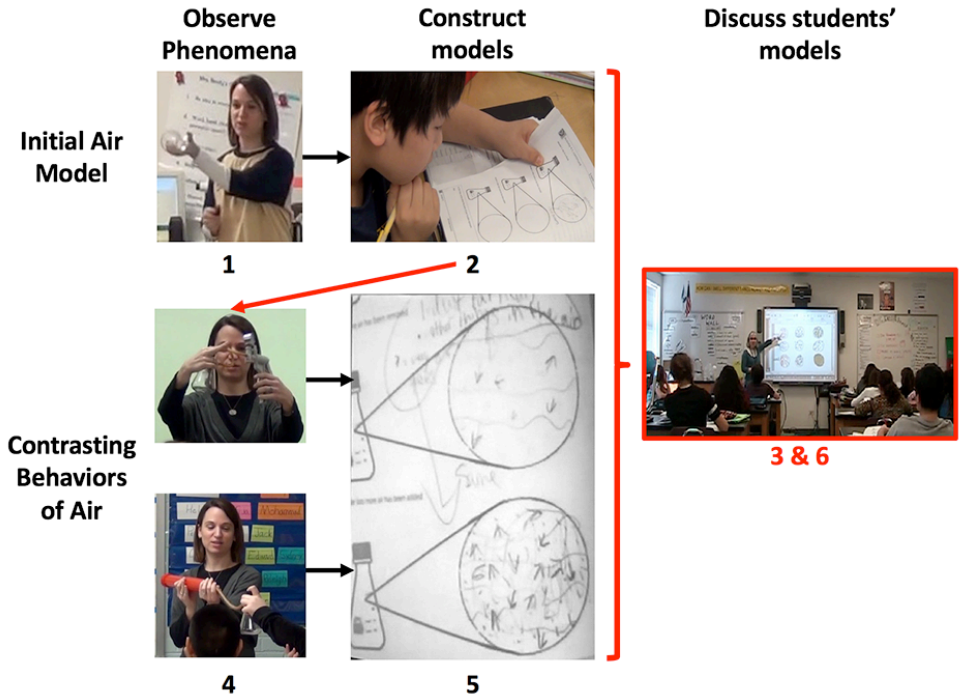

Figure 6.2. Kami's enactment of Lesson 4. I outlined in red differences from intended curriculum sequence (see Figure 6.1)

Kami's students observed and constructed diagrammatic models for each situation before discussing all three situations at the same time (see combined Steps 3 and 6, Figure 6.2). Before the whole-class discussion, Kami asked three students to draw their models on the SmartBoard. She then asked the other students to compare their models with the displayed models. Kami stood next to the SmartBoard to facilitate the class discussion, while the students were seated.

1.3 John

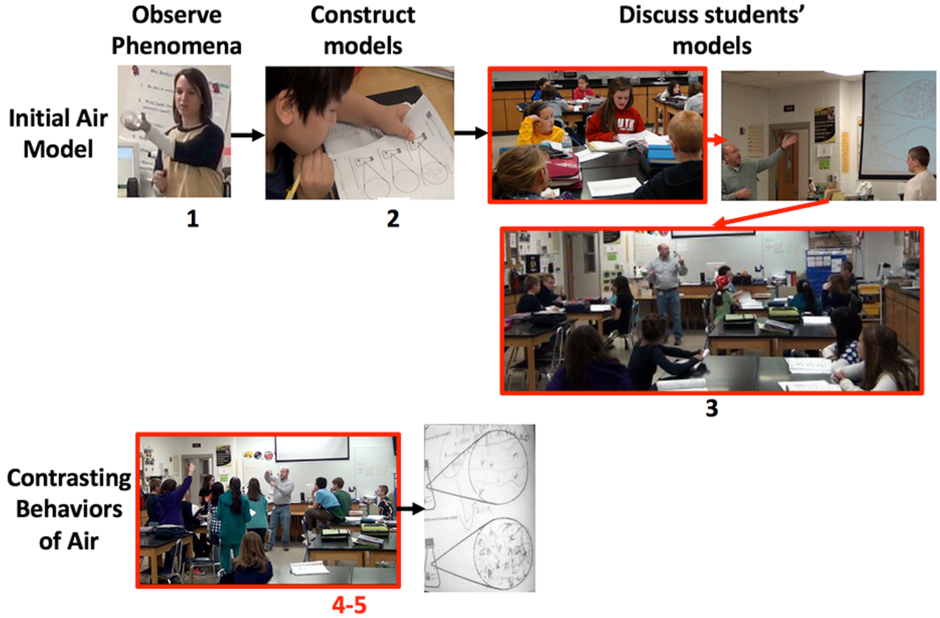

Figure 6.3. John's enactment of Lesson 4. I outlined in red differences from intended curriculum sequence.

John's students used curriculum-provided, model evaluation criteria (see Chapter 4, Section 3.3) to evaluate one another's initial air models in small groups before the whole-class discussion (see Step 3, top left, Figure 6.3). Students projected their air models using a document camera. John commented on the students' models before opening the conversational floor to the students. After the initial air model discussion, John polled his students' views about the nature of the space between the air and organized an impromptu debate (see Step 3, bottom) to convince students of the presence of empty space. To persuade one additional student, John used the contrasting behaviors of air as a context to test the validity and explanatory power of the class' "empty space" model. The teacher co-constructed a consensus model of the contrasting behaviors of air with the students, who then represented these ideas diagrammatically in their workbooks (see Steps 4-5). As such, there was no Step 6 in John's classroom.

Due to these enactment differences, I analyzed the whole-class modeling discussions for all three situations together to examine differences in what epistemic considerations guided students' and teachers' decisions and the distribution of knowledge-building responsibilities between the students and teacher. Where possible, I present the findings from the initial air model discussions for John and Laura's classroom separately from the aggregate data to examine the success and challenges observed when enacting the target activity structure. I discuss Kami's findings at the aggregate level, since she discussed all three situations together.

2. Epistemic aim: What goal guided students' work?

When examining the meaning applied to students' scientific work, the epistemic aim lens examined 1) what epistemic aim guided students' knowledge-building work and 2) what guidance the teacher provided to communicate how and why this work was worthwhile from the perspective of the discipline and students. Both components were important for supporting meaningful engagement in scientific practices for two reasons. First, it would ensure that students understood the disciplinary importance of the question that students were investigating and its coherence with prior learning. Thus, the first analysis examined what expectations the teacher provided students for how the air investigations would be helpful for explaining the odor phenomenon. Second, it was important that the teacher communicated how and why using diagrammatic models could help students mediate their knowledge-building work with others and accomplish their goal of explaining the target phenomena. Because many students have little experience using diagrammatic models, teachers could contribute to students' perception that the modeling practices of constructing, sharing, and evaluating one another's diagrammatic models was a meaningful, rather than a rote, activity.

Because no student interviews occurred immediately before or after the focus lesson, the analyses for this analytical lens focus on teacher's statements rather than students' explicit statements about their interpretation of the epistemic aim. In Section 3, I use evidence of the epistemic considerations guiding students' and teachers' decisions to infer what epistemic aim might have guided their decisions.

2.1 Why are we investigating air?

Because this lesson used air as a representative gas to investigate the behaviors of gases in general, students might not understand how and why investigating air would be useful for explaining the odor phenomenon. To ensure that this investigation was meaningful rather than just another activity for students to complete, I examined the rationale that teachers provided for investigating this phenomenon context (Step 1, Situating air investigations) to identify evidence that the teacher explained how investigating behaviors of air would help students explain the odor phenomenon. In doing so, teachers could help students notice the activity's coherence with prior learning and how it would be helpful for answering the broader questions framing the unit.

2.1.1 Kami: Focus on the process for constructing diagrammatic models rather than why. When explaining the air investigations, Kami did not explain why her students investigated these air behaviors; rather, her focus was on the process by which students constructed their diagrammatic models, "You're gonna be thinking, but you're gonna be thinking slowly. Alright? Cause it's not simple thinking you're gonna be doing" (Kami Observation, 2/2/12). Kami's students had an epistemic aim of constructing models to represent their ideas about air. However, there was less focus on *why* they were constructing them. Consequently, students might have perceived the air investigations as additional activities for the students to complete without understanding how they were important for enhancing their own learning. Thus, the epistemic aim lens examined not only *what* work students were going to be doing, but also *why* this work was worthwhile.

2.1.2 Laura: Identified similarities between air and odors. When reviewing existing knowledge about gases, air, and odors, the class identified commonalities between characteristics of air and odors. For example, the class recognized that air and odors were both gases, “There you go. Same thing. Same thing. So, odor is as a gas, air is a gas” (Laura Observation, 1/27/12). Because this review occurred before the framing of the air investigations, students might have been primed to consider the relevance of the air investigations for explaining the odor phenomena. However, this relationship was not explicit when Laura framed the lesson’s activities.

2.1.3 John: Articulated relevance of air investigations. When framing the air investigations, John distinguished between the short-term epistemic aim of explaining the air investigations and the long-term epistemic aim of explaining the odor phenomenon.

> So, we're learning things about air, but we're going to apply all of those things to scents and odors. Remember what our original question is, "How can I smell things from a distance?” Right? That's what we want to be able to get to. (John Observation, 12/12/11)

Although he argued for the relevance of the air investigations, he did not justify how the air investigations would be relevant for explaining the odor phenomenon, such as explaining how air and odors were both gases or how certain gas characteristics applied to all gases. Later in the lesson, John ascribed value to the students’ investigation of the contrasting behaviors of air by considering how this context could provide additional evidence to support the class’ empty space model, “If I can add air in, does that help our argument that there’s empty space or does it hurt our argument, for Michelle’s sake?” (John Observation, 12/14/11).

2.1.4 Summary. There were classroom differences in the extent to which teachers helped students understand how and why students were explaining these contrasting behaviors of air. In Kami’s classroom, there was no explicit discussion for how the air investigations would be helpful for explaining the odor phenomenon. John and Laura contributed several components. John was the only teacher that justified the epistemic value of investigating air behaviors for explaining the odor phenomenon, but did not explain how. Although Laura's students recognized similarities between air and odors, the relevance of the air investigations for explaining the odor phenomenon was not explicit. Thus, some combination of John and Laura's explanation could provide students with an understanding of how and why the air investigations would be relevant for explaining the anchoring phenomenon.

2.2 Meaningful use of diagrammatic models

To investigate these air behaviors, students used diagrammatic models to make visible and communicate their ideas to others. Because many students have little experience using diagrammatic models in scientifically meaningful ways, I examined the meaning that teachers ascribed to students' use of diagrammatic models. The first analysis examined how teachers described the worthiness of constructing diagrammatic models, while the second analysis examined the worthiness of discussing students' models.

2.2.1 In what ways did teachers ascribe value to students' use of diagrammatic models? For this analysis, I examined teachers' statements that explained why constructing diagrammatic models was a worthwhile activity for students to engage. John and Kami drew parallels between the students' scientific work and authentic scientific practice when explaining modeling activities. Kami often drew upon her own experience as a scientist to explain how her students' work was like scientists' work. Although there were no explicit references to authentic scientific practice during the focus lesson, Kami cited similarities between students' and scientists' work when using a similar activity structure during the first chemistry lesson.

> So now, when scientists get up in front of other scientists and share their models, okay, one of the reasons they do that is to get what we call feedback from other scientists. […] Other scientists, your colleagues in this room, are now going to take a look at these models, and we're gonna make sure we understand them. (Kami Observation, 1/17/12)

Similarly, John framed model revision as a "part of science," "Now again, guys, *part of science* is revising your models as we go as we learn new information, right?" In both cases, teachers' reference to scientists' work provided extrinsic motivation for why students were revising or providing feedback on one another's models. Interestingly, Laura did not make connections between the students' and scientists' work during the focus lesson; rather, Laura prompted students to consider how and why diagrammatic models were helpful for their own learning. For example, at the beginning of the second day of the focus lesson, Laura elicited students' ideas about why they were constructing diagrammatic models, "So, what is the purpose of models? Why are we doing models?" (Laura Observation, 1/31/12). One student shared that models helped them explain and understand one another's ideas more effectively than verbal explanations alone, "If it's hard to explain and somebody can't understand what you're trying to say, but you can visualize it in your head… If you make it, then explain, then maybe show what you're trying to do, then all of the other people can understand it better" (Laura Observation, 1/31/12). Through these efforts, Laura provided students to consider the intrinsic motivation for engaging in this modeling work.

In summary, all three teachers showed evidence of attempting to ascribe meaning to students' use of diagrammatic models. Kami leveraged aspects of authentic scientific practice to enhance the worthiness of students' use of diagrammatic models. In contrast, Laura relied on the usefulness of diagrammatic models for one's own learning as the primary motivation for using diagrammatic models rather than seeking external motivation for their use. In other words, the perspective for how and why students' use of diagrammatic models was in the context of the scientific endeavor in Kami classroom, whereas it was the students in Laura's classroom. John was somewhere in the middle, as he also framed students' modeling work as an authentic scientific activity, yet also positioned it as an activity that could enhance students' learning.

Along the same lines, teachers ascribed meaning to students' diagrammatic models by explaining how students would use them to accomplish their desired epistemic aims. One of the reasons for why John and Laura's students labeled their models was that both teachers explained how students would be projecting and using their diagrammatic models to explain their ideas to the rest of the class. Thus, recognizing how students would be using their diagrammatic models provided meaning to what otherwise might be a procedural practice because students understood how it would help them accomplish a desired epistemic aim.

2.2.2 What epistemic aim guided the discussion of students' models? I analyzed teachers' statements that communicated the epistemic aim guiding the discussion of one another's models. I coded the model sharing discussions as *neutral*, if students were simply one another's ideas without evaluating the presented ideas; *evaluative*, if participants were evaluating the presented ideas with no broader goal guiding their work; or *consensus-building*, if students' efforts to evaluate one another's models was in service of developing some consensus understanding of the phenomenon (see Table 5.4 for more information).

John and Kami: Evaluative. I coded the model sharing epistemic aims in John and Kami's classrooms as *evaluative*, as the teachers discussed students' use of epistemic criteria to evaluate the presented ideas without explaining the underlying epistemic aim guiding this evaluative work. For example, John explained that the students would use criteria to evaluate one another's initial air models without explaining how this work would advance students' understanding of the phenomenon.

> This is evaluate — using these criteria and what we've done as a class, thinking about the evidence and challenging people to think things in different ways. OK? […] Let her [student presenter] explain first, and then, if you [peers] have any questions or comments... OK? (John Observation, 12/12/11)

Kami asked her students to evaluate their models' consistency with existing knowledge about the characteristics of air and gases without considering how these criteria might help students better explain the behaviors of air, "What do you think? Does this show what we know about air so far?" (Kami Observation, 2/2/12).

Laura: Consensus-building. In contrast, I coded Laura's model discussions as *consensus-building*, as Laura explained how the students' model discussion would help the class generate a consensus understanding of what air looked like under a special microscope. Thus, there was an epistemic aim guiding the discussion and evaluation of students' models.

> So, her [student presenter] job is going to be to explain to you [students] what she thinks it [the air] looks like under the special microscope. […] And, your job is going to be to ask personal questions that would *help us*, because *we want to come up with a consensus*. *We want to try to figure out really what does air look like.* (Laura Observation, 1/27/12)

In this framing, Laura used collective pronouns ("us" and "we") to refer to who would be participating in and benefiting from this joint knowledge-building endeavor. Thus, the students were the sources of the ideas about the nature of air come from the students, the students would be the agents responsible for evaluating those ideas, and the students would be working together to accomplished this shared goal of developing this consensus understanding.

The presence of an epistemic aim guiding the discussion of students' models could inform and enhance the meaning applied to students' modeling decisions. For example, labeling is an important procedure when constructing students' models because it facilitates an external audience's ability to understand one's ideas. When students shared their models during the whole-class discussions, the presented models in John and Laura’s classrooms were labeled, whereas the models in Kami’s classroom were not. One explanation is that John and Laura explained how the members of the class would serve as an external audience and use the ideas found in students’ models. For example, John explained that the students would be using the document camera (i.e., Elmo) to share their ideas with the class, “And then I'm going to ask for representatives or call on people to come up using the Elmo and on the board and then we're going to do this [model evaluation] as a class.” Thus, students’ models needed to be labeled so that others could understand and evaluate the presented ideas. Given the limitation of what was viewable on the projected screen, Laura argued that her students needed to label their models, rather than relying on a key alone, so that students could understand the presented ideas “Because it's hard if the key on the bottom, when we show it on a document camera, we can't see the key. So, if you actually label it in the circle, then we would understand it better” (Laura Observation, 1/31/12).

In contrast, Kami framed labeling as a behavior that students “always do,” rather than explicitly discussing how it would help students accomplish a specific goal, “One of the things we always do with models is label the parts, but I don't see any labels up here.” (Kami Observation, 2/2/12). John also communicated expectations that students should label their models, both through verbal reminders (“I walked around. I didn't see everybody's that had labels on it. We've talked about that before,” John Observation 12/12/11), and using model evaluation criteria (e.g., Clarity of communication: How is the model organized and labeled?). However, John helped labeling become a more meaningful practice, because he explained how labeling would help them engage with one another’s ideas.

2.3 Epistemic Aim Summary

The epistemic aim lens examined teachers' attempts to enhance the meaningfulness of the epistemic aim and the scientific practices used to achieve the epistemic aim. To do so, I first examined what epistemic aim, if any, guided students' knowledge-building work and teachers' attempts to explain why this work was worthwhile from the perspective of the discipline and students. The presence of both components was important, as it communicated to students how and why their work was worthwhile for their learning. I applied this analytical lens in two ways. First, I examined teachers' attempts to persuade students of the worthiness of the air investigations and their relevance for explaining the odor phenomenon. Second, I examined teachers' attempts to enhance the meaning applied to students' use of diagrammatic models to ensure that it's not done by rote, but used in meaningful ways to achieve the students' desired epistemic aims.

There were classroom differences in teachers' motivation for why students were investigating these behaviors of air. Kami did not discuss how and why students were investigating these behaviors of air, whereas John and Laura included components that could enhance the meaning applied to students' air investigations. For example, John stated that students could apply their knowledge about air to explain the odor phenomenon. In contrast, Laura inferred that the knowledge from one phenomenon would be relevant for explaining the other by identifying similarities between air, odors, and gases. However, Laura did not make this connection explicit to her students. Thus, a hybrid of John and Laura's framing could enhance the meaning applied to the air investigations, as it would justify how and why the air investigations were coherent with students' prior learning and could help students develop an understanding of the nature of matter.

When examining the meaning applied to the scientific practices used to achieve the desired epistemic aim, Kami and John did not discuss what epistemic aim would be guiding their use of epistemic criteria. Of the three teachers, Laura was the most attentive to how and why using diagrammatic models would be helpful for students' own learning. Rather than enhancing the epistemic value of students' scientific work by leveraging similarities with authentic scientific practice, Laura's actions demonstrated a commitment to persuading students that discussing one another's models was helpful for developing a consensus understanding of the phenomena. At the end of the lesson, John implied that the discussion of students' models was useful for students' own learning, as students could revise their models to account for ideas learned by others. However, this framing was not consistent throughout the model discussion.

In summary, meaningful engagement in scientific practices involves students understanding what epistemic aim was guiding students' engagement in scientific practices and how and why these scientific practices were helpful for accomplishing these scientific goals. Although John had several of these components, Laura provided regular reminders to prompt student to think about why students were constructing models and whether asking questions was helpful for students' learning. These findings suggest that teachers' accounting for these components when framing expectations for what students would be up to at the beginning and reinforcing these expectations during the enactment could be useful for enhancing the meaningfulness of students' engagement in scientific practices.

3. Epistemic considerations: What epistemic considerations are guiding students' and teachers' decisions?

The epistemic aim lens examined the extent to which teachers and students understood the goal of students' knowledge-building work and why it was important. The epistemic consideration lens analyzed the epistemic issues and questions that guided students' and teachers' decisions in service of achieving the desired epistemic aims, which in this context involved the construction and evaluation of explanatory models of air. To do so, the first level of analysis involved coding the classroom discourse for evidence that the issues posed by Berland et al. (2016)'s epistemic considerations (EC) might have guided students' and teachers' decisions (see Chapter 5, Section 4 for coding rules): 1) *Nature of Account*: What type of answer should our account of the phenomenon provide?; 2) *Audience*: Who will use our account of the phenomenon and how?; 3) *Justification*: How do we justify our account of the phenomenon?; and 4) *Generality*: How does our account of the phenomenon relate to other scientific phenomena and ideas? For the *audience* consideration, I identified instances in which participants attended to the clarity of the communication of one's ideas to others (*audience-clarity*) or the persuasiveness of one's claim or argument (*audience-persuasion)* (see Chapter 5, Section 4.3 for rationale). Next, I calculated *relative attention profiles* for each classroom to show what ECs might have guided students' and teachers' decisions. For example, one might expect students' efforts to persuade others of the validity of one's claims to be guided by issues related to *audience (clarity and persuasion)* and *justification*, as students choose appropriate evidence to persuade others of the validity of one's claims over posed alternatives.

The epistemic considerations lens was helpful for identifying the successes and challenges involved in supporting meaningful scientific practices, because it examined students' and teacher's interpretation of the epistemic aim, which might differ from the teachers' verbal expectations, and what participants needed to do to achieve their desired goals. The next phase of the analysis considered the implications of any observed classroom differences on students' and teachers' knowledge-building work. For example, I used each EC to understand the rationales guiding students' and teachers' decisions and analyze how differential attention to these ECs might help or hinder students' and teacher's ability to achieve their desired epistemic aims.

3.1 Analysis of ECs guiding whole-class modeling discussions

As a foundation for discussing the successes and challenges involved with students' and teachers' interpretation of what was needed to achieve the desired epistemic aims, it was important to characterize the similarities and differences in what epistemic considerations might have guided students' and teachers' decisions in each classroom. In this section, I build on the coding rules for the ECs explained in Chapter 5 to explain how I constructed and interpreted the relative attention profiles for each classroom. I then use classroom examples to illustrate the implications of observed classroom differences on participants' ability to achieve their desired epistemic aims, which in this case of this study involved evaluating and developing a consensus model of air.

3.1.1 Constructing relative attention profiles. As explained in Chapter 5, I analyzed students' and teachers' statements and rationales to infer what ECs might have guided their decisions. The EC coding occurred at the sentence level. Thus, I coded the entire sentence for a given EC if a teacher or student showed evidence of attending to one or more issues related to an EC. I then calculated the proportion of words showing evidence of implicit or explicit attention to issues related to each EC. In doing so, I had a measure of emphasis to show differences in the amount of time spent discussing each epistemic issue. The columns in Table 6.2 show the proportion of attention to each EC. I rounded percentages to the nearest 0.1%. For example, 27.3% of the whole-class discourse (2,494 out of 9,127 words) showed evidence of attending to issues related to *audience-clarity* in John's classroom. The sum of the percentages within a row could exceed 100% since participants could attend to multiple ECs within a given sentence.

Table 6.2
Analysis of proportional attention to Berland et al. (2016)'s ECs during whole-class model discussions

	Audience				
Classroom	**Clarity**	**Persuasion**	**Generality**	**Justification**	**Nature of Account**
John	**27.3%**	**14.0%**	**6.8%**	**19.5%**	**51.3%**
(9,127 words)	**[2]**	**[4]**	**[5]**	**[3]**	**[1]**
Kami	**29.7%**	**5.4%**	**7.0%**	**11.5%**	**43.6%**
(2,453 words)	**[2]**	**[5]**	**[4]**	**[3]**	**[1]**
Laura	**46.7%**	**37.6%**	**14.1%**	**34.0%**	**67.3%**
(7,440 words)	**[2]**	**[3]**	**[5]**	**[4]**	**[1]**

This table shows the proportion of whole-class, modeling discourse in which students and teachers attended to each EC. The total word count is in parentheses. The bracketed numbers indicate the relative rank for each EC (1 highest, 5 lowest).

To understand what ECs were most influential for guiding students' and teachers' decisions, I compared and ranked the percentages (1=highest, 5=lowest) for each EC to construct *relative attention profiles* for each classroom. For example, John's relative attention profile was *nature of account* (51.3%, 1st), *audience-clarity* (27.3%, 2nd), *justification* (19.5%, 3rd), *audience-persuasion* (14.0%, 4th), and *generality* (6.8%, 5th).

In addition to comparing differences in what ECs guided students' and teachers' decisions, I could analyze differences in the amount or proportion of attention to a given EC. For example, *audience-clarity* was the 2nd highest EC in each classroom. However, when I compared the percentages between the classrooms, there was more attention to *audience-clarity* in Laura's classroom (46.7%) compared to Kami (29.7%) and John's (27.3%) classroom. Further analysis could be done to consider the implications of these differences.

3.1.2 Interpreting relative attention profiles. In this section, I examine what was similar and different between each classroom's relative attention profile. Each classroom exhibited high attention to *nature of account,* because students were discussing their ideas related to the phenomena. The second highest EC was *audience-clarity*, which made sense because students were explaining their ideas and asking questions to clarify their understanding of features ("So, these red lines, what are those?", Kami Observation, 2/2/12) or ideas in students' models ("So, you think all the arrows should be going to one place?", Laura Observation, 1/31/12).

There was more emphasis on discussing the justification for students' ideas than persuading others in John and Kami's classrooms. In contrast, there was slightly more attention to persuading others in Laura's classroom than in the other two classrooms. Since the amount of attention to *audience-persuasion* and *justification* were close in Laura's classroom, participants likely used evidence to convince others about the validity of one's claims. *Generality* was the least attended to EC in John and Laura's classroom, which suggests that the primary focus of the classes' work was explaining the focus phenomena rather than considering the applicability of knowledge across situations. *Generality* was ranked fourth in Kami's classroom, which was due to the class considering the consistency of students' models with existing knowledge about air and gases. Thus, this general knowledge provided the basis for evaluating the presented ideas.

In summary, Kami and her students focused on understanding students' explanatory ideas rather than justifying or defending the validity of students' claims. Attention to *generality* was aligned with the epistemic criteria used to evaluate students' ideas. Laura and her students focused on clarifying their understanding of students' ideas. There was marginally more attention to *audience-persuasion* than *justification*, which suggests that students used evidence in service of persuading others of the validity of one's claims. Although there was less attention to the relevance of knowledge from other situations, there was more attention to *generality* in Laura's classroom than in the other classrooms. John and his students also focused on clarifying their understanding of students' ideas, yet there was proportionally less attention to *audience-clarity* than in the other two classrooms. As observed in Kami's classroom, there was more emphasis on discussing the justification for one's ideas than persuading others of the validity of one's claims.

These classroom comparisons raise several questions: 1) Why were there differences in the classroom's relative attention to *audience-persuasion* and *justification*? Despite differences in the rankings of *audience-persuasion* and *justification,* why was there more attention to these ECs in Laura's classroom than in the other classrooms? What do these differences suggest about students' and teachers' interpretation of the epistemic aim guiding the discussion of students' models?

3.1.3 Analyzing ECs guiding persuasive discourse. The previous analysis suggested a relationship between students' use of evidence (*justification*) and their' efforts to persuade others (*audience-persuasion*). For this analysis, I sought to understand 1) what ECs might have played a role in guiding students' and teachers' efforts to persuade others and 2) how differential attention to these ECs might have influenced students' and teachers' ability to evaluate students' ideas and reach consensus. Table 6.3 shows the relative attention profiles for each classroom during *audience-persuasion* discourse. The total word count during *audience-persuasion* is in parentheses.

Table 6.3

Analysis of what ECs students and teachers attend to during audience-persuasion discourse

Classroom	Audience-clarity	Generality	Justification	Nature of Account
John (1,279 words)	**38.3%** **[2]**	**9.1%** **[4]**	**36.0%** **[3]**	**78.3%** **[1]**
Kami (132 words)	-	**62.1%** **[2]**	**55.3%** **[3]**	**72.0%** **[1]**
Laura (2,794 words)	**43.7%** **[3]**	**20.8%** **[4]**	**62.2%** **[2]**	**86.5%** **[1]**

This table shows the proportion of *audience-persuasion* discourse in which students and teachers attended to the other ECs. The total audience-persuasion word count is in parentheses. The bracketed numbers indicate the relative rank for each EC (1 highest, 5 lowest).

There was high attention to the *nature of account* in each classroom, as the focus of argumentation likely involved some aspect of the explanatory model. John's classroom's relative attention profile during persuasive was like the aggregate findings, yet there was proportionally more attention to *justification* during persuasion in John and Laura's classroom. In John's classroom, the relative proportion of attention to *justification* (36.0%) increased and was closer to *audience-clarity* (38.3%). In Laura's classroom, the relative ranking of justification increased to 2nd, compared to 3rd in the aggregate findings. In addition, there was a greater proportion of *justification* in Laura's classroom (62.2%) than in John's classroom (36.0%). In Kami's classroom, there was attention to *generality* and *justification*, which suggests discussions about the consistency of students' models with existing knowledge. Interestingly, there was no coded attention to issues related to *audience-clarity* when persuading others in Kami's classroom. These findings raise several questions. Why was there more attention to *justification* in Laura's classroom than in the other classrooms? What were the implications for these classroom differences on participants' ability to persuade others?

3.1.4 What was the relationship between the teacher's framing and the observed relative attention profiles? Before explaining the observed classroom differences, I examined each teacher's framing to examine the extent to which the teacher's discussion of the epistemic aims and considerations that should guide students' knowledge-building work could explain the observed relative attention profiles. In general, the observed relative attention profiles for each classroom were consistent with the teacher's framing.

John. When framing the discussion of students' initial air models, John explained that students would be listening to one another's ideas and using the curriculum-provided epistemic criteria (named in parentheses, see also Chapter 4, Section 3.3) to evaluate the presented ideas. There was high attention to the *nature of account*, as John wanted his students to evaluate whether students' models accurately represented the "key parts" (*key ideas*) of the "air inside the flask" (*accuracy*). There was attention to *audience-clarity*, as he asked his students to label their models (*clarity of communication*) and listen to one another's ideas so that they could ask questions about and evaluate the presented ideas. There was also attention to *audience-persuasion*, as students used their interpretations of students' ideas to challenge or persuade others to think differently. John attended to issues related to the *justification* consideration, as he wanted his students' models to include ideas for which students had evidence from class activities, "So, do you have extra stuff that doesn't belong there that you haven't talked about yet or that we don't have evidence for?" (*consistency* and *simplicity*).

Despite this alignment, it was not clear how these epistemic criteria influenced students' knowledge-building work, as they were provided after the students had constructed their models, but before the students' small group evaluation discussions. Thus, students had the opportunity to practice using these epistemic criteria before the whole-class discussion. However, these criteria were never mentioned again explicitly beyond what issues were discussed when framing the activity. Although John mostly read the criteria verbatim without explaining them, the ones that he did elaborate upon overlapped with ECs highly attended to during the discussion: *nature of account, audience-clarity*, and *justification*. Thus, John's evaluation of the presented ideas might have been guided by his interpretation of the epistemic criteria and what issues were important.

Kami. There was no explicit framing at the beginning of Kami's whole-class model discussion. However, the prevalence of issues related to *audience-clarity* and *nature of account*, could be explained by Kami's efforts to label students' unlabeled models. Kami's request for students to evaluate the model's consistency with what they knew about air could explain the class' attention to *generality*.

When framing the activity, she asked her students to listen to one another's ideas in service of reaching a consensus understanding of what air looked like inside the flask. The findings suggest that the class' high attention to the *nature of account* and *audience-clarity* considerations could be due to students' efforts to understand the presented ideas, while students' attention to *justification* and *audience-persuasion* could be explained by students defending and evaluating the suitability of students' ideas for construct the class consensus model.

3.1.5 What are the implications of these observed differences? While there was consistency between the issues that teachers articulated when framing the activity and those observed during the enactment, there were classroom differences in what ECs guided students' and teachers' discussion of students' models and more specifically during argumentation. I consolidated the raised questions into three questions:

1. Why were there differences in attention to *audience-persuasion* and *justification*?
2. How did attention to *audience-clarity* influence students' and teachers' ability to persuade others?

3. What were the implications for these observed differences on students' and teachers' ability to persuade others?

Given the absence of a stated epistemic aim guiding the model discussions in Kami and John's classroom, I analyzed the epistemic considerations guiding students and teachers' decisions to infer what epistemic aim might be guiding their decisions. As part of this analysis, I investigated the extent to which students' models were constructed in service of explaining the phenomena or whether they focused on having the correct model ideas related to the particle nature of matter. In the next section, I use the examples from the classroom discourse to address these questions.

3.2 Why were there differences in attention to audience-persuasion and justification?

The intended goal of the focus lesson involved issues related to *audience-persuasion* and *justification*, as students used evidence to reach consensus. However, there was more attention to *audience-persuasion* and *justification* in Laura and John's classroom than in Kami's classroom. I considered how differences in each class' interpretation of the epistemic aim could explain these differences. Because there was much less attention to *audience-persuasion* in Kami's classroom, I first examined why there was more attention to *audience-persuasion* and *justification* in Laura's classroom than in John's classroom before investigating why there was so little attention to *audience-persuasion* and *justification* in Kami's classroom.

3.2.1 Why was there more attention to *audience-persuasion* and *justification* in Laura's classroom than in John's classroom? I argue there were two plausible explanations for why there was more attention to *audience-persuasion* and *justification* in Laura's classroom than in John's classroom. First, there were differences in teachers' expectations for students to justify or defend their ideas. Second, there were differences in the scope of what ideas were the target of persuasive discourse and how this might be related to the teacher's attention to the content goal during the discussion.

Explanation 1: Different expectations for students to justify or defend their ideas. There were less consistent expectations for students to justify or defend their ideas in John's classroom compared to in Laura's classroom. For example, Lenny had components of the particle model of the matter, such as the presence of space between the moving air particles. However, Lenny explained his initial air model without justifying the validity of his ideas (see Figure 6.4), "Circles — air [particles]; blank [between air particles] — that's some air, but there's some space; and the air particles are moving around" (John Observation, 12/12/11). Furthermore, he did not explain how there could be both "more air" and "some space" between the depicted air particles. Without this explanation, Lenny could have included "some space" because other students might have talked about it without considering the phenomenological or explanatory significance of this idea.

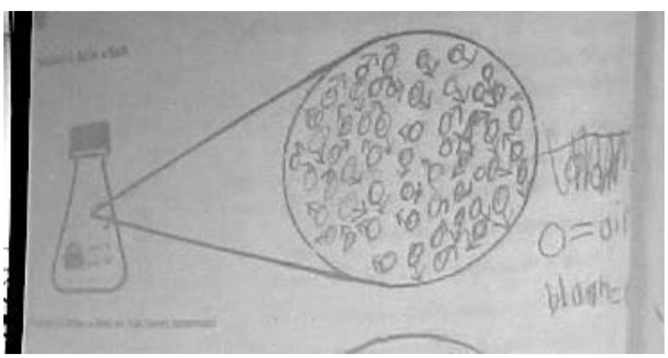

Figure 6.4. Lenny's air model

Rather than pressing Lenny to justify his ideas, John attempted to persuade Lenny that there could not be "some air" between the air particles, the incorrect model idea. To do so, John reformulated Lenny's claim to make visible the aggregate effects of having "some air" between the air particles, "So, you are also feeling that there's air from top to bottom, [bottom to top in here [the flask]" (turn 1).

Turn	Type	Interactional Units
1	T-SP	T: So, you are also feeling that there's air from top to bottom, [bottom to top in here [the flask].
2	T-SP	LENNY: [No! No.
3	T-SP	T: Or is there a little bit of empty space?
4	T-SP	LENNY: There's some [empty space.
5	T-SP	T: [Well, you drew some empty space.
6	SP-T	LENNY: Well, these [air] are moving.
7	SP-T	T: Ok.
8	T-SP	T: So, what... What did you say the blank space was?
9	T-SP	LENNY: Some more air.
10	T-SP	T: But there's nothing there.

(John Observation, 12/12/11)

Once Lenny rejected this characterization, John restated the other correct model ideas in his model without pressing Lenny to explain his decision or justify the validity of the correct model ideas. This pattern of behavior occurred throughout the initial air model discussion. In the interaction below, John provided implicit validation of Dean's ideas, which included all the correct model ideas, by asking whether his students agreed with the presented ideas, "Everybody good with that one?" (turn 5), without providing students time to respond before moving to the next presentation.

Turn	Type	Interactional Units
1	SP-X	DEAN: These are like the things that make up air. Like all of the different gases in the air and all the gases together make up the air. This space in-between is the little space that has the molecules are able to move around in.
2	T-SP	T: Alright, so you're saying that the molecules could actually move around, the particles could move around, there's empty space, and the different dots represent the different things that make up air,
3	T-SP	DEAN: Yes.
4	T-SP	T: which we don't know about yet, but at some point, we will discover it. OK?
5	T-0	T: Any questions or comments for Dean? Everybody good with that one?

(John Observation, 12/12/11

In contrast, there were expectations for Laura's students to justify and defend all responses, regardless of their correctness. In the following excerpt, Hilary justified the presence of water vapor and carbon dioxide in her air model (see Figure 6.5).

> And these things that are upside-down u's kind of, I think that's like the *water vapor*, because I kind of think there's water vapor in the air too, because like everyone's talking about it, so it kind of made me change my mind about what I had first. And then, the squiggly lines are *carbon dioxide* because everyone's breathing it out. (Laura Observation, 1/27/12)

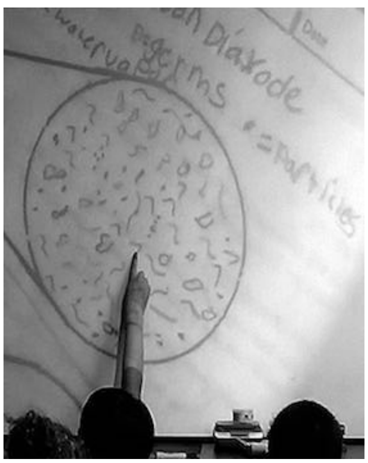

Figure 6.5. Hillary's air model

In her explanation, Hillary used opinion to defend the presence of water vapor and a known explanatory process, respiration, which would give rise to carbon dioxide in the air. Students also showed evidence of justifying their claims during the question and answer period. For example, Lindsey challenged Hillary's idea that there was water vapor in the air.

> About the water vapor, I thought we only had water vapor when like there's humidity in the air, because that's like when water vapor or humidity makes you feel like wet and sticky and your hair gets frizzy. Like right now, it's kind of like cool. (Laura Observation, 1/27/12)

Lindsey associated water vapor with the presence of humidity ("I thought we only had water vapor when like there's humidity in the air") and used her model explaining how and why it was humid on a hot summer day to justify her argument for why water vapor could not be in the air. In that explanation, she identified heat as an important causal factor leading to humidity, "If it was like really hot, like on a summer day, then maybe there would be some humidity." She argued that there could not be water vapor or humidity in the air due to the absence of heat ("It's kind of like cool") and identified two additional *perceivable indicators* for the presence of humidity ("you feel like wet and sticky and your hair gets frizzy"). Thus, Lindsey justified her argument using everyday experiences from a hot summer day and the absence of perceivable indicators.

In summary, I argue that there was more attention to *justification* in Laura's classroom than in John's classroom because there were normative expectations for Laura's students to justify and defend their ideas. In contrast, there were inconsistent expectations for students to justify their ideas in John's classroom, particularly those involving correct model ideas. Students' justification did not have to be empirical, as the analyses identified the range of ways in which students sought to justify their ideas.

Explanation 2: Different expectations for what ideas were the topic of persuasive discourse. I argue that the level of attention to *audience-persuasion* differed depending on whether the idea was related to what was between the air particles and whether it was the correct answer. For example, Lenny claimed that the blanks in his model were both "some air" and "some space." However, John attempted to persuade Lenny that there could not be "some air" rather than pressing Lenny to defend the validity of the correct idea, having "some space" between the air. For this analysis, I identified all the model ideas that students discussed when presenting their ideas and organized them into four categories (see Figure 6.6). I used parentheses to indicate the number of presentations that discussed an idea (n=6) and bolded ideas that were also discussed in Laura's classroom. I found that attempts to persuade others (colored yellow) were limited to incorrect ideas related to the content goal, as there were no efforts to defend or persuade others to revise other incorrect ideas, such air being "one point water two points air."

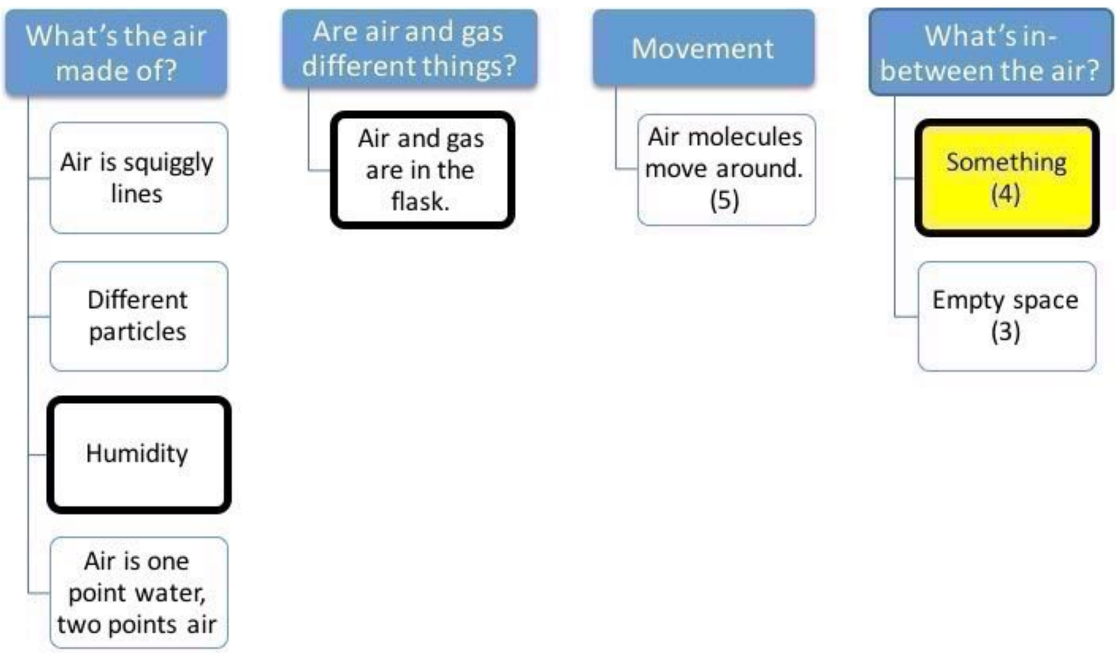

Figure 6.6. Analysis of topics discussed during John's initial air model discussion. I used parentheses to indicate the number of student models that discussed an idea. I colored in yellow topics discussed during persuasive discourse. I bolded the topics discussed in Laura's classroom.

In contrast, the extent to which students' ideas were related to the content goal did not influence whether it was the topic of persuasive discourse. There were no attempts to persuade the two students who thought there was "something" between the air to revise their claim. As seen in Figure 6.7, a range of ideas were the target of persuasive discourse, including other incorrect ideas, such as air sinking as it filled a container, as well as "correct" ideas, such as having water vapor or humidity in the air. These findings suggest that the discussions were more open-ended and dependent on what students were compelled to discuss rather than constrained by whether the idea was correct or related to the content goal.

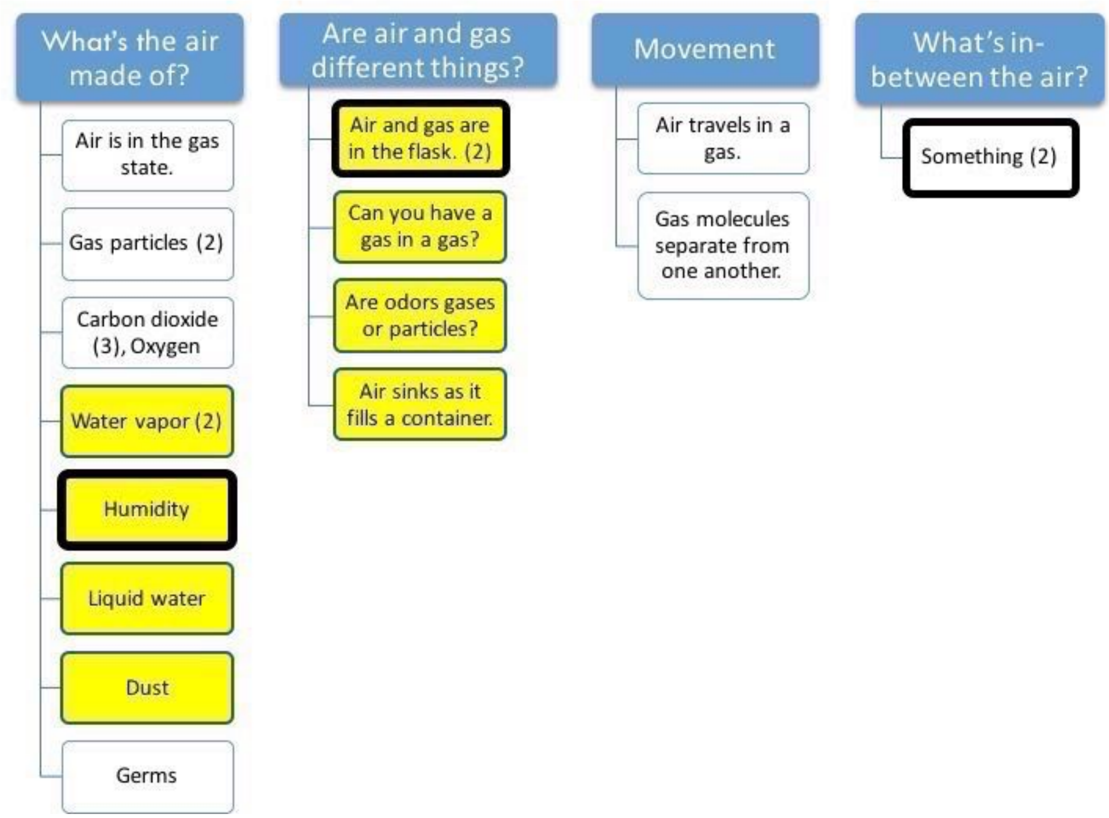

Figure 6.7. Analysis of topics discussed during Laura's initial air model discussion. I used parentheses to indicate the number of student models that discussed an idea. I colored in yellow topics discussed during persuasive discourse. I bolded topics that John's classroom also discussed.

In summary, I argue that there was less attention to *audience-persuasion* in John's classroom compared to Laura's classroom, because topics for persuasion were limited to topics related to incorrect ideas related to the content goal, whereas the range of ideas that were target of persuasion in Laura's classroom extended to other topics. Since students' and teachers' efforts to persuade others often uses evidence to justify their claims, limiting persuasion to incorrect topics related to the content goal could also explain why there was less *justification* in John's classroom.

3.2.2 Why was there less attention to *audience-persuasion* and *justification* in Kami's

classroom? The previous analysis investigated why there was more attention to *audience-persuasion* and *justification* in Laura's classroom than in John's classroom. In comparison, there was much less attention to these ECs during the whole-class modeling discussions in Kami's classroom. One reason might be that there was more focus on clarifying the referents for students' model features rather than justifying or defending the ideas' validity. For example, Kami described differences in the amount of air for each situation without pressing him to explain or defend his ideas, "So, Steven's model shows that there's *some* air here [regular flask], there's *less* air here [removed], and there's *more* air here [added]" (Kami Observation, 2/2/12, see Figure 6.8). When probing students' ideas about what might be between the air, Steven claimed that there were some places where there was no air, "I think there's some areas where there's… It's not all air. Like some empty area." Thus, there was more emphasis on what students' ideas were rather than why.

Figure 6.8. Steven's air models. The teacher labeled the model (black writing) during the whole-class discussion.

When evaluating the consistency of students' models with existing knowledge about air, there were no efforts to justify assessments about the model's validity or open the floor to others who might have disagreed with the model's ideas, which might have led to more attention to *audience-persuasion*.

Turn	Type	Interactional Units
38	T-0	T: So, this is a… We think this is a pretty good model of air. Right?
39	T-S	T: How many people had a model that looked a lot, looked pretty similar to Steven's model?
40	T-S	NATHAN: [raises hand]
41	S-SP	STEVEN: Yeah, Nathan.
42	T-S	T: Just a few? OK. Cool. Great.
43	T-S	NATHAN: [uses hands to “raise the roof"]

(Kami Observation, 2/2/12)

Given Kami’s understanding of how diagrammatic models mediate scientists’ sensemaking, it was puzzling that there was little discussion about the validity of students’ ideas. From her perspective, it was important for her students to learn how to effectively represent their ideas so that their audience could use their diagrammatic model to understand their ideas.

> This is a skill they need to have. They need to be able to represent what they know in a form that communicates their ideas to other people. And that piece, that communication piece is, I think, fundamentally important to the whole scientific endeavor. (Kami Interview, 5/3/12)

Thus, Kami’s choice to use this lesson to foreground the development of students’ representational skills rather than discuss the validity of students’ ideas could explain why there was less attention to *audience-persuasion* and *justification* in Kami’s classroom compared to John and Laura’s classroom. It is not to say that the other teachers were not interested in helping students improve their representational skills, as there was evidence of students and teachers asking clarifying questions about the referents of students’ model features. However, the audience’s efforts to understand students’ ideas in John and Laura’s classrooms led to more substantive discussions about the validity of students’ ideas.

3.2.3 Summary. In summary, the observed differences in the amount of attention to *audience-persuasion* and *justification* could be explained by varied expectations for students to justify and defend their model ideas and teachers’ interpretation of the epistemic aim guiding the discussion of students' models. If students were simply using their models to communicate their ideas to others, there was little need for students to justify or defend their ideas. In contrast, there was more attention to these ECs in Laura's classroom because reaching consensus required students to assess and defend the validity of the presented ideas. John's implicit attention to the content goal might have limited what topics students discussed and whether students understood the justification for the "correct" model ideas. Even if he did not state this goal explicitly, students likely recognized that empty space was an important feature due to implicit cues based on what topics John raised and his choice to hold a debate to convince students about the presence of empty space. Taken together, this analysis identified how students' and teachers' interpretation of the epistemic aim guiding the discussion of students' diagrammatic models could influence students' opportunities to use evidence and argument to mediate student sensemaking.

3.3 What are the epistemic challenges involved in engaging in argumentation?

In this section, I used epistemic considerations as analytical lenses to investigate the implications for these classroom differences on how students engaged in argument and their ability to persuade others. For this analysis, successful engagement in argumentation occurred when the students or teacher understood what changes were required and why. First, I examined how students' and teachers' differential attention to *audience-clarity* influence their ability to persuade others. Next, I used the *nature of account* lens to examine whether students considered the explanatory significance of their ideas or whether models were constructed to obtain the right answer. Third, I examined how students' and teachers' beliefs about models as a collection of coherent or discrete ideas influenced the approaches used to persuade others.

3.3.1 How did students' and teachers' differential attention to *audience-clarity*

influence their ability to persuade others? In this section, I examine how differential attention to *audience-clarity* could account for some of the successes and challenges observed in students' and teachers' ability to persuade others. To persuade others to revise their models or accept the validity of a competing model, I argue that students and teachers need to ensure that their target audience understood the weaknesses in their argument and how the proposed ideas were better able to explain the phenomenon. For this analysis, I compared the approaches used in John and Laura's classroom due to the limited attention to *audience-persuasion* in Kami's classroom.

Building on previous analyses of Lenny's model discussion (see Section 3.2.1), I used the *audience-clarity* lens to understand why John was unable to persuade Lenny that there could not be "some more air" between the air particles. John's approach involved reformulating Lenny's claim to prompt Lenny to consider the aggregate effects of having "some air" between the air particles, "So, you are also feeling that there's air from top to bottom, [bottom to top in here [the flask]" (turn 1). Lenny rejected this John's characterization of his idea, yet he persisted in his belief that the blank spaces were "some more air" (see turn 9). In what follows, I identify three challenges related to the *audience-clarity* consideration that could help explain why John was unable to persuade Lenny.

Challenge 1: Did the student understand the intent of the teacher's argumentative move? John's reformulation strategy could have helped students consider the phenomenon that emerged due to the aggregate micro-level interactions (see Wilensky & Resnick, 1999). However, there was no evidence that John took steps to ensure that his target audience, Lenny, understood the emergent effects of having "more air" between the air particles, such as pressing Lenny to explain the rationale for rejecting the reformulated claim. Thus, Lenny could have rejected the reformulated claim without making claims about the nature of the space between the air particles.

Challenge 2: Did the teacher take appropriate steps to ensure that he had an accurate interpretation of the student's idea? John likely interpreted Lenny's affirmation of the presence of empty space ("There's some empty space," turn 4) as evidence that he had persuaded Lenny that the blanks could only be empty space. I argue that this misinterpretation could be due to John not eliciting the justification for why Lenny rejected John's reformulated claim or checking for evidence of model revision. Further probing could have revealed a more accurate interpretation of Lenny's ideas.

Challenge 3: When persuading others, did the teacher address the audience's ideas or concerns? Another potential stumbling block was that John's approach did not probe Lenny's rationale for why there had to be "some air" between the air or how this idea could co-exist with "some empty space." Consequently, it is a challenge to persuade others of the validity of an idea without an accurate understanding of the audience's ideas or concerns. As an additional example, one of John's students, Michelle, indicated that she was still unconvinced about the presence of empty space after the debate. Rather than pressing Michelle to articulate what lingering issues persisted, John asked his students to consider how the ability to add air into the flask could further justify the presence of empty space in their consensus model.

Turn	**Type**	**Interactional Units**
1	T-S	T: If I can add air in, does that help our argument that there's empty space or does it hurt our argument, for Michelle's sake?
2	T-S	Ss: Hurt.
3	T-S	T: [confused look]
		[…]
9	T-S	T: So that'll hurt her [Michelle] argument. It'll help your argument that there is empty space in there so that's where that extra air is going.
10	T-S	S: Yeah.

(John Observation, 12/14/11)

John considered how the class' empty space model could explain another situation. In doing so, he showed implicit evidence of considering a type of metamodeling knowledge, in which a model's validity could be enhanced by demonstrating its ability to explain multiple situations. From a scientific perspective, there was nothing wrong with the epistemic considerations guiding his approach. However, his approach did not account for Michelle's reservations about the empty space model. Thus, he failed to consider how his approach could achieve his epistemic aim of persuading his audience. Furthermore, John made strong claims about how the application of the class model could "hurt" Michelle's argument before taking the necessary steps to understand the nature of Michelle's reservations. As with Lenny's example, more meaningful engagement in argumentation could have occurred if John checked his understanding of the students' ideas and rationales before attempting to persuade students to revise their models.

Using the *audience-clarity* lens, I identified three challenges influencing John's ability to successfully persuade a student to revise their ideas. These analytical questions could be generalized to apply to students' and teachers' actions: *1) Did the audience understand the intent of the student or teacher's argumentative move? 2) Did the student or teacher take appropriate steps to ensure that he or she had an accurate interpretation of the audience's understanding? 3) When persuading others, did the students or teacher attend to and address the audience's ideas or concerns?* In the following section, I use Laura's students' discussion of Hillary's model as a contrasting example to show how attention to these issues could help students persuade others of the validity of one's claims.

In this section, I build on previous analyses (see Section 3.2.1) to show how Hillary and Sally's implicit attention to *audience-clarity* helped convince Lindsey that there was water vapor in the air. In the excerpt below, both students argued for how it was possible for there to be water vapor in the air despite not being able to “feel it” (turn 2). In doing so, students directly addressed concerns raised by the target audience.

Turn	Type	Interactional Units
1	S-SP	LINDSEY: About the water vapor, I thought we only had water vapor when like there's humidity in the air, because that's like when water vapor or humidity makes you feel like wet and sticky and your hair gets frizzy. Like right now, it's kind of like cool. So...
2	S-SP	HILLARY: Well, I kind of think that even if you don't feel it, there's still definitely some sort of water vapor in the air because like... I just think kind of when like it's hard to explain, but like when you're talking, and you kind of like spit, kind of. Like there's spit there's humidity in the air, so it's not like it's completely dry. Like there's some sort of water.
		[…]
3	S-S	SALLY: I kind of agree too, because if there was like no humidity in this classroom, we'd be all dried up and drinking water [laughing]. She'd be like... We should put water vapor in the air. Yeah, we'd be all like... Our skin would be all dried up.
4	S-S	LINDSEY: I see what you're saying.
5	T-S	T: What do you mean you see what she's saying?
6	T-S	LINDSEY: Like what she like, what Sally said, also like, even though we can't see it or feel it, like if there was no water vapor we'd be all dry and all like ashy, but like we need some water vapor to keep our skin moist and... Yeah.

(Laura Observation, 1/27/12)

The students used two lines of reasoning to address Lindsey’s concerns that there were no perceptible indicators of water vapor. First, Hillary provided plausible mechanisms that could give rise to water vapor in the air, such as a student spitting into the air while speaking, “When you're talking, and you kind of like spit, kind of. Like there's spit there's humidity in the air, so it's not like it's completely dry” (turn 2). Second, Sally built on Hillary’s argument, which referenced the absence of dry air (“so it's not like it's completely dry”), to proposed an alternate set of perceivable indicators for the *absence* of water vapor in the air: dry skin and thirst.

The teacher pressed for evidence of model revision by asking Lindsey to clarify what she meant by, "I see what you're saying." In doing so, she checked whether the goals guiding students' arguments had been achieved and provided Lindsey with the opportunity to make visible any lingering issues that needed to be resolved. Lindsey's explanation implied that it was Sally's alternative set of perceivable indicators that was important for persuading Lindsey, "Even though we can't see it or feel it, like if there was no water vapor we'd be all dry and all like ashy, but like we need some water vapor to keep our skin moist" (turn 6). In addition, the teacher reinforced the norm that claiming agreement with others' ideas was not sufficient; rather, students were expected justify their answers.

In summary, Hillary and Sally could persuade Lindsey their arguments addressed each of Lindsey's concerns. In contrast, John was less successful because his approach was guided by a superficial understanding of students' claims and the justifications supporting those ideas. These differences in attention to *audience-clarity* showed up not only in the qualitative analyses, but also in the higher proportion of attention to *audience-clarity* in Laura's classroom (46.7%) compared to John's classroom (27.3%).

3.3.2 Were models constructed in service of explaining phenomena? For this analysis, I used the *nature of account* consideration as a lens for analyzing the purpose for including the various ideas in the model. For example, did students simply want to include all the correct model components, such as including space between the particles, or did students consider their models as a coherent set of ideas for explaining a phenomenon? Using evidence from the discussed topics, I coded model discussions as seeking to construct *descriptive*, *correct answer*, *mechanistic, or explanatory* accounts (See Table 6.4 for coding rules and Ch. 5, Section 4.2.3 for more information).

Table 6.4
Nature of account consideration coding

Code	Indicators
Descriptive	• Describes observations or what happened
Correct answer	• Model components are present without considering the explanatory significance of the ideas
Mechanistic	• Shows evidence of generating an internally consistent model without considering how students could use their model to explain phenomena.
Explanatory	• Identifies explanatory processes • Identifies relationships between model components and ideas • Considers ideas at multiple levels or time scales • Considers effects of mediating factors (e.g. temperature)

Kami: Mechanistic. I coded Kami's initial air and contrasting behaviors of air model discussions as *mechanistic*, as students did not show evidence of considering how their model ideas could explain the contrasting air behaviors. For example, Kami asked her students to specify the nature of the "empty area" to ensure that students were thoughtful about how they were using their models to communicate their ideas to an external audience, "I want them to realize that everything inside that circle is part of the model. And, if there's an empty space, that means something. It has meaning" (Kami Interview, 1/17/12). In addition, the model evaluation criteria considered the model ideas' coherence with existing knowledge about gases rather than the model's ability to account for the phenomena. Kami alluded to something causing there to be "more empty" after she removed some air from the flask, "He shows there's some air, then there's less air, but there's more empty. Somehow, we got more empty. Ok?" (Kami Observation, 2/2/12). However, she did not open the conversation to consider how and why these changes occurred or the explanatory significance of these differences.

John: Mechanistic and explanatory. I coded John's initial air model discussions as *mechanistic*, as John and his students considered whether the model ideas were internally consistent with existing knowledge about gases. For example, students argued that there needed to be empty space for the air molecules to move inside the flask. In contrast, I coded the contrasting air behavior model discussions as *explanatory*, as John considered how the empty space model could account for the contrasting behaviors of air. For example, John explained how the empty space provided a place for the "extra air" to go when he added air to the flask. Students also considered the explanatory implications of their ideas. For example, Michelle's reservations about the empty space model involved how it was possible for the air's volume not to change inside the flask after John removed some air, "If the air in the flask was completely full, how then, if you took it out… Wouldn't the volume of the air naturally change because you took it out?" (John Observation, 12/14/11).

Laura: Explanatory. I coded the initial air and contrasting behaviors of air model discussions as *explanatory*. Students justified the air components by citing explanatory processes that could give rise to these components, such as respiration for the presence of carbon dioxide ("everyone's breathing it out") or evaporation for the presence of water vapor ("maybe some of us drinking water and the water evaporated and then it got in Ms. B's [flask]," Laura Observation, 1/27/12).

Although the class did not reach consensus about the presence of empty space, the students' efforts to justify their model components involved explaining observations from phenomena. For example, students showed evidence of considering how the removal of air could lead to less air and the presence of empty space in the flask, "I mean I guess if you take air out, there's less air, but like it's like empty like in-between, a random amount of no air" (Laura Observation, 1/31/12). Thus, students considered how components within students' models could account for the phenomenon. As another example, when debating the direction that air molecules traveled after Laura added or removed air from the flask, Jerome argued that the air molecules needed to travel in a single direction to create enough pressure to "pop off" the stopper when Laura added excess air to the flask, "But doesn't there have to be like, air particles pushing up then to get the cork to go up?" (Laura Observation, 1/31/12). Thus, Jerome used observations from the phenomenon as evidence to support the plausibility of the proposed model ideas.

In summary, Kami and John's initial air model discussions were mechanistic, while Laura and John's contrasting behaviors of gases discussions were explanatory. The key differentiator between the three classrooms involved whether students' ideas about empty space were justified based on the plausibility of areas without air (Kami's classroom), the internal consistency in students' models (John's initial air models), or the role that empty space could have for explaining the phenomena (John and Laura).

3.3.3 Did participants consider models to be a set of discrete or a coherent set of ideas for explaining the phenomenon? The previous analysis examined the extent to which the justification for students' model ideas accounted for observations from the phenomenon, their internal consistency with existing knowledge, or the desire to have the correct answer. For this analysis, I examined whether students and teachers considered models as a collection of individual ideas or a coherent set of interconnected ideas for explaining a phenomenon. In the former situation, students and teachers might consider the plausibility of individual model ideas in isolation, while the latter situation might consider an idea's relationship with others for explaining the phenomenon.

I argue that John used a component-like approach when attempting to persuade Lenny that there could not be "some air" between the air particles. Beyond reformulating the idea of "some air," there was no argument for why the flask could not be filled with air. Although Lenny did mention that there was some empty space and moving air in his model, it was not clear whether Lenny was just listing a set of a discrete facts or whether Lenny understood how and why empty space was needed for the air particles to move past one another. In other words, it was not clear whether Lenny recognized how having "some air" between the air particles was incoherent with the other ideas in his model.

Viewing models as a coherent set of ideas was helpful for evaluating and persuading students to revise their models. In contrast to John's approach, Jackie's approach showed evidence of evaluating the coherence between the stated ideas, "If the blank was air, how are they [particles] moving? Because they're all packed in there then" (John Observation, 12/12/11). In this single turn of talk, Jackie made visible to Lenny the relationship between having "some air" between the air and having the flask being "packed in" with air. In addition, she made visible to Lenny how having "more air" between the air would prevent the air from being able to move inside the flask. Thus, her argument leveraged multiple lines of reasoning that made visible the implications of Lenny's model ideas that helped her persuade Lenny that there had to be empty space between the air particles.

As another example, Jessi shared an air model that involved waves ("squiggly lines") moving air in all directions, as evidenced by the arrows (see Figure 6.9).

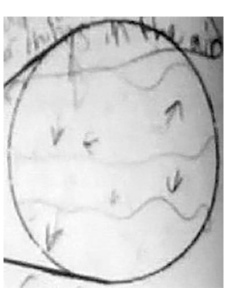

Figure 6.9. Jessi's models showing the removal of air from the sealed the flask. The lines represent the waves that are moving the air (arrows) in all directions.

Turn	Type	Interactional Units
1	S-SP	RACHEL: Wait so with the lines, that represents the air?
2	S-SP	JESSI: Yeah, it's like if you go like this, when you're pumping it in, then like, it starts to move.
3	S-SP	RACHEL: But why are the arrows be going everywhere if they're only going straight like that?
4	S-SP	JESSI: Well, I don't think they're [arrows] all going straight. I think they're all going different directions, but some of them go straight and some of them=
5	S-SP	RACHEL: =Like how you drew it, they're all like going straight.
6	S-SP	RACHEL: Do you mean they're all going like all the way up and all around or…?
7	S-SP	JESSI: Well, yeah, I would probably change it like... [starts revising model]
8	T-SP	T: Wait, how would you, I'm sorry. What are you doing?
9	T-SP	JESSI: Like could you say that all those waves… Like the wave are all going one direction, but now that I'm thinking about it, I would change it to all going different directions.

(Laura Observation, 1/31/12)

One student, Rachel, observed that Jessi's model showed the air traveling in all directions, yet the waves responsible for moving the air traveled in a single direction, "But why are the arrows be going everywhere if they're [squiggly lines] only going straight like that?" (Laura Observation, 1/31/12). When confronted with these incoherent ideas, Jessi revised the waves' directions so that they would move the air in all directions. Taken together, these findings suggest that participants' ability to persuade others was enhanced when students approached models as a coherent set of ideas rather than using a component-like approach.

3.4 Epistemic considerations summary

The epistemic considerations lens used evidence from students' and teachers' actions and stated rationales to infer their interpretation of the goals guiding their work and what was needed to achieve those goals. Using these findings, I identified classroom differences in what epistemic considerations guided students' and teachers' engagement in argumentation and assessed the implications for these differences on students' ability to persuade others. I argued that differences in attention to *audience-persuasion* and *justification* were due to differences in what epistemic aim guided students' and teachers' engagement in argumentation. There was more attention to *audience-persuasion* and *justification* because the goal of the model sharing discussions involved reaching consensus, whereas in John's classroom there was more emphasis on persuading students about the presence of empty space or understanding students' ideas in Kami's classroom. Students' and teachers' who attended to issues related to *audience-clarity* when persuading others were more likely to persuade others because their efforts involved negotiating students' understanding of one another's ideas. In doing so, the constructed arguments could directly address identified student concerns or potential weaknesses in students' arguments.

In addition, there were classroom differences in the extent to which the students and teachers' approach to persuading others considered the model's internal consistency and its ability to explain a phenomenon. Students were better able to persuade students when they used multiple lines of reasoning that leveraged not only the implications of individual model ideas on other ideas and their ability to account for observations from the phenomenon. In addition to considering the emergent properties of having "more air" between the air particles, Jackie could persuade Lenny to reconsider the validity of his model because she made visible how moving air molecules needed to space to move. In addition, participants in John and Laura's classroom considered their model's ability to explain observations from phenomena. Taken together, reasoning related to the *nature of account* consideration provided additional lines of reasoning to support students' arguments.

4. Epistemic agency: Who's responsible for achieving the epistemic aim?

One of the core shifts in NGSS involves positioning the students as the agents responsible for using scientific practices in meaningful ways to construct, evaluate, and revise scientific knowledge. I used the *epistemic agency* lens to identify the successes and challenges involved in teachers' attempts to support students' opportunities to shape the classroom consensus knowledge. This analysis was done in three phases. In the first phase, I characterized the nature and distribution of the students' and teachers' knowledge-building roles by investigating the questions, "Who's doing the work?" and "Who has the authority?" The second phase involved identifying the classroom factors, such as students' ability to access the conversational floor, that could explain the observed participation roles and students' opportunities to shape the class consensus knowledge. The third phase identified what factors influenced how student ideas contributed to the classroom consensus knowledge by investigating the question, "How were students' ideas used during instruction?"

4.1 Phase 1: Who's doing the work? and Who has the authority?

Phase 1 characterized the nature and distribution of students' and teachers' knowledge-building roles. To do so, I first analyzed observed patterns of interaction to understand the extent to which students initiated and responded to one another's ideas. Next, I constructed relative attention profiles for students and teachers to analyze the distribution of responsibility for constructing convincing, evidence-based models of phenomena. Lastly, I examined whether students had epistemic authority to validate student ideas or whether the teacher continued to hold this traditional knowledge-building role.

4.1.1 Analysis of patterns of interaction. I used word counts to calculate the proportion of each interaction type during the whole-class discussions. Figure 6.10 shows the patterns of interaction for each classroom. The main bar (bottom) shows the distribution of teacher (blue) and student-initiated (red) interactional units during whole-class discussions, while the top bar indicates who responded to the student-initiated discourse: the teacher (S-T), students (S-S), or no one (S-0).

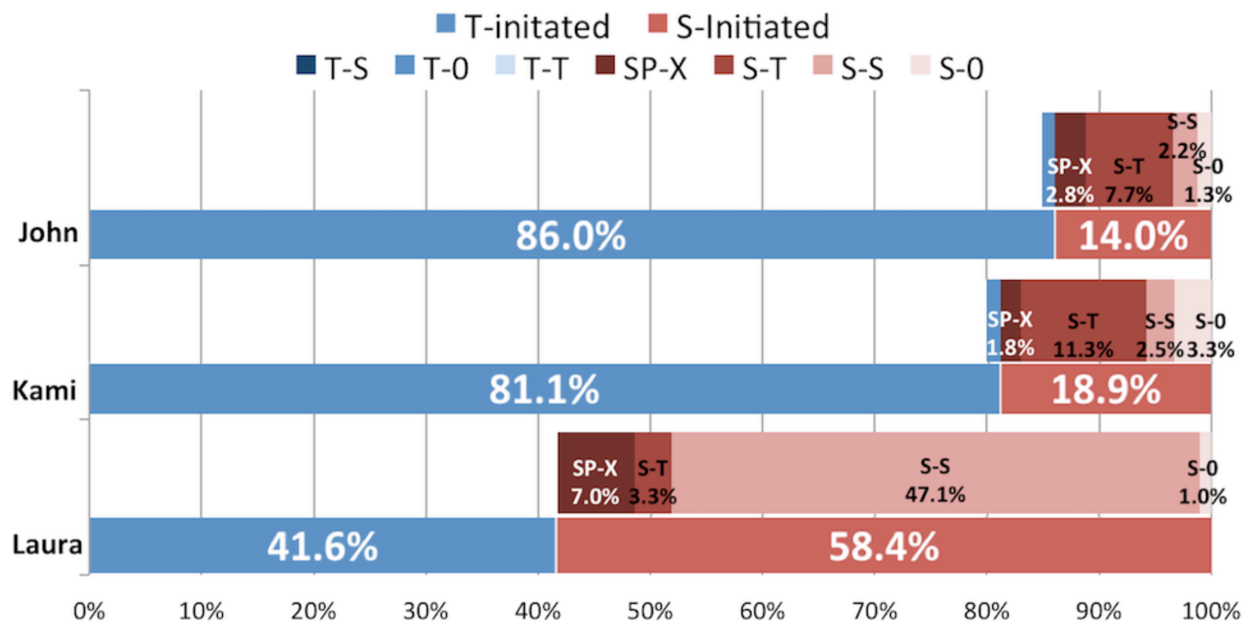

Figure 6.10. Patterns of interaction during focus lesson. This figure shows the proportion of total whole-class discourse (John: 9,127 words; Kami: 2,453 words; Laura: 7,440 words) coded for each *interaction type*. The main bar shows the distribution of student and teacher-initiated discourse, while the top bar teases apart student-initiated discourse by interaction type.

One measure of the students' knowledge-building role involved examining the proportion of the whole-class modeling discourse in which the students presented their ideas to the class (SP-X). There was more time, as measured by word count, devoted to students presenting their models in Laura's classroom (7.0%) than in John (2.8%) or Kami's (1.8%) classrooms. Table 6.5 shows the number of student presentations during the focus lesson. John did not have his students construct or present individual models explaining the contrasting air behaviors. Kami discussed models for all three situations at the same time.

Table 6.5
Number of student presentations during Lesson 4

Teacher	Initial air models	Contrasting behaviors of air
John	6	N/A
Kami	3	3*
Laura	5	2

*Done at same time as initial air model discussion

When analyzing the students' knowledge-building role, I compared the percentages of student and teacher-initiated classroom discourse to identify whether the students or teacher were the first individuals to pose questions or comment on the presented ideas. Heritage (2009) found that the individual who first states an idea has more epistemic authority compared to someone who later discusses the same idea. During the focus lesson, there was more teacher-initiated interaction in John (86.0%) and Kami's (81.1%) classroom, while there was more student-initiated interaction (58.4%) in Laura's classroom. The teacher was the first to ask a question or comment on the presented ideas in John and Kami's classroom, while it was the students in Laura's classroom. I also analyzed the proportion of whole-class discourse involving student to student interactions (S-S) to characterize students' opportunities to construct knowledge with others. There was more discussion between students (S-S) in Laura's classroom (47.1%) than in John (2.2%) and Kami's (2.5%) classrooms. Taken together, the teacher played a greater role in mediating the discussion of students' ideas in John and Kami's classrooms compared to in Laura's classroom.

When I limited the analysis to discussions involving the target activity structure, the overall trends were the same, yet the proportion of student-initiated interactions increased from 14.0% to 21.8% in John's classroom and 58.4% to 73.6% in Laura's classroom. The proportion of student-student interactions (S-S) increased from 47.1 to 61.5% in Laura's classroom, while the amount of S-S discourse marginally increased by 2% in John's classroom. These findings suggest that the target activity structure had the potential to increase students' opportunities to initiate and respond to one another's ideas, yet there was less change in John's classroom compared to in Laura's classroom. Why was there such an increase in the proportion of student-student discourse in Laura's classroom compared to in John's classrooms? I investigate this question further in Section 4.2.2.

4.1.2 Distribution of knowledge-building responsibilities. Since the motivation of science reforms involves supporting *students'* meaningful use of scientific practices, it was important to examine the *distribution of responsibility* between teachers and students for developing convincing, evidence-based, explanatory accounts of phenomena. To do so, I constructed relative attention profiles for student and teacher-initiated interactional units (second and third rows of Table 6.6) to determine the students' and teachers' relative contribution to the aggregate level findings. I divided the number of coded words for each EC during student and teacher-initiated interactional units by the total word count. For example, of the 2,494 words (27.3%) coded for *audience-clarity* in John's classroom, 2,082 words (22.8%) occurred during teacher-initiated interactional units, while 412 words (4.5%) occurred during student-initiated interactional units. The sum of the teacher and student-initiated percentages equaled the total. I calculated each percentage individually, so any discrepancies are due to rounding (e.g., *audience-clarity* for Laura's classroom). As before, I compared the EC percentages within each row and used brackets to show the relative ranking for each EC.

Table 6.6

Relative attention profiles for students and teachers during whole-class model discussions

Classroom	Audience		Generality	Justification	Nature of Account
	Clarity	Persuasion			
John	**27.3%**	**14.0%**	**6.8%**	**19.5%**	**51.3%**
(9,127 words)	**[2]**	**[4]**	**[5]**	**[3]**	**[1]**
T-initiated	22.8%	11.1%	6.4%	16.5%	42.4%
	[2]	[4]	[5]	[3]	[1]
S-initiated	4.5%	2.9%	0.4%	2.9%	8.9%
	[2]	[3]	[5]	[3]	[1]
Kami	**29.7%**	**5.4%**	**7.0%**	**11.5%**	**43.6%**
(2,453 words)	**[2]**	**[5]**	**[4]**	**[3]**	**[1]**
T-initiated	25.2%	1.6%	4.7%	8.5%	39.2%
	[2]	[5]	[4]	[3]	[1]
S-initiated	4.4%	3.8%	2.3%	3.0%	4.4%
	[1]	[3]	[5]	[4]	[1]
Laura	**46.7%**	**37.6%**	**14.1%**	**34.0%**	**67.3%**
(7,440 words)	**[2]**	**[3]**	**[5]**	**[4]**	**[1]**
T-initiated	12.7%	8.3%	2.1%	10.5%	16.9%
	[2]	[4]	[5]	[3]	[1]
S-initiated	33.9%	29.3%	12.0%	23.5%	50.4%
	[2]	[3]	[5]	[4]	[1]

This table shows relative attention profiles for students and teachers during the whole-class model discussions. For each classroom, I present the findings at the classroom-level (1st), all teacher-initiated interactional units (2nd), and all student-initiated interactional units. The total word count is in parentheses. For each level of analysis, the bracketed numbers indicate the relative rank for each EC (1 highest, 5 lowest).

To assess the distribution of knowledge-building responsibilities, I compared the students' and teachers' relative attention profiles. Individuals with higher percentage for a given EC showed evidence of initiating more discussions related to those issues. In general, the findings were consistent with the observed patterns of interaction, as the teacher was responsible for initiating much of the discussions related to each EC in John and Kami's classroom, while the students were responsible for initiating discussions related to each EC in Laura's classroom.

John. In John's classroom, the teacher was the agent responsible for clarifying, seeking justification, and persuading others to revise their models. The students' relative contribution to this work was minimal. Interestingly, John's students' relative rank for *audience-persuasion* and *justification* were the same, which suggests that students used evidence when persuading others.

Kami. Kami was responsible for clarifying the meaning of students' ideas and pressing students to evaluate the consistency of students' models with existing knowledge about gases, air, and odors. There were minimal attempts to persuade others during teacher-initiated discourse. Interestingly, Kami's students' relative attention profile resembled Laura's students' profile in that used evidence to persuade others of the validity of one's claims.

Laura. Laura's relative attention profile showed slightly more attention to *nature of account* than *audience-clarity*, which suggests that the instances in which initiated discussions were in service of clarifying students' ideas. While her students were primarily responsible for using evidence to persuade others, Laura's role involved initiating discussions around the justification of those ideas or prompting students to defend their ideas. There was much less attention to *generality* during teacher-initiated discourse than student-initiated discourse, which suggests that students were responsible for considering the relevance of other situations or general knowledge for explaining phenomena.

These findings raise several questions: Why did Laura's students have a more substantive, knowledge-building role than John and Kami's students? When framing the whole-class discussion, John noted that the students should be the ones evaluating students' ideas, yet it was the teacher who held that responsibility during the enactment. Why were there differences between the students' intended and observed knowledge-building roles?

Table 6.7

Students' and teachers' relative attention profiles during audience-persuasion

Classroom	Audience-clarity	Generality	Justification	Nature of Account
John	**38.3%**	**9.1%**	**36.0%**	**78.3%**
(1,279 words)	**[2]**	**[4]**	**[3]**	**[1]**
T-initiated	36.0%	7.9%	23.3%	63.1%
	[2]	[4]	[3]	[1]
S-initiated	2.3%	1.2%	12.7%	15.2%
	[3]	[4]	[2]	[1]
Kami	-	**62.1%**	**55.3%**	**72.0%**
(132 words)		**[2]**	**[3]**	**[1]**
T-initiated	-	18.9%	-	25.8%
		[2]		[1]
S-initiated	-	43.2%	55.3%	46.2%
		[3]	[1]	[2]
Laura	**43.7%**	**20.8%**	**62.2%**	**86.5%**
(2,794 words)	**[3]**	**[4]**	**[2]**	**[1]**
T-initiated	6.7%	1.0%	15.4%	9.5%
	[3]	[4]	[1]	[2]
S-initiated	37.0%	19.8%	46.7%	77.0%
	[3]	[4]	[2]	[1]

This table shows the proportion of *audience-persuasion* discourse in which students and teachers attended to the other ECs. The total *audience-persuasion* word count is in parentheses. For each level of analysis, the bracketed numbers indicate the relative rank for each EC (1 highest, 5 lowest).

Table 6.7 shows the students and teachers' relative attention profiles during *audience-persuasion* discourse. In other words, what epistemic considerations guided students' and teachers' engagement in argumentation? There was proportionally more student-initiated attention to *justification* during persuasive discourse compared to the aggregate data. *Justification* was the most attended to EC during teacher-initiated persuasive discourse in Laura's classroom. In contrast, Kami pressed her students to consider their model's consistency with existing knowledge than justifying or clarifying their ideas. John's relative attention profile changed little from the aggregate data.

4.1.3 Who has the authority? The last Phase 1 analysis investigated the extent to which students had the epistemic authority to assess the validity of students' ideas.

Kami: Teacher. In general, Kami held the authority to evaluate and assess the validity of students' ideas. Kami did not elicit students' ideas when they were given the opportunity to compare their models with the presented models. Kami invited her students to assess the consistency of Steven's model with existing knowledge about gases ("What do you think? Does this show what we know about air so far?"). However, Kami validated Steven's model without providing evidence, "So this is a… We think this is a pretty good model of air. Right?" (turn 38, Kami Observation, 2/2/12). Thus, the validity of Steven's model relied on Kami's institutional authority rather than the epistemic authority of the presented evidence. Furthermore, there was no evidence that Kami's assessment accounted for the gas characteristics discussed by her students. Interestingly, Kami's initial phrasing ("So this is a…) suggested that she was going to assess the model, before revising her statement to include the collective pronoun, "we," to signal that the evaluation responsibilities should be shared with the students.

In addition, it was possible that Kami's endorsement of Steven's model might have led the other student presenters, Ariana and Alana, to consider the presence of empty space in their own models. For example, Ariana explicitly mentioned empty space in her model (see Figure 6.11), "Same thing that Steven said. That like the green is the air, and the other part is the empty space" (Kami Observation, 2/2/12). Since both students' models were unlabeled, it was unclear whether the students held these ideas before the model discussion.

Figure 6.11. Ariana's model. Green lines are air. Black arrows were added to show movement.

In addition to potentially validating the presence of empty space, Kami pressed students to include movement in their models by calling out the presence of this idea in Alana's model and its absence in the other models.

Turn	Type	Interactional Units
4	T-S	T: Now that's something that nobody else had in their diagram -- in their models. Um, does air move?
5	T-S	Ss: Yeah. Yes.
6	T-S	T: So, should we have movement in the models?
7	T-S	STEVEN: Uh, huh.
8	T-S	T: We really should. Right?
		[…]
15	T-0	T: Is this something about air, gas, that we know is true? It moves around in all different directions? Right?
16	T-0	T: So, take a look at your model. If your model doesn't show movement, you should add that in. Revise your model.

(Kami Observation, 2/2/12)

Rather than letting students make the final decision, Kami affirmed Steven's opinion ("We really should.") and prompted students to revise their models to include movement (turn 16). Thus, the teacher, rather than the students, was the ultimate source of epistemic authority to determine what ideas should be included in students' models.

John: Teacher. John's students had some epistemic authority to state whether they were convinced of the presence of empty space between the air. For example, Michelle stated that was unconvinced by arguments for the empty space model, which prompted John to use the contrasting air behaviors to convince her of the model's validity. However, John was the primary agent responsible for evaluating students' ideas and persuading students that there had to be empty space between the air particles. When Lenny maintained his belief that there was "some more air" between the air, John explicitly told him that there was "nothing there." In doing so, he did not support his students' authority to interpret and use evidence to support a claim; instead, John told him he was incorrect and did not consider alternative ways for persuade him. In addition, John determined what counted as relevant knowledge for achieving the stated epistemic aims. For example, Micah considered the mechanisms by which air moved inside the flask. However, John, rather than his students, deemed his idea to be irrelevant because there was no wind inside the flask and did not give Micah access to the conversational floor to further argue his case or consider the opinions of other students.

Turn	Type	Interactional Units
5	T-S	T: Also, how much wind is inside this flask right now?
6	T-S	Ss: None. Nothing.
7	S-T	MICAH: But there's still air.
8	S-T	T: I know, but realize we're dealing with what's inside the…
9	S-T	T: I know what you're saying. Alright? But, we're dealing with what's inside this sealed flask. It's got a rubber stopper on the top. Ok?

(John Observation, 12/12/11)

Laura: Students. Laura positioned the students as the agents responsible for assessing the validity of the presented ideas. In the following example, Alyssa asked Laura whether the model explaining the removal of air would be the same as their initial air model. However, "tossed" the onus of responsibility for assessing students' ideas back to the students (c.f.,van Zee & Minstrell, 1997).

Turn	Type	Interactional Units
1	S-T	ALYSSA: Ms. B, wouldn't it be the same as the last one?
2	S-T	T: That's what I want to see. See what you would think, if I removed some of the air.

(Laura Observation, 1/31/12

In addition, the students had the epistemic authority to assess the progress the class had made towards investigating the target question. For example, there was an expectation that students who posed questions would have the opportunity to assess whether their concerns had been resolved (e.g., "So Allie, did she answer your question?"). At the whole-class level, Laura asked her students to reflect on the class' progress towards answering the driving question and decide whether more work was needed.

Turn	Type	Interactional Units
1	T-S	T: Ok hang on. Do we have an answer yet?
2	T-S	Ss: No.
3	T-S	T: We gotta keep on going.

(Laura Observation, 1/27/12)

4.1.4 Summary. In summary, I used three related analyses to determine whether the students were primarily responsible for shaping the classroom consensus knowledge. The first analysis examined each classroom's patterns of interaction to assess students' opportunities to initiate and respond to one another's ideas. There was more student-initiated discourse in Laura's classroom whereas there was more teacher-initiated discourse in John and Kami's classroom. There were more student-student interactions in Laura's classroom than in the other classrooms.

The second analysis compared the students' and teachers' relative attention profiles to assess the distribution of knowledge-building responsibilities between the students and teacher. In general, the findings showed that the students' knowledge-building responsibilities were less in John and Kami's classroom compared to in Laura's classroom. However, the students' relative attention profiles were similar across the three classrooms. Thus, students might have adopted a more active role had they been given the opportunity.

The third analysis examined whether the students had the ultimate responsibility for evaluating or validating students' ideas. Although John and Kami provided students with the opportunity to evaluate the presented ideas, the teachers exercised their epistemic authority to assess the validity of student's claims or direct students towards the correct answer. In contrast, Laura's students were the primary agents responsible for evaluating students' ideas and shaping the trajectory used to achieving the desired epistemic aim.

The target activity structure was designed to create opportunities for students to present and evaluate one another's ideas. However, there were classroom differences in students' opportunities to initiate and respond to one another's ideas. These findings lead me to wonder: Why weren't the students more involved in shaping the knowledge in John and Kami's classroom? Why were there differences in students' intended and observed knowledge-building role in John's classroom? In the next section, I investigate what classroom factors might explain these questions and classroom differences.

4.2 Phase 2: What classroom supports influence these observed participant roles?

In this section, I explore the classroom norms or supports that could explain the observed differences in students' opportunities to shape the class consensus knowledge. First, I examined whether the teacher explicitly articulated the students' roles and the rationale for why students' participation was important. Second, I examined whether students had access to the conversational floor to comment on and defend students' ideas. Third, I examined the teacher's adopted evaluative stance when discussing students' ideas to assess whether the teacher privileged students' ability to evaluate students' ideas. Lastly, I examined how students' opportunities to make sense of phenomena could enhance their ability to participate.

4.2.1 Teachers specify and value students' knowledge-building role. First, I examined whether the teacher specified at the beginning and during the discussion the nature of students' knowledge-building role and how and why their participation was important.

Kami: No explicit student expectations. Kami did not articulate expected student roles for the whole-class model discussions, which might have contributed to her adopting an active role in interpreting and evaluating students' models, while her students adopted an observer role and had to be reminded to stay on-task and pay attention to the work in which she and the student presenter were engaging, “Eyes up here on the board, please. Because when I say, ‘Here’ and point to something, you won't know what I'm talking about unless you're looking at me. Ok?” (Kami Observation, 2/2/12).

John: Articulated general norms that did not privilege the students’ evaluative role. John communicated that the class would use criteria to evaluate the presented ideas and ask questions to “challeng[e] people to think things in different ways” (John Observation, 12/12/11). During the discussion, John provided feedback to help his students evaluate one other’s ideas in more productive ways. For example, John asked students to consider their level of agreement with the presented ideas (turns 1 and 3) and reframe critiques in the form of questions (turns 6 and 8).

Turn	Type	Interactional Units
1	T-S	T: Does everybody agree with her model?
2	T-S	Ss: Yeah. Sure.
3	T-S	T: Does anybody NOT agree with her model?
4	T-S	NATHANIEL: Just one little thing...
5	T-S	ISAIAH: Needs more air...
6	T-S	T: Does anybody want to *ask* her something?
7	T-S	S: [Inaudible Ss crosstalk]
8	T-S	T: Not just like, "That's wrong,” but actually ask her something?

(John Observation, 12/12/11)

Although there were implicit expectations that the students would be responsible for evaluating students’ ideas, there were no norms present that privilege the students’ role and communicated expectations that the teacher would have a secondary role. For example, John communicated that student presenters should be prepared to defend their models, “So if you're classmates don't do it, I probably will challenge you and ask you questions and stuff, so be prepared for that as well" (John Observation, 12/12/11).

Laura: Articulated and reinforced participant roles. In contrast, Laura articulated and reinforced students' roles and explained why these roles were important. Preceding the first initial air model discussion, Laura articulated student roles that positioned them as the source of ideas and the agents responsible for constructing the consensus model.

> Ok, so let me explain Becky [*student presenter*] and your [*student peers'*] job. So, her job is going to be to explain to you what she thinks it [the air] looks like under the special microscope. […] And, your job is going to be to ask personal questions that would help us, because we want to come up with a consensus. We want to try to figure out really what does air look like. […] So, try to listen to what she's got. (Laura Observation, 1/27/12)

Students were responsible for asking questions and evaluating the validity of the presented ideas ("ask personal questions that would help us […] come up with a consensus"). Thus, the students, rather than the teacher, were positioned as the student presenter's audience. To support this work, the *teacher* would ensure that students were participating appropriately and monitor the students' progress towards reaching consensus, "And then I'm [Laura] listening for your questions to see if we could get some...help in." Unlike John, who stated that he would evaluate students' ideas if the students did not adopt the desired role, Laura established expectations that the students should fulfill their responsibilities.

During the enactment, Laura reinforced expectations that all students should participate in the discussion of one another's ideas. To hold students accountable, students documented instances when they posed questions during class discussions, "I do want you to record discussion questions, discussion is very important. […] So, make sure you remember what you're doing, because I want everyone to be part of it all here" (Laura Observation, 1/27/12). In addition, Laura called on students to ensure that everyone was participating and tracking the conversation ("Larry, what do you think about that?" Laura Observation, 1/27/12). At the same time, Laura wanted her students to consider why their participation was important. For example, Laura asked her students to reflect on whether asking questions was helpful for their own learning ("Does it help to ask people questions?" Laura Observation, 1/27/12) as a means for reinforcing these expected participation roles throughout the multi-day lesson, "While we're listening, do we also want to ask questions? Is that part of it? Yeah, because that helps us understand what's happening" (Laura Observation, 1/31/12). In addition, she made praised students' participation and reinforced its value for students' own learning, "Good job trying to ask... We learned a lot from asking questions" (Laura Observation, 1/27/12).

Summary. There were observed differences in the specificity and reinforcement of students' participation role. I argue that students played a less significant role in classrooms where the teacher underspecified or did not reinforce the students' role during the enactment. Although there were implicit expectations that John's students would be the agents responsible for evaluating the presented ideas, Laura privileged her students' status as the agents responsible for evaluating student ideas by communicating why their participation was important and held students accountable for these expected roles throughout the model discussion. Thus, the absence of this reinforcement and accountability measures could explain why the John and Kami's students played less of a role in evaluating students' ideas than in Laura's classroom.

4.2.2 Students had access to the conversational floor. In addition to specifying and reinforcing the students' knowledge-building role, I examined whether students had privileged and equitable access to the conversational floor to state their ideas when desired.

Kami: Minimal student access to conversational floor. Before the whole-class model discussion, the students had done some individual work comparing each other's models.

However, Kami did not invite the students to share their findings before or during the whole-class discussion. Rather than giving student presenters the opportunity to explain their ideas, Kami interpreted and evaluated students' ideas. Kami did invite students to evaluate the consistency of students' models with existing knowledge about gases. However, these assessments were *teacher-directed* and in response to teacher's questions (T-S, 81.1%), rather than giving students unhindered access the conversational floor to pose questions and evaluate one another's ideas (S-S, 2.5%).

John: Teacher had privileged access to conversational floor. John had privileged access to the conversational floor, as he was the first individual to pose a question for the student presenter and only opened the conversational floor to students once he completed his assessment of the presented ideas and could revoke students' access when desired. In the following example, Jackie asked Lenny to consider the implications of "more air" on air's ability to move.

Turn	Type	Interactional Units
11	S-SP	JACKIE: Um, well. If the [laughs]... If the blank was air, how are they [particles] moving? Because they're all packed in there then.
12	S-SP	LENNY: Wawawah?
13	T-0	*T: See what we're saying?*
14	S-0	JACKIE: [Is it no air or air?]
15	T-S	T: You're say[ing that blank space] is air, when technically it's just…?
16	T-S	S: Air.=
17	T-S	T: =Blank space. It can't be both things.
18	T-S	JACKIE: Yeah.
19	T-0	T: Ok? Does that make sense?
20	T-S	T: Any other questions or comments?
21	S-0	JACKIE: Wait, which one is it?

(John Observation, 12/12/11)

In response to Jackie's idea, John posed a question, "See what we're saying?" (turn 13), which signaled that John and Jackie shared the same concern. Rather than permitting Jackie to pursue her line of questioning, John revoked Jackie's access to the conversational floor, as indicated by a sequence of teacher-initiated interactions with the student presenter (T-SP) and no responses to Jackie's questions (S-0) in lines 14 and 21.

In addition to revoking student access, John also interrupted students when they had the conversational floor. In the following example, Jackie asked the student presenter whether the stopper might have compressed the air inside the flask. Before the student presenter could respond, John asked Jackie three questions to clarify what she meant by compression.

Turn	**Type**	**Interactional Units**
1	S-(SP)-T	JACKIE: In that flask, would it be kind of compression?
2	T-S	T: What's compression? I don't know what you mean, [what's compression?
3	T-S	JACKIE: [I mean, when you put the little rubber stopper on --
4	T-S	T: You mean, it's going to sound like a....
5	T-S	JACKIE: No.
6	T-S	ISAIAH: No, she's asking [if it's like pushing on it...
7	T-S	JACKIE: [Like if you push it down], would the [air be (inaudible)?
8	T-S	T: [Oh, is it compressing the air a little bit?
9	T-S	JACKIE: Yeah.
10	T-S	T: A little bit, possibly.
11	T-S	NATHANIEL: Not that much.

(John Observation, 12/12/11)

John's interruptions hindered student agency in three ways. First, John's interruptions prevented Jackie from being able to ask or clarify the intent of her question in a coherent way. Second, it hindered the student presenter's opportunity to respond to the posed question, as the teacher and another student used their interpretations of the student's model to answer Jackie's question. Rather than allowing students the opportunity to negotiate the meaning of Jackie's question and address any raised concerns, John controlled access to the conversational floor to ensure that Jackie resolved his concerns first before addressing Jackie's question.

To explain differences in the amount of attention to *audience-persuasion* and *justification*, the EC analyses revealed differential expectations for student to justify their ideas and differences in what topics were the target of persuasion. Another explanation is that the teacher did not give students with alternative opinions access to the conversational floor. For example, during the empty space debate in John's classroom, the empty space group (5 students) had access to the conversational floor to explain their arguments to the class, yet the other ten students (no empty space, 6 students; undecided, 4 students) were not given the opportunity to explain their reservations or rationales for why they thought there was no empty space in the air. Many of his students were prepared to explain their reasoning, yet did not have access. For example, one of the undecided students, Emma, wanted to explain how and why she was convinced to revise her model. However, John did not give her access to the conversational floor to explain her reasoning.

Turn	**Type**	**Interactional Units**
12	S-T	GISELLE: We… I think most of us made up our mind.
13	T-S	T: Already?
14	T-S	GISELLE: Yeah.
15	T-S	T: Wow, that was fast.
16	S-0	EMMA: I was thinking...
17	T-S	T: Alright, find a table that you want to go to.
18	T-S	Ss: [All but one student moves to empty space table]
19	S-S	TYLER: Yup, yup. That's it, that's it.

(John Observation, 12/14/11)

Laura: Students had privileged access to conversational floor. Laura's students were the first to pose questions for each student presentation. In addition, the student presenter was responsible for calling on one another, which minimized the need for Laura to mediate students' access to the conversational floor. Consequently, Laura could play a role in monitor students' participation and access to the conversational floor. For example, she ensured that diverse perspectives ("Does somebody have a model that looks a little bit different that did not get to go up?" Laura Observation, 1/31/12) and all students had access to the conversational floor ("Kevin, what was your question going to be for Lindsey?" Laura Observation, 1/27/12).

Summary. In summary, students' ability to access the conversational floor was important for supporting students' opportunities to shape the consensus knowledge of the classroom. Kami and John had privileged access to the conversational floor, as evidenced by the teacher's ability to participate when desired. In contrast, Laura's students had privileged access to the conversational floor, as evidenced by students' ability to comment on the presented ideas and the students' responsibility for allocating turns in the classroom. In addition, Laura adopted a supervisory role to ensure that all students and perspectives had access to the conversational floor.

4.2.3 Teacher maintains neutral evaluative stance. In addition to articulating the students' knowledge-building role and privileging student access to the conversational floor, a third support for supporting student agency involved whether the teacher adopted a neutral stance during whole-class modeling discussions. In doing so, the teacher was less likely to bias students' ideas and allow students the opportunity to decide for themselves whether a given claim is valid or construct their own explanation of the phenomenon.

John and Kami: Challenges with maintaining neutral stance. Challenges with maintaining a neutral evaluative stance during the discussions might have contributed to John and Kami adopting a greater knowledge-building role than intended. John attempted to adopt a neutral knowledge-building stance by claiming to restate or revoice students' ideas. In the following example, Layla argued that empty space was needed for air molecules to move.

Turn	Type	Interactional Units
1	SP-T	LAYLA: Plus, they need space — there has to be a place for them to move by one another. Otherwise, they'll keep running into each other.
2	SP-T	T: Right.
3	SP-T	LAYLA: and they won't be able to move.
4	T-S	T: We all agree that they're moving, right?
5	T-S	Ss: Right.
6	T-S	T: *So, she's saying that* for them to move, there has to be some empty space. Otherwise, you got, it's like being filled up with BB's.
7	T-S	S: Yeah.
8	T-S	T: Would there be a way for the BB's to move around in there, then?
9	T-S	S: No.
10	T-0	T: But if there is empty space, *I'm just saying what they're saying just so everybody heard it*. *They're saying that* there has to be empty space because that's how the molecules have room to move around and bump into each other, *which is what Tyler said*, right? Things like that.

(John Observation, 12/14/11)

John attempted to revoice students' ideas ("So, [Layla's] saying that" and "which is what Tyler said") and remind students that these were student ideas ("I'm just saying what they're saying just so everybody heard it," turn 10). However, his summarizing work was not completely neutral, as John lent implicit support to Layla's argument restating ideas from his previous argument that having "more air" between air particles was similar to having a flask filled with BB's (line 6). In other situations, John provided implicit signals that students' answers were incorrect while trying to maintain an impression that students were reaching conclusions on their own. For example, when John asked his students to consider whether the ability to add air into a sealed flask could support students' empty space model, his students initially stated that it would "hurt" their argument before revising their answers in response to John's "confused look" and restatement of the question (turns 4-6).

Turn	Type	Interactional Units
1	T-S	T: If I can add air in, does that help our argument that there's empty space or does it hurt our argument, for Michelle's sake?
2	T-S	Ss: Hurt.
3	T-S	T: [confused look]
4	T-S	T: If I could add air in,
5	T-S	Ss: Oh!
6	T-S	T: does it strengthen your argument?
7	T-S	Ss: Yes.
8	T-S	TYLER: Because the air is already taking up the space and you can't add more air because then it'll just blow up.
9	T-S	T: So that'll hurt her [Michelle] argument. It'll help your argument that there is empty space in there so that's where that extra air is going.
10	T-S	S: Yeah.
11	T-S	T: That's what you're saying? There would be [less empty space.
12	T-S	Ss: [Wait, wait, wait.

(John Observation, 12/14/11)

Throughout this episode, he ascribed ownership of the argument to the students and claimed to be repeating what student were saying ("That's what you're saying?"). However, his attempts to maintain a neutral stance were not always successful. For example, Tyler claimed that the class would *not* be able to add additional air into the flask because there was already air "taking up the space" inside the flask (turn 8). However, John did not accurately interpret Tyler's idea and purported to use his student's argument to advance his own argument for the presence of empty space. In summary, John was attentive to the desire for his students to be the agents responsible for constructing the knowledge through his efforts to revoice his students' ideas. However, he encountered challenges with maintaining this neutral stance, as his efforts often went beyond restating students' ideas and used students' ideas to advance his own arguments.

Kami also attempted to maintain a neutral stance by seeking to clarify the meaning of students' model features without evaluating their validity. However, there were challenges maintaining this stance, particularly when probing students' ideas about empty space. Her attention to empty space was framed as a neutral question, as she sought to understand the meaning the "white stuff" in Steven's model. By referring to these spots as "white stuff," rather than asking the question in a more neutral way (e.g., "What was between the air?"), Kami might have inadvertently signaled to students that this feature was "something" worth labeling. In addition, Kami's lack of attention to Steven's reservations about labeling the empty space and her assessment of the "goodness" of Steven's model might have led subsequent students to consider the presence of empty space in their own models -- independent of their initial ideas about the nature of this space.

Laura: Teacher maintained neutral stance. Overall, Laura was more successful in maintaining a neutral evaluative stance, as her discourse moves involved clarifying students' ideas without evaluating them, as evidenced by higher attention to *audience-clarity* than *audience-persuasion*. For example, Jerome proposed a competing model in which the air particles moved in a single direction when the Laura removed air from the flask. Although this idea was incorrect, Laura asked a question to clarify her understanding of Jerome's idea, "So you think all the arrows should be going to one place?" rather than evaluating his idea. She also adopted a neutral stance when discussing topics related to the content goal. Although Laura prompted students to think about what might be between the air, Laura did not attempt to persuade students to revise their idea if they stated that there was something other than empty space between the air.

Summary. These findings suggest differences in teachers' evaluative stances that led teachers to inaccurately represent students' ideas or lend support to one idea over another. To further enhance students' opportunities to figure things out on their own, teachers need to be aware of whether they are accurately revoicing students' ideas and ensure that it is the students, rather than the teacher, who are making decisions about the validity of students' ideas.

4.2.4 Teacher provides students with opportunity to make sense of phenomena before whole-class discussion. Previous supports for student agency involved the teacher articulating the students' role, privileging students' access to the conversational floor, and adopting a neutral evaluative stance. A fourth support involved providing students time to make sense of the phenomenon before discussing their ideas with others. For example, John's students expressed mixed responses and incorrect understandings when asked whether the class' empty space model could account for the ability to add air into the flask. One explanation is that John did not give his students time to consider their ability to apply their model before requesting their public response. In contrast, when John gave his students time to individually construct their initial air models and discuss their ideas in small groups, they were better able to defend and justify their initial air models during the whole-class discussion. In Laura's classroom, this individual sensemaking time allowed students to consider how their models aligned with other and to use their own models in the context of argumentation. For example, Lindsey used her air models to argue against the presence of water vapor. However, providing students with individual sensemaking time alone was not sufficient for supporting students' participation in argumentation. For example, Kami's students had the opportunity to construct their diagrammatic models for each situation, yet could not participate productively in the evaluation of students' ideas without access to the conversational floor.

4.3 Phase 3: How were students' ideas used during instruction?

In Section 3.2, I found that John's emphasis on students getting the right answer could explain why there was more attention to *audience-persuasion* during topics related to the content goal. In contrast, the distribution of topics was more open-ended in Laura's classroom. In this section, I use the *epistemic agency* lens to explain why discussions were more open-ended than others. For this analysis, I first analyzed what proportion of the *nature of account* discourse involved discussions related to the content goal — particularly during the target activity structure, where students and teachers both had the opportunity to influence the trajectory of the discussion (see Table 6.8). Due to the enactment differences, I did a separate analysis of John and Laura's initial air discussions from the aggregate whole-class data.

Table 6.8
Proportion of nature of account discourse related to content goal

Classroom	Initial Air Model	All Whole-Class
John	59.2%	61.8%
Kami	*	30.6%
Laura	5.3%	7.0%

* Kami discussed all three models together, so I was unable to tease apart discussions of students' initial air models.

During all whole-class discussions, the proportion of attention to topics related to the content goal was 61.8% in John's classroom, 30.6% in Kami's classroom, and 7.0% in Laura's classroom. When I limited this analysis to the initial air model discussions, the proportion of *nature of account* discourse decreased slightly to 59.2% in John's classroom and 5.3% in Laura's classroom. I identified two factors that could explain why John's discussions were more focused on the content goal when compared to Laura's classroom. Since the teacher was aware of the lesson's content goal, there might have been more attention to the content goal if the teacher, rather than the students, played an active role in directing the trajectory of the discussion. Second, the extent to which the conversation was open-ended could be determined by the teacher's understanding of the timeline and trajectory for helping students reach the conclusion about the particle nature of matter.

4.3.1 Relationship between agency and attention to content goal. The findings suggest that when the teacher had a greater role in evaluating the presented ideas, there was more discussion of topics related to the content goal. Although Kami and John were the primary agents responsible for evaluating student ideas, there was approximately 50% less attention to topics related to the content goal in Kami's classroom than in John's classroom. One explanation was that Kami's attention to empty space was framed as a representational question to understand the meaning of students' ideas without considering the explanatory significance or validity of this idea. Thus, there would be less attention to these topics if there was less discussion justifying, defending, or persuading others about the presence of empty space. In contrast, John's actions showed evidence that he wanted his students to have empty space in their models by the conclusion of the focus lesson, as evidence by the topic analysis of the initial air model discussion, the empty space debate, and the use of the contrasting air behaviors for justifying the empty space model.

I argue that there might have been less attention to empty space in Laura's classroom because students were unaware of the content goal for the investigations and had agency to pursue topics they found problematic or worthy of discussion. In addition, there was nothing in the flask scenario that would have compelled them to consider this non-intuitive idea. It's not to say that there were not any discussions related to the content goal, as Laura asked her students about what might be between the air. Unlike John, Laura did not attempt to revise students' models if they claimed that there was "something" other than empty space between the air. In the following example, Jade questioned whether it was possible to have less air after the teacher removed some air from the flask, as it would mean that there would be some "random amount of no air" (turn 4) between the air.

Turn	Type	Interactional Units
1	S-SP	JADE: How is there less air? Isn't air, like air?
2	S-SP	JESSI: No, for the second one, there's less, where we took some air out there's less air, then for the third one, there's just more air...
3	S-0	S: We didn't see the first one up there.
4	S-SP	JADE: Isn't there like the same (cloud/amount) there? You can't like... I mean I guess if you take air out, there's less air, but like it's like empty like in-between, a random amount of no air.
5	S-SP	JESSI: Well, I put, you can't really see it.
6	T-SP	T: Yeah, so what's in-between? I hear what you're saying. It still is air.
7	T-S	JADE: [inaudible response]
8	T-SP	T: but what's in-between then the air?
9	T-SP	JESSI: Like, dust particles. I drew it here but you can't really see it up there. I drew a bunch of dots as dust particles.
10	T-SP	T: So, what's in-between one dot and another dot?
11	T-SP	JESSI: Air...
12	T-S	Ss: Air? Air?
13	T-SP	JESSI: and stuff.

(Laura Observation, 1/31/12)

Once Jade raised the possibility of having empty space between the air, Laura posed a follow-up question to Jessi about the nature of the space between the air, "Yeah, so what's in-between [the air]?" (turn 6). Laura did not attempt to persuade Jessi to revise her idea after Jessi responded that she thought there was more air and other stuff (e.g., dust particle) between the air. In doing so, Laura maintained students' position as the agents responsible for figuring out the explanatory significance of empty space in their models.

In summary, each classroom teacher probed students' ideas about the nature of the space between the air, yet there was more attention to topics related to the content goal in classrooms where the teacher was the primary agent responsible for evaluating students' ideas. To understand why discussions were more focused on the content goal in teacher-directed classrooms, I examined what guidance teachers might have received in the curriculum materials for enacting the focus lesson.

4.3.2 Challenges involved in teachers probing students' ideas while supporting student agency. Since the topic of empty space was not an intuitive idea for students, the curriculum materials encouraged teachers to ask students about what might be between the air to prompt them to consider the idea as something worth discussing (See Chapter 4, Section 3.3). However, the intent was for teachers to use these prompts to explore and clarify students' ideas rather than point students to the correct answer.

> It may be tempting to rephrase what Ss [students] are saying, but the goal is to get Ss to clarify what they are thinking by asking them questions. You want to determine what Ss are thinking and explore their ideas, not give them the correct model. These activities are designed to clarify Ss ideas throughout the unit, with the expectation that the Ss' ideas will change as they observe new phenomena. (Krajcik, Merritt, et al., 2013, pp. 4, Lesson 4)

However, teachers might have found it challenging to balance the responsibilities for probing students' ideas about the nature of the space between the air with privileging students' opportunities to use evidence from the phenomena to reach their own conclusions about the space between the air. In contrast, students who did not have knowledge about the lesson's goals might not have been biased towards one set of ideas over another.

4.3.3 Teachers' understanding of the timeline and trajectory for achieving epistemic aim. There were no curricular expectations for students to conclude that there was empty space between the air by the conclusion of the focus lesson; rather, students were to use evidence from the unit's activities to develop this idea over time. In this section, I explore how teacher's interpretations of the trajectory and timeline for developing the particle model of matter might explain differences in teachers' attention to the content goal during the focus lesson. Since Kami and Laura had more experience using the curriculum than John, they might have had a better understanding for how students would use subsequent contrasting phenomena to collect evidence for the particle nature of matter, while John was not aware or attentive to the curricular trajectory for achieving this goal. As such, John might have wanted his students to have the correct model for this phenomenon before moving to the next lesson.

In addition to this knowledge of the curriculum, I argue that Laura's commitment for students to figure things out on their own was important for supporting student agency in the classroom. For example, it was important Laura's students, rather than the teacher, to be the first to raise the potential of empty space between the air so that they would "own" their conclusions, "I could even say it, like, I don't know, "Is that really something there?" And then, as soon as somebody gets it, then their view is in then" (Laura Interview, 4/26/12). In addition, Laura was prepared with a range of strategies to compel students to think about the presence of empty space on their own.

> So, then I think then we go back to the idea of the balloon or the compression/expansion of a syringe and say, like, so if we make that bigger but we didn't add any more, then what could be there? […] And then if that didn't work, I would have like a bunch of kids be the molecules and spread them out. (Laura Interview, 4/26/12)

Without this experience and curricular knowledge, it might be challenging for teachers to give students agency to reach the conclusions on their own without a clear understanding of trajectory for achieving the desired epistemic aim and assurance that students would be able to reach this conclusion on their own. During the end-of-unit interview, John acknowledged his frustration with his students not adopting a more active knowledge-building role, yet acknowledged his role in limiting students' opportunities to figure things out on their own.

> I think I told them too much maybe or having time constraints with class periods and stuff like that just instead of letting them hash it out for a couple days. […] So, maybe I chimed in too much as opposed to letting them figure it out and again having the first time taught this — kind of figuring out what my role is. (John Interview, 3/23/12)

John cited perceived time constraints and a lack of familiarity with the curriculum as reasons for why he might not have allowed students more opportunities to figure things out on their own. Teachers using a curriculum for the first time might focus on day-to-day planning rather than attending to the overall goals of the unit and how each lesson contributes to achieving the desired goal. John's activity framing showed evidence of understanding how students could use their models to explain other situations and the pedagogical rationales for using the contrasting air behaviors to support the idea of empty space. However, there was more emphasis on students reaching consensus about the presence of empty space rather than developing a robust understanding of the explanatory significance for this idea.

4.3.4 Summary. Section 4.3 examined the factors that could explain why there was more discussion about issues related to the content goal in John's classroom compared to Kami and Laura's classroom. Because the teacher was aware of the content goal and responsible for probing students' ideas about what might be between the air, it was easy for teachers to adopt more traditional knowledge-building roles and persuade students about the presence of empty space. In contrast, students might have been less likely than the teacher to be biased towards attending to topics related to the content goal. Secondly, I considered how the teacher's understanding of the timeline and trajectory for achieving the epistemic aim could have influenced their expectations for what students were to have figured out by the conclusion of the focus lesson. Less experienced teachers might not have understood the pedagogical rationales for using the unit's activities to test and revise students' ideas about the presence of empty space. By focusing on achieving the content goal by the end of the focus lesson, John sacrificed opportunities for students to figure this idea out on their own, an observation that he recognized was a weakness in his enactment of the unit. In contrast, Laura expressed the most explicit commitments for her students to figure this idea out on their own and its importance for "owning" the knowledge. As such, there was less emphasis on discussing topics related to the content goal because the teacher might have understood that there would be multiple opportunities for students to test and revise their ideas over time.

4.4 Epistemic agency summary

The epistemic agency lens examined the successes and challenges of supporting students' opportunities to construct and evaluate one another's models to reach consensus. I examined the patterns of interaction and relative attention profiles to characterize students' and teachers' knowledge-building roles. Next, I explored how the presence of classroom supports could explain differences in the students' participation roles. I found that students were more likely to have an active knowledge-building role if 1) the teacher specified and reinforced the value of students' knowledge-building role, 2) the students had equitable access to the conversational floor, and 3) the students had the opportunity to individually make sense of the phenomena before discussing their ideas with others. In addition, teachers maintaining a neutral evaluative stance during the whole-class discussions was important for allowing students to figure things out on their own without bias from the teacher. The last analysis examined the factors that could explain why discussions were more open-ended in Laura's classroom than in John and Kami's classroom. There were challenges involved with teachers balancing the responsibility for probing students' ideas about empty space, while privileging students' opportunities to use the designed sequence of phenomena to develop their ideas on their own. I argue that there were two factors that enhanced student agency during classroom discussions: 1) teacher's understanding of the trajectory for achieving the epistemic aim and 2) the teacher's commitment for students to figure things out on their own and why it was important.

Chapter 7: Discussion of Successes and Challenges

Study 1 involved using the analytical lenses of epistemic aims, considerations, and agency to investigate the successes and challenges involved in using an activity structure designed to enhance students' opportunities to construct and evaluate one another's ideas. Through participating in the construction and evaluation of knowledge, students would learn science-as-practice by developing an understanding of how to use scientific practices in meaningful ways to construct robust disciplinary knowledge. I divide this discussion into three parts. The first part discussed the challenges related to the meaningfulness of the epistemic aim and the scientific practices used to achieve those epistemic aims. The second part uses three analytical lenses to examine the epistemic challenges involved in persuading others. The third part attempts to explain the observed differences in the students' knowledge-building roles.

1. What's the epistemic aim guiding our work?

1.1 Meaningfulness of epistemic aim

The epistemic aim lens examined the meaning that students applied to the epistemic aim and the practices used to achieve the epistemic aim. There was observed variability in the amount of guidance teachers provided to justify the epistemic value of classroom activities and how they were coherent with prior learning. These findings have implications on how we support students' participation in phenomenon-based instruction, particularly when students are engaged in a sequence of investigations that likely involve different phenomena contexts to answer a driving question. For example, Kami did not discuss the rationale for why students were engaged in the air investigations during the focus lesson. During the next lesson, Steven questioned the epistemic value for engaging in a subsequent investigation to investigate two additional air behaviors.

Turn	Type	Interactional Unit
1	S-T	STEVEN: What does a syringe have to do with smelling, "How can I smell different things in your body?"
		[…]
4	T-S	T: Why are we learning about air?
5	T-S	CALLIE: Cause you told us to.
6	T-S	T: Shh.
7	S-S	STEVEN: Yeah.
8	T-S	T: Why are we learning about air? What does air have to do with odors? Does anyone know?
9	T-S	STEVEN: But wait, but no, [this experiment has nothing to do with odors.

(Kami Observation, 2/6/12)

This excerpt highlights the consequences for teachers not attending to the meaning that students apply to their knowledge-building work and its relative importance for promoting shifts towards meaningful science learning for students.

1.2 Who are models for?

Diagrammatic models are useful tools for mediating students' sensemaking work with others, such as helping students think about their theoretical ideas for explaining the phenomenon and communicating those ideas to others. There were observed differences in the ways that teachers framed the use of diagrammatic models as tools to support students' own learning. Schwarz and White (2005) found that explicit attention to metamodeling knowledge, or the knowledge about the nature and purpose of using models, had a positive effect on students' inquiry skills and physics content knowledge. Taken together, these findings suggest that teachers making explicit this metamodeling knowledge could enhance the meaning that students apply to their scientific work, as students not only could understand how models could be helpful in the context of the scientific endeavor, but also how diagrammatic models could help *them* accomplish *their* scientific goals.

However, verbal statements alone cannot promote meaningful use of diagrammatic models; rather, these statements need to be coupled with students using diagrammatic models in service of achieving some broader goal. Although Kami explained how scientists used diagrammatic models in the context of their work, the observed model discussions focused on refining students' ability to represent their ideas to an external audience rather than to discuss the validity of students' ideas or make sense of the phenomenon. Similarly, Passmore et al. (2014) found that students and teachers often focus on the constructing representations rather than using models to discuss one's explanatory ideas. From Kami's perspective, this was a scientifically meaningful task, as *she* understood how and why this skill could be applied within the context of her understanding of the scientific endeavor, yet the context of her students' use was not in the context of supporting their scientific work. Alternatively, students could have refined their representational skills in the context of using diagrammatic models to reach consensus with others. Edelson (2001) made similar arguments in his Learning for Use framework, in which students derive meaning from knowledge when they understand how it will be used. In doing so, students recognize the importance of labeling students' models not because their teacher told them to do so or because scientists do it, but because it helps them communicate and reach consensus with their classmates. In addition, they might learn how to better represent their ideas because their classmates might have difficulty understanding their ideas, which might prompt them to consider what features to include to help their audience understand their ideas better.

2. Epistemic challenges related to persuading others

In this section, I build on the successes and challenges identified in the previous chapter to consider how synergistic analysis of the same enactment using the different lenses could provide a more complete explanation of the observed findings and suggest potentials solutions to resolve identified issues.

2.1 What epistemic aim guiding the discussion of students' diagrammatic models?

The findings from this study support research suggesting that helping students understand the epistemic aim and considerations that should guide their work could enhance students' knowledge-building role. I argue that the presence of a consensus-building epistemic aim in Laura's classroom provided meaning for why students were explaining their ideas or asking one another questions and enhanced student agency by creating a need for students to respond to and build on one another's ideas (Berland & Reiser, 2011). In addition, students had the epistemic authority to assess their progress towards investigating the driving question and make informed decisions about whether more work was needed to achieve it.

(Ford, 2012) argued that foregrounding students' role in constructing and evaluating knowledge of construction and evaluation of knowledge, rather than the resulting explanation itself, focuses the work on sensemaking and allows the achievement of the epistemic aim and the development of a grasp of practice to emerge. However, this study's findings show that it can be easy for teachers to focus on the work that students are engaged in rather than why this work is important or what goal they are working towards. For example, the absence of an epistemic aim guiding the evaluation of students' models in John and Kami's classroom hindered student agency because they did not have a clear idea about what goal should be guiding their work. Without this guidance, students were dependent on the teacher for cues for evaluating students' models rather than having an epistemic aim or question to guide their work. Based on the topics that the teacher raised about the students' models, students could infer that the lesson goal involved understanding students' ideas in Kami's classroom and having students reach consensus about empty space in their models during the initial air discussion in John's classroom.

Furthermore, the provided epistemic criteria were general and not directly applicable for investigating the target phenomena. Although there were no explicit epistemic considerations discussed when Laura framed the activity, the consensus-building epistemic aim informed what epistemic considerations were important for jointly achieving students' epistemic aim with others, such as students needing to use evidence and argument to reconcile competing ideas and reach consensus with their classmates. Thus, the epistemic aim of reaching consensus about the phenomena along with explicit attention to who was responsible for achieving this epistemic aim was critical for supporting students' position as epistemic agents in Laura's classroom.

In the focus lesson, the students constructed models to explain contrasting air behaviors to collect evidence to support the particle nature of matter. There were differences in the goals guiding the discussion of students' models that had implications for the robustness of students' understanding of the explanatory significance of the particle nature of matter and students' position as epistemic agents in the classroom.

Laura's model discussion was guided by the goal of reaching consensus with others. As such, students' efforts to share and discuss one another's ideas in Laura's classroom and use evidence to justify, defend, and reconcile competing ideas was *in service of* developing a consensus understanding of the phenomenon with others. This consensus-building epistemic aim also supported student agency because the students were positioned as the agents responsible for assessing the validity of one another's ideas and asking questions to press for further clarification or evidence to be convinced of a given claim.

In John's classroom, the epistemic aim guiding the model discussions involved persuading students of the presence of empty space between the air rather than considering the explanatory significance of this idea as a part of a coherent set of ideas for explaining the phenomenon. This focus on students having the "right answer" led to less need for students to justify their claims about empty space and the teacher overlooking challenges that students had with applying the empty space model or evidence of inaccurate understandings. Taken together, the push towards having the correct model components led to challenges related to meaningful practice, as students might be persuaded to have empty space in their model, yet not have a complete understanding for why this idea is true or valid.

Furthermore, the goal of persuading students about the right answer might hinder student agency for several reasons. First, achievement of this goal does not require students' involvement, as the teacher could easily adopt the role of evaluating students' ideas. Second, there were no observations from initial air model task that would have provided evidence to compel students to think about the presence of empty space. Thus, the teacher's efforts to press students to draw conclusions about the validity of empty space came from the teacher rather than from students themselves. In other words, there was nothing in the phenomenon that would have compelled students to think about the potential explanatory role of empty space without intervention from the teacher. In contrast, Laura pressed students to think about the presence of empty space in the context of explaining the contrasting air behaviors, where the idea had explanatory significance. To support student agency, Laura created a space for students to reach this conclusion of their own as they tested their model's ability to explain subsequent contrasting phenomena.

2.2 Importance of attending to audience-clarity

Curricular scaffolds like the claim-evidence-reasoning framework (e.g. McNeill et al., 2006) could help students and teachers identify what components are needed to construct an evidence-based argument. However, this study documented the ways in which attending to the epistemic considerations, rather than the structural aspects of argumentation, were important for guiding and improving students' ability to engage in argumentation. Although implicit or explicit attention to issues related to the *audience-clarity, audience-persuasion,* and *justification* considerations individually could be useful for identifying the epistemic challenge related to persuading others, I argue that the study's findings showed the importance of recognizing and leveraging synergies between these three epistemic considerations (see Figure 7.1) to enhance students' ability to construct persuasive arguments.

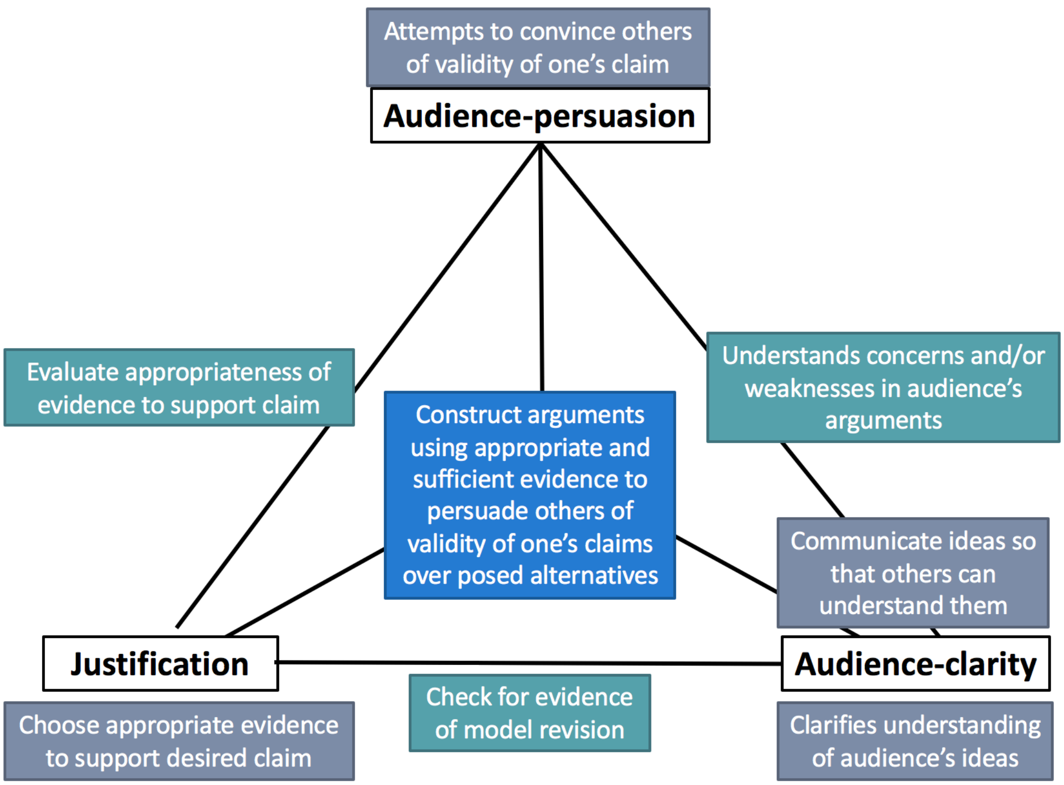

Figure 7.1. Synergies between audience and justification considerations for persuading others.

The grey boxes describe the epistemic issues posed by the individual epistemic considerations, while the green boxes show what happens when students and teachers attend to more than one EC. For example, when student jointly attended to issues related to *audience-persuasion* and *justification*, students might choose evidence that is appropriate for supporting a given claim. When students jointly attend to issues related to *audience-clarity* and *audience-persuasion*, the persuaders ensure that he understands the issues or concerns preventing others from being convinced of a given claim and accounts for those concerns when constructing an argument. For example, John attempted to persuade Michelle of the presence of empty space by explaining how the ability to account for an additional phenomenon could provide further justification for the class' empty space model. From a scientific perspective, this argument leveraged sophisticated understandings of the generatively of knowledge and its usefulness for explaining multiple situations. However, John's argument did not address or resolve Michelle's concerns about the empty space model, which involved questioning the ability to remove air from the flask without changing the volume of air. Although Michelle's concerns certainly involved the presence of empty space, John's lack of attention to issues related to *audience-clarity* led him to construct an argument that did not address Michelle's actual concerns and did not contribute towards convincing Michelle of the empty space model's validity.

By jointly attending to these three epistemic considerations, as shown in blue, students might be more likely to be persuaded because the argument uses evidence that addressed concerns that hindered students' attempts to accept the validity of one's claim. For example, Laura's students were better able to persuade others of the plausibility of water vapor in the air because they took the time to first understand the students' concerns and propose an alternate set of mechanisms and perceived indicators that could explain why there could be water vapor in the air despite the inability to "feel" it.

This study also reinforced the importance of the persuader checking for and responding to evidence of model revision to identify further issues requiring clarification or model revision. This step is reflected in the side of the triangle between *audience-clarity* and *justification.* For example, Laura and her students checked for evidence of model revision by asking students to explain whether their concerns had been addressed and to explain their rationales. Although John checked for evidence of model revision, he did not probe Lenny's justification for why he rejected the reformulated claim or explain why he was still not persuaded of the presence of empty space in the model. Thus, checks for model revision during and after an argument might be helpful for preventing misinterpretation about students' understanding and inform next steps for persuading others. Furthermore, checking for evidence of model revision supports students' epistemic authority to assess the validity of the consensus knowledge and make decisions about whether further work is needed to achieve the desired epistemic aim.

2.3 Benefits of inviting diverse perspectives during argumentation

The presence of a consensus-building epistemic aim could enhance student agency because it created a need for student participation (see Section 2.1). At the same time, the study's findings demonstrated the importance of granting students access to the conversational floor and how access to diverse perspectives could enhance students' ability to reconcile competing ideas and reach consensus. For example, John's attempts to persuade Lenny by reformulating his idea of "some air" between the air was unsuccessful. However, when another student, Jackie, was given access to the conversational floor, she better communicated John's argument by 1) making visible the connection between "some air" and having the flask being packed in with air and 2) explaining that there could be not be some air because it would prevent the air from being able to move. By opening the conversational floor to others, John afforded his students the opportunity to address weaknesses in his own argument and jointly accomplish a shared goal. As another example, Hillary and Sally used appropriate reasoning to convince Lindsey of the presence of water vapor, Lindsey cited Sally's argument as the rationale for why she was ultimately convinced to revise her model. Taken together, these findings provide evidence for why giving students with diverse perspectives access to the conversational floor is important for helping students reconcile students' diverse needs and concerns and allow the classroom community to reach consensus.

2.4 Implications: Teachers' use of ECs

This study leveraged Berland et al. (2016)'s ECs as a lenses for understanding the successes and challenges involved in constructing and evaluating students' explanatory models. Using these findings, I argue that teachers could use the issues posed by Berland et al. (2016)'s ECs to identify and respond to epistemic challenges that emerge to enhance the meaningfulness of student's engagement in argumentation. For example, if students are stating that their idea is right while the other side is wrong, the teacher might press students to articulate the justification used to support their own claims and how their ideas align with those of others. In doing so, students might identify weaknesses in competing arguments and consider how their own model might account for those concerns and explain the phenomenon. If students report that they don't know the evidence that could be used to support a claim, teachers might recognize the need to help students coordinate claims with evidence that the students have collected during class activities.

3. Supporting student agency

It was not a challenge for teachers to buy-in to the goal of positioning students as the agents responsible for constructing knowledge or trying new methods. For example, John reminded his students that the new curriculum required students to explain and justify their ideas rather than passively receive knowledge.

Turn	Type	Interactional Unit

1	T-S	T: You need to explain things. I warned you guys about the new curriculum, right? There's a lot of reading and there's a lot more?
2	T-S	S: Writing.
3	T-S	T: Writing. And you're going to have to write detail – in depth things.

(John Observation, 12/14/11)

Kami and her fellow teachers codified this shift in knowledge-building responsibility by regularly posing the question, “I don’t know. What do you think?” (Kami Interview, 11/9/11). Despite this awareness, there were challenges with enacting these shifts in knowledge-building responsibility.

The curriculum materials communicated expectations that the students should be the agents responsible for constructing knowledge in the classroom. Although the teachers were to probe students’ ideas about the space between the air, teachers were supposed to give students the opportunity to figure things out on their own. What can we learn from these teachers’ experiences to help teachers design learning experiences that respond to and advance students’ understanding, yet support students’ opportunities to figure things out on their own? I argue that teachers should attend to three important factors to enhance students’ knowledge-building role: 1) teachers should understand how their role is distinct from, yet complementary, to the students’ knowledge-building role; 2) teachers should be continuously aware of the distribution of knowledge-building responsibilities between the teacher and students; and 3) teachers should leverage activity structures that explicitly privilege students’ opportunities to construct and evaluate scientific knowledge with one another.

3.1 Lack of clarity on teacher’s role

An important finding from this study is the need for teachers to cultivate a vision for how their role must change when implementing reform instruction and how it is distinct from and supportive of the students’ knowledge-building role. It was not enough for teachers to state expectations or enact lesson plans that position students as the agents responsible for evaluating one another's ideas. Without explicit expectations for what the teacher would be doing in support of the student's role, there was nothing to prevent teachers from defaulting to more traditional and perhaps familiar knowledge-building roles and discourse patterns (Mehan, 1985). Given Kami and her students' role as joint participants in their communities of scientific practice, there was attention to what the participants as a group would be doing rather than distinguishing between the students' or the teacher's roles. Without any distinctions or clarifications about who was responsible for constructing knowledge, there were no norms or expectations to prevent the teacher from dominating the model discussion. Similarly, John argued that his lack of clarity of what his role is in the classroom should be when adopting these new practices likely contributed to him adopting a more traditional knowledge-building role than he had intended.

In contrast, Laura was more explicit about the nature of her role and how it would complement the students' role. She explained that she would be tracking the students' participation and conversation by "listening for students' questions," which also signaled that the students would be responsible for asking the questions. In addition, she physically positioned herself to the periphery of the classroom, which was an implicit reminder that the students, rather than the teacher, would be the student presenter's audience. However, this secondary role did not mean that she was not involved during the discussion. At times, she chimed in to clarify students' ideas or press students to justify their ideas. She prompted students to think about the nature of the space between the air, yet was committed to her students being the agents who first considered the plausibility of the presence of empty space. In doing so, she might have brought attention to the issue, yet sequentially positioned her follow-up questions and responses to build off a student's idea or question. Without monitoring the conversation, she would not have been able to identify entry points to help students make progress in their explanations and consider the role of empty space for explaining the phenomenon.

3.2 Awareness of distribution of knowledge-building responsibilities

In addition to specifying the nature of the teacher's role, teachers need to be explicitly aware of who has access to the conversational floor to ensure that the students, rather than the teacher, have privileged access the conversional floor. Although the contribution of student-initiated discourse was smaller than the teacher-initiated discourse in John and Kami's classroom, the students' relative attention profiles showed evidence of attending to important epistemic issues when they were given the opportunity to participate. Thus, John and Kami's students could have adopted a greater role in shaping the classroom knowledge had the teacher recognized that the teacher, rather than the students, was dominating the classroom discussion and not giving students the space to participate.

Creating opportunities for John to reflect on his students' participation resulted in him considering how his decisions might have hindered his students' opportunities to engage in the work and consider what he might have done differently, "And the more you go through it, teacher wait time kind of thing, they're all looking at you waiting for the right answers so to speak. I'm not going to give it to you. […] Eventually someone will say something" (John Interview, 3/23/12). This reflection opportunity prompted him to think about wait-time strategies that could place the onus of responsibility on the students, rather than the teacher. John's reflections suggest that sensitizing teachers to attend to the distribution of knowledge-building responsibilities and how their actions support or hinder students' opportunities to participate in the knowledge-building work could enhance students' knowledge-building role.

In addition to being aware of who has access to the conversational floor, van Zee and

Minstrell (1997) argued that teachers need to respond to students' ideas in a neutral way to ensure that students can assess the validity of a given idea for themselves. However, it was challenging for teachers to maintain a neutral evaluative stance. For example, John's attempts to revoice students' ideas sometimes extended or emphasized ideas. Thus, teachers need to also be aware of how they are using students' ideas to ensure that they are not extending or reformulating students' ideas and to privilege students' opportunities to deliberate between alternatives.

3.3 Trajectory for achieving epistemic aim

While teachers should be aware of the distribution of knowledge-building responsibilities between the teacher and student, it was also important that teachers to plan and enact sequences of instructional activities that allow students to test and revise their ideas in service of developing a target explanatory model. Since each teacher had access to the same curricular resources, classroom differences in students' position as epistemic agents could be explained by teachers' interpretation of goals for each activity and how they would be used as a coherent sequence of instruction to achieve the desired learning goals. There are various ways in which teachers develop this *curricular knowledge*, or an understanding of what curricular resources are available and how to use them to achieve one's goals (Shulman, 1986). Researchers have argued for the inclusion of *educative features*, which Davis et al. (2014) defined as "text and graphics that [could] be incorporated into curriculum materials with the intention of supporting teacher learning" (p. 25), to help teachers correctly interpret the pedagogical rationales for activities and understand the principles guiding the curriculum's design.

Although the IQWST materials had existing educative features to support practices-centered instruction, the study's findings suggest the need for educative features to help teachers understand what students are expected to figure out during each part of the lesson, what questions students are likely to pose, and how students could build on prior learning to develop aspects of the explanatory model over time. This curricular knowledge might encourage teachers to give students more freedom to figure things out on their own if they understood how the curriculum was designed to help students develop robust understandings without needing the teacher to tell them the right answer. For example, when John's students discussed their initial air models, John might not have pressed his students to make conclusions about the presence of empty space had he known that the sequence of contrasting phenomena were deigned to elicit and develop this non-intuitive idea over time. Furthermore, the empty space debate could have been used more productively later in the unit after the students collected additional evidence to support this idea. In addition, educative features might help teachers navigate the challenge of adopting a neutral evaluative stance during classroom discussions by providing examples of prompts to facilitate student discussion or common pitfalls that teachers might encounter, such as the difference between revoicing and reformulating students' ideas. Thus, the presence of educative features could be useful for helping teachers operationalize their desire to promote student agency in the classroom and promote shifts in students and teachers' classroom practices.

3.4 Developing culture for supporting students' knowledge-building work with others

Of the described factors, the study's findings suggest that the teacher's commitment to designing and using instructional supports that privileged interactions between students was a critical factor for supporting a student directed classroom. In many ways, this commitment guided the teacher's interpretation of the curriculum's goals and the means to realize the goal of positioning the students as epistemic agents in the classroom. During the post-interview, Laura shared how she designed and implemented scaffolds to support the development of a classroom culture that promoted student agency.

> So, I mean, just at different points, I do different things. But at some point, I want them to say something, and it doesn't matter what they say. And then at other points, at least, like I will give them the paper, and it says, like, “What did somebody else say?” and “What could you have contributed if you had more time?” […] I don't do that sheet right away, because I think that builds too much stress. So, at first, it's just, “I just want to hear from everybody,” and I want to hear — I will just do like a little checklist for myself so that those didn't talk I can talk to and say, “I need to hear your voice.” (Laura Observation, 4/26/12)

The discussion sheet could enhance and support students’ participation in argumentation, because it could sensitize students to the need to attend to and respond to one another’s ideas and consider how they might do so in the future if they did not have the opportunity to voice their ideas during the discussion. At the same time, she expressed the challenge accomplishing this goal, “It’s hard to pull all these new things in sixth grade, so it takes a little while to get there.” For example, her initial goal involved encouraging all students to participate. She recognized that the teacher keeping an informal checklist, rather than asking students to record their questions, might be a more accessible way to encourage student participation and establish norms that supporting student agency.

In addition to encouraging student participation, meaningful engagement in argumentation requires epistemic aims that create a need for students to attend to and respond to one another’s ideas (Berland & Reiser, 2011). The establishment of a consensus-building epistemic aim in Laura’s classroom created a need for students to engage with and pose questions about one another’s ideas. Furthermore, Laura explained how she leveraged IQWST activities that created a need for students to work together as part of scaffolding the development of this classroom culture.

> I think with the beginning, with the light unit, […] I like the lab where you put the different objects in different places and you know, I think they kind of work together. It's

> not, "Everybody's going to get the same answers." They had to listen to other people as to, "Oh, that's right. You saw it over there, but I couldn't." (Laura Interview, 4/26/12)

In addition to designing activities that create a need for students to engage with one another's ideas and encouraging student participation, Laura citied the importance of normalizing differences in students' ideas so that students felt comfortable sharing their ideas with others. Hogan and Corey (2001) and Herrenkohl and Guerra (1998) have argued that classrooms need norms that encourage students to voice their opinions without fear of being wrong or personally criticized. One way that Laura did so was to encourage students to brainstorm their ideas for explaining the phenomenon rather than worrying about the correctness of their ideas, "There's no right or wrong right now. Right? We're just kind of trying to figure out what it is. What would we see?" (Laura Observation, 1/27/12). Laura normalized the model revision process by reminding students that their ideas likely would be revised as they learned new information., "Like, it's not like we grade you on the first one. Right? And that's how life is. It's continually learning and going through" (Laura Observation, 1/31/12).

In addition, Laura called out instances of student disagreement to signal to students that differences of opinion were expected and valued. In doing so, it might help students feel more comfortable voicing their ideas, regardless of whether others might agree with them.

> And then, I think just when someone says something that they don't agree with, like the first week, I think I am just very quick to say, "That's great. You should have your own opinion and that's what we want to hear. And so, does anybody else have a different opinion?" And then, as they keep hearing me say the same thing, that everybody has their own sense of it and that I'm not rushing through it, they just learn that that's how it's going to be in the class. (Laura Interview, 4/26/12)

Normalizing and praising differences in opinion were also evident in Kami and John's classroom. Kami praised the different ways in which students sought to represent their ideas about air, "So, everybody has a slightly different way of looking at it" (Kami Observation, 2/2/12). Kami also discussed her attempts to create norms that supported the discussion of students' ideas, "And if someone says, 'Well, I think so-and-so should have done whatever,' I'm like, 'We don't care who did it. Can you say that again in a way that talks about the model rather than the person?'" (Kami Interview, 11/9/11). Similarly, John cautioned his students against attacking or criticizing others, "Remember, this is not an attack to make someone feel small about themselves. Okay? This is evaluate — using these criteria and what we've done as a class — thinking about the evidence and challenging people to think things in different ways" (John Observation, 12/12/11). By privileging the use of epistemic criteria to evaluate students' ideas, the students' attention would be more focused on the ideas rather than the individuals posing the ideas.

4. Conclusion

In summary, this section explored how the cultivation of a classroom culture in support of student sensemaking was critical to supporting the students' role as epistemic agents. It was not enough simply to communicate expectations for students to participating in the knowledge-building work; rather, Laura used routines, such as the use of discussion question lists, and strategic use of classroom activities that created a need for students to work with one another to scaffold the development of this culture over time. There was evidence that all three teachers attempted to minimize the stigmatism about differences in opinion or articulating the "wrong answer" by focusing on the objective ways to evaluate one another's ideas rather than the students' themselves. Taken together, these norms support a culture in which students feel comfortable sharing their ideas with one another in service of advancing the consensus knowledge of the classroom community.

In summary, this study's findings suggest that this analytical framework could be useful for analyzing the extent to which students are using scientific practices in meaningful ways and understanding the successes and challenges involved in promoting shifts in students' and teacher's classroom practices. I sought to argue in this chapter how synergistic use of the analytical lenses could provide a more complete understanding of the issues involved in promoting meaningful scientific practice in classrooms (see Figure 7.2). For example, achievement of a consensus-building epistemic aim is enhanced when students and teachers jointly attend to issues related to Berland et al. (2016)'s epistemic considerations to ensure that students' approaches to persuading others are responsive to students' ideas and concerns. In addition, providing opportunities for students to engage in the knowledge-building work could enhance students' ability to persuade others, because it provides additional perspectives that might be more effective at persuading others. Encouraging students to attend to one's audience when constructing one's arguments (*ECs*) could enhance students' epistemic authority (*agency*), as it positions the students as the agents responsible for assessing what counts as scientific knowledge and whether the class had achieved the desired epistemic aim. In addition, there are additional synergies between the epistemic aim and agency, because if the goal is for students to be involved in the work, there should be something in the phenomena or question that compels students to investigate the phenomenon. Thus, teachers need attend to make explicit the epistemic value for this activity and how and why it is important for students' own learning.

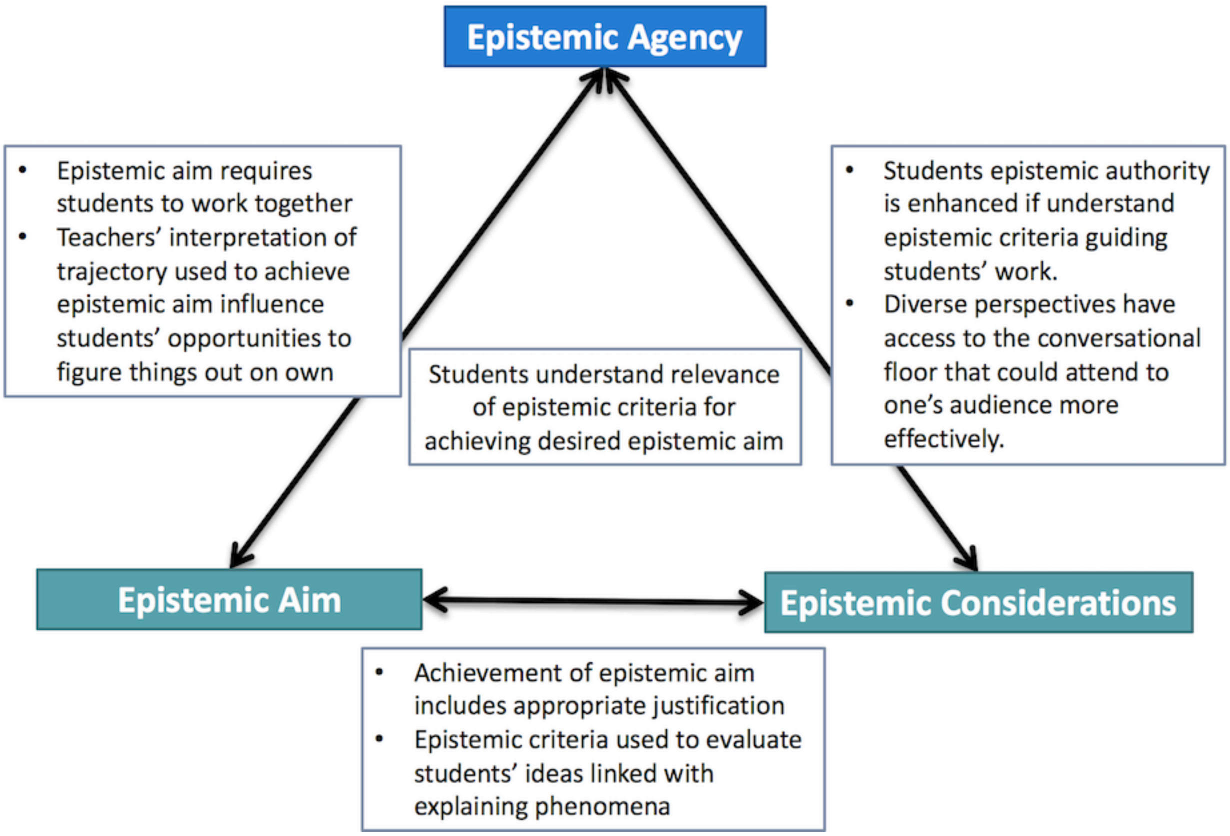

Figure 7.2. Sample synergies between analytical lenses.

Chapter 8: Study 2 Methods

With the increasing adoption of NGSS by states in the US, we need to consider generative ways to promote shifts in classroom practices. Study 1 considered how the three analytical lenses could be used in synergistic ways to understand the successes and challenges involved in promoting meaningful scientific practice in classrooms. In response, I desired to explore how we could help teachers understand what aspects of classroom scientific practice are important to attend to when promoting shifts in classroom practice. I wanted to explore how explicit attention to the issues posed by the three analytical lenses (epistemic aims, considerations, and agency) could help teachers interpret classroom events and enhance the meaningfulness of students' use of scientific practices. Study 2 investigated Research Question 2, "How can we help teachers understand and enhance the meaningfulness of their students' engagement in the construction and evaluation of explanatory models?" The goal of this work is to provide empirical evidence to support whether researchers and teachers could use this analytical framework to not only analyze one's classroom practice, but also promote shifts in students' and teachers' classroom practices.

This chapter has two goals. First, I explain how I used Grossman et al. (2009)'s *Framework for Teaching Practice* to design a professional learning approach to help one of the Study 1 teachers, Kami, use the issues posed by the three analytical lenses to analyze her classroom practice and consider ways to enhance her students' position as epistemic agents and meaningful users of scientific practices. Second, I explain the research methods used to operationalize this approach in Kami's classroom and the data used to analyze shifts in the students' and teacher's classroom practices from January to June 2013. In Chapter 9, I present two important shifts from the first three months of the intervention that established the foundation for subsequent, observed shifts in her classroom practices.

1. Study Context

Kami's classroom was a rich context for exploring how to enhance the meaningfulness of students' engagement in scientific practices for several reasons. One explanation for why meaningful science learning does not happen in classrooms is that teachers lack experiences with authentic science (e.g.,Windschitl, 2003). However, Kami had experience developing and using models as a professional scientist.

> I know from actually working in academia and at a biotech company that nobody does this stuff really by themselves. They think about it. They fiddle with their own models, and then they present it or they talk about it or they explain their ideas to somebody. (Kami Interview, 5/3/12)

Second, authentic epistemologies guided her instructional approach. To help students understand the "basic organizational principles" that guide how the world works, Kami would show students how similar mechanisms and properties were evident across phenomena contexts. For example, Kami showed students examples of phase changes across multiple situations to help student move beyond the specifics from the individual situations to considering general mechanisms for how matter changes from one phase to another.

> In my head, what I was pushing is the idea that the basic organizational principles of matter apply to all matter in all conditions — all the time. […] Like, if I showed them melting, I didn't just show them water melting. I showed them metal melting and I showed them air melting. There's a YouTube video where somebody freezes air and then shows it melt and evaporate like in an instant. […] So, I did make an effort to give them multiple examples. (Kami Interview, 5/3/12)

Third, she had three years of experience using reform curriculum materials and pedagogy. Kami and her fellow teachers recognized that a key shift from previous practices involved students playing a greater knowledge-building role and used the phrase, "I don't know. What do you think?" to remind one another of this shift (Kami Interview, 11/9/11).

Despite expressing a sophisticated view of what authentic scientific practice should look like in classrooms, Kami expressed challenges that aligned with issues related to the three analytical lenses. Kami identified issues related to epistemic agency. Although Kami recognized that the students should be the agents responsible for using evidence to deliberate between alternatives, she found herself taking on more of that responsibility.

> I've noticed that rather than pushing, pushing, and pushing on the, "How would you prove that?" […] I keep trying to stop myself, but, like, I feel like I might be pointing them in the direction of the answer more than I have other years. (Kami Interview, 1/24/13)

In addition, Kami reported challenges involved with engaging students' participation and convincing students of the epistemic value of the epistemic aim.

> I'd like them to do more of the work. They don't want to do the work a lot of times. It's hard. You should teach to IQWST teachers — You should teach a course in how to motivate kids to get involved [and] express their opinions. Like I have to work so hard for that. (Kami Interview, 1/24/13)

In response to the question, "Why should the students care about this task?", she responded, "Why should they care? Because it's so interesting! Because it's a part of their everyday. Because they have an opportunity to explain — it's part of a complex process that allows them to explain their own sensory perception of the world" (Kami Interview, 1/28/13). Thus, Kami could identify the multitude of ways in which this work was epistemically valuable from the perspective of the discipline and the teacher. At the same time, she acknowledged the challenge of understanding why this work might not compel student interest, "Maybe that's the problem. It's so inherently fascinating to me, I can't figure out why anyone wouldn't be just like tickled [laughter]" (Kami Interview, 1/28/13).

Kami's observations suggest that it was not enough for students to engage in scientifically meaningful tasks or for teachers to have authentic epistemologies or experience with authentic science to support students' meaningful engagement in scientific practices. Researchers often cite teacher's inadequate subject matter content knowledge, pedagogical content knowledge, and curricular knowledge as reasons for teachers' inability to support students' meaningful engagement in scientific practices (e.g.,Windschitl, 2003; Windschitl et al., 2008). Due to Kami's expert subject matter and curricular knowledge, I would argue that Kami's challenges involved issues related to her *pedagogical content knowledge* (Ball, Thames, & Phelps, 2008; Shulman, 1986), or an understanding of how to operationalize her commitments and vision for classroom practice. Thus, using Kami as a case allowed me to focus on developing her pedagogical content knowledge to make progress towards realizing the reform vision in her classroom. This work could contribute to our understanding of how to address the complex problem of promoting the NGSS shifts and consider ways to help teachers who encounter similar challenges promote changes in their own classrooms (Bereiter, 2013).

2. Study Design

Recognizing the challenges that Kami faced with the pending chemistry unit, in which she reported having issues with motivating students (Kami Interview, 1/28/13), I designed an intervention, which took place from January to June 2013, to address the concerns that she had identified related to the motivating student participation and enhancing the meaningfulness of her students' use of scientific practices. Two questions framed our work together. The first question, "How could we get Kami's students to do more of the work?", involved helping Kami assess her students' knowledge-building roles and provide explicit opportunities for students had to construct and evaluate one another's ideas. The second question involved considering the question, "Why should they care?", which considered the students' implicit and explicit motivation for engaging in the knowledge-building work. Thus, the worthiness of the knowledge-building work should not only be assessed by whether it was epistemically valuable according to the discipline, but also *personally meaningful* to the students.

Research Question 2, “How can we help teachers understand and enhance the meaningfulness of their students’ engagement in the construction and evaluation of explanatory models?”, guided my work to promote shifts in Kami's classroom practices. To do so, I first had to understand the extent to which the issues identified the previous year (Year 1) were also applicable in the current year (Year 2). Although the findings presented for Study 1 focused on a single lesson, my analysis of the issues encountered in Kami’s classroom extended a full year from October 2011 to May 2012. Next, I had to understand the underlying commitments and rationales that guided Kami’s decision making and interpretation of classroom events and Kami’s desired vision for teaching and learning in her classroom. Third, I explored a range of methods to help Kami use the issues posed by the three analytical lenses to analyze and reflect on her classroom practice and inform her decision making. In the next section, I explain the theoretical framework that guided the professional learning approach design.

3. Perspectives on Teacher Learning

Practice-centered instruction is a complex practice in which teachers are creating and facilitating opportunities for students to make sense of phenomena and test, investigate, and revise their initial ideas with each other. So how do we help teachers learn to engage in such ambitious pedagogy? The approach used to support teacher learning leverages two perspectives of teacher learning. First, teachers’ decisions are informed by what they notice and find salient in a classroom situation (Jacobs et al., 2011). Second, I used Grossman et al. (2009)’s *Framework for Teaching Practice* as a model for teacher learning to help novices learn how to engage in complex, relational practices. Through this approach, I designed ways to shift what

Kami noticed in the classroom so that she noticed and acted on aspects of classroom practice that were important for supporting students' engagement in scientific practices.

3.1 Refining teachers' professional vision

What teachers notice is guided by their understanding of the classroom context and principles guiding effective learning and instruction (van Es & Sherin, 2002). Given the complex situations in classrooms, there are many things that teachers could take notice of or attend to at any given time, such as students' responses to teacher's decisions (M. G. Sherin & van Es, 2005) or the procedural aspects of scientific practice (e.g.,Talanquer, Tomanek, & Novodvorsky, 2013). However, the findings from Study 1 suggest that helping teachers attend to the *epistemic* aspects of scientific practice could be fruitful for enhancing the meaningfulness of students' engagement in scientific practices. To do so, it would require refining teachers' *professional vision*, which Goodwin (1994) defined as the "socially organized ways of seeing and understanding events that are answerable to the distinctive interests of a particular social group" (p. 606).

Much of the focus in teacher noticing research has involved studying how teachers' attention to student thinking contributes to deeper conceptual understanding for students (e.g.Carpenter, Fennema, Peterson, Chiang, & Loef, 1989; Fennema et al., 1996; van Es & Sherin, 2002). However, (Jacobs, Lamb, & Philipp, 2010) has argued that teachers' responses to students thinking requires a disciplinary lens — a new framework for attending to, interpreting, and responding to students' thinking that accounts for the disciplinary context of the classroom. Although most of the work in teacher noticing has occurred in the context of mathematics, there is comparatively less, but growing, body of literature in science education to understand *what* science teachers notice in the context of pre-service teacher education. When observing video of students engaging in an investigation, Talanquer et al. (2013) found that teachers were more likely to attend to students' process skills of inquiry, such as how students posed hypotheses or questions, rather than students' explanations of the data. When exploring what one science teacher noticed in the context of her own classroom instruction, Luna, Russ, and Colestock (2009) found that there was more attention to student ideas during whole-class discussions compared to during lab activities, where captured moments involved procedural talk. As a whole, Luna et al. (2009)'s findings showed that teachers were capable of attending to moments that involved student reasoning, yet there was less analysis done to understand how these identified moments influenced teacher's instructional decisions.

Other studies have examined teachers' *responses* to student ideas. To counter an argument made in the literature that novice teaches were unable to attend to student thinking before establishing classroom routines and identities as teachers, Levin, Hammer, and Coffey (2009) identified examples of novice teachers asking students to explain their reasoning, rephrasing student ideas, or shifting the "flow of classroom activity" to address a student's idea. Kang and Anderson (2015) investigated pre-service teacher's (PST) use of assessments to interpret students' conceptual understanding and consider their response. Barnhart examined PSTs' discussion of a moment in which they responded to and advanced students' thinking while students were making sense of data. The authors found that pre-service teachers (PST) who participated in a course on teacher noticing were better able to attend, analyze, and respond to the student thinking in the classroom than to pre-service teachers who did not participate. This research lends greater credibility to arguments that state that expertise with attending to students thinking comes from time intentionally trying to attend to and leverage students' thinking in the context of classroom instruction rather than the number of years of experience alone (Franke, Carpenter, Levi, & Fennema, 2001; Jacobs et al., 2010; van Es, 2011).

Learning science-as-practice involves attention to the disciplinary ideas and the practices used to construct that content (Lehrer & Schauble, 2006b). Thus, this study desires to build upon the science teacher noticing literature to help teachers not only attend to students' ideas, but also attend to the epistemic issues that are important for interpreting the validity of students' ideas and assessing the meaningfulness of students' use of scientific practices. In addition, this study seeks to build teachers' capacity to attend to these aspects of meaningful practice in the context of classroom instruction and use their interpretations to inform their decision making. Thus, this work seeks to not only engage in retrospective noticing to understand what they noticed and how they accounted for it, but also to account for these interpretations to make in-the-moment and future decisions to enhance the meaningfulness of students' engagement in scientific practices.

3.2 Grossman et al. (2009)'s Framework for Teaching Practice

I used Grossman et al. (2009)'s *Framework for Teaching Practice* to help Kami learn how to enhance the meaningfulness of her students' engagement. The framework involves the use of three strategies: decomposition, using representations of practice, and approximating the practice. The first step in this process involves *decomposing* the complex practice into its components so that teacher educators have a language to talk about the practice and explain how and why each component contributes to the overall activity. In this study, the components of scientific practice that I wanted Kami to notice were the epistemic issues posed by the three analytical lenses (see Figure 8.1).

Figure 8.1. Operationalization of Grossman et al. (2009)'s *Framework for Teaching Practice*

To help Kami notice these aspects of classroom practice and understand how and why these lenses were important, I chose *representations of practice* to make visible elements of the practice that you want novices to notice and learn. For example, to help a teacher understand how to support argumentation in one's classroom, it might be helpful for teachers to see instances where students are using evidence to argue for how and why their account is better able to explain the phenomenon compared to other posed alternatives. Using the video, the teacher educator could help the novice notice the ways in which students are using evidence and building on one another's ideas to persuade others of the validity of one's claims. Through this work, the novice might begin to think about what is needed to support students' engagement in argumentation. In the context of this professional learning approach, where teachers have existing understanding of the practices, I used classroom video and anecdotes from classroom observations as representations of practice to make visible issues related to the three analytical lenses and discuss how these issues influenced the meaningfulness of her students' engagement in scientific practices. The goal of these collaborative discussions was to develop Kami's *knowledge-based reasoning*, which M. G. Sherin (2007) described as the knowledge that Kami and other teachers use to reason about what she noticed, and help Kami consider these issues on her own as she reflected on her classroom practice and made in-the-moment instructional decisions.

The third strategy involved teacher educators providing novices with the opportunity to experiment doing aspects of complex practice and make mistakes in low-risk environments (e.g., a university setting) in preparation for use in more authentic situations. For example, novice teachers might design a tool to support students' meaningful use of evidence during argumentation and receive feedback on the use of the tool in a university methods course or in a professional development setting where the novice's peers serve as "students." However, these approximations might not be authentic to the situations that are teachers are likely to encounter in classrooms with actual students (Grossman et al., 2009). Since this study occurred in real-time to enhance the meaningfulness of Kami's classroom practice, Kami did not have the opportunity to experiment in a "low-risk" environment before using it in the context of her instruction. To reduce the level of risk involved in designing and enacting revised activities or instructional approaches, we discussed the planning of these activities together prior to the enactment and I was present to support the enactment and debrief afterwards.

4. Professional Learning Design

Using the theoretical framework described in Section 3, I designed an intervention to help Kami use the issues questions posed by the three analytical lenses to reflect on and enhance the meaningfulness of her students' use of scientific practices. The professional development approach was embedding in the context of Kami's classroom practices so that Kami could apply what she had learned to inform her planning and instruction (Borko, Jacobs, & Koellner, 2010; Darling-Hammond, Wei, Andree, Richardson, & Orphanos, 2009; Garet, Porter, Desimone, Birman, & Yoon, 2001). Rather than providing a list of prescriptive actions for Kami to do, I wanted Kami to build Kami's professional capacity to understand how and why attention to the issues posed by the analytical lenses were important for supporting her students' learning and consider ways to account for these issues in her instructional decisions. There were three stages of the intervention: 1) analyzing the classroom enactment, 2) understanding the teacher's underlying considerations and commitments, and 3) helping Kami reflect on and enhance the meaningfulness of her students' use of scientific practices. My approach was flexible to respond to issues that arose from our work, such as the need to respond to classroom management issues, yet focused on the two questions that framed the goal of our work together: 1) How could we get Kami's students to do more of the work?, which focused on issues of student agency, and 2) Why should they care?, which examined the meaning that students applied to their scientific work.

4.1 Step 1: Analyze classroom enactment.

Since the intervention occurred at the beginning of the second unit, I wanted to devote time to understanding the extent to which the issues related to meaningful engagement identified the year prior also applied to the current enactment or whether there might be additional factors to consider when promoting shifts in Kami's classroom practice. Because Kami desired for the students to "do more of the [knowledge-building] work" (Kami Interview, 1/24/13), I paid particular attention to the role that the students played in initiating and responding to each other's ideas and how students' ideas contributed to and shaped the class consensus knowledge. In response to Kami's desire for her students to be more engaged and motivated to participate, I examined whether the epistemic aims compelled students to participate and the extent to which her students found the activities epistemically valuable.

4.2 Step 2: Understand teacher's underlying considerations and commitments.

In addition to understanding the enactment from my own perspective, I sought to understand the considerations or commitments that might have implicitly or explicitly guided

Kami's decisions. In doing so, I hoped to identify *epistemic stances*, attitudes towards learning Chinn et al. (2011), or *pedagogical commitments*, implicit or explicit assumptions concerning aspects of teaching and learning activity (Erickson, 2011, p. 28), that might support or hinder the desired shifts in Kami's classroom.

4.2.1 Vision Casting. Recognizing the disconnect between her desires and what was happening in the classroom, I asked Kami to articulate her ideal vision for effective teaching and learning and the role that the students and teacher would play (see Appendix F). Hammerness (2006) argued that teachers' vision statements could be instrumental for helping teacher educators learn about a teacher's beliefs about effective teaching, help teachers broaden their perspective for what is possible, identify inconsistencies between teacher's goals and beliefs and plan interventions to revise teachers' beliefs, and develop strategies to identify and achieve realistic goals. The process of writing vision statements provided Kami the opportunity to explicitly attend to issues related to student agency and consider how her role supported or hindered her students' knowledge-building role. Once articulated, we could use the vision statement to evaluate her expectations and take steps to bridge any perceived gaps between the classroom enactments and her desired vision.

4.2.2 Watching classroom video. Researchers have argued for using video to help teachers reflect on and promote changes to teachers' and students' classroom practices. For example, M. G. Sherin (2004) found that allowing teachers to watch videos of their own classrooms provided them with the opportunity to discuss the rationale behind their decisions and interpret student ideas that might have been difficult to understand or access during instruction. I chose video clips from Kami's classroom that made visible one or more issues related to the meaningfulness of her students' engagement in scientific practices to examine the extent to which Kami was attentive to these issues prior to our intervention. In other words, Steps 1 and 2 did not involve conscious efforts on my part to change Kami's classroom practices. Rather, these steps involved trying to understand the issues that might influence the meaningfulness of students' engagement in scientific practices. I made a conscious decision to use video from Kami's classroom so that she had the situational context to interpret classroom events and later to apply what we had learned to improve her own classroom (c.f., Franke et al., 2001; Santagata, 2011; van Es & Sherin, 2002). Since teachers act on what they notice and find salient in a classroom situation (Jacobs et al., 2011), I hoped to understand the *knowledge-based reasoning* that Kami used to reason about what she noticed and guide her decision-making (M. G. Sherin, 2007) and consider how the intervention might lead to changes in what Kami noticed and her knowledge-based reasoning. Because a central goal of this work involved making visible and enhancing the meaning that students apply to their scientific work, I also had students watch the same video clips to understand their interpretation of classroom events and assess its alignment with the teacher's interpretations.

4.3 Step 3: Engage in cogenerative dialogues.

Step 3 involved engaging in *cogenerative dialogues*, during which classroom stakeholders (the teacher, students, and researcher) used their privileged insight to co-construct understandings of classroom events and share responsibility for developing and carrying out solutions to improve students' learning (W.-M. Roth & Tobin, 2004; Tobin, 2006; Tobin & Roth, 2003). In contrast to traditional classroom interviews, during which the interviewer posed questions to elicit teachers' responses, I, as the researcher, was a participant in and stakeholder during these cogenerative dialogues. Researchers have found that the formation of professional learning communities, characterized by trusting relationships and opportunities to collaborate with others, was important for helping teachers make sense of and implement reform practices, reflect on one's teaching practice, and sustain gains in professional capacity (Desimone, 2009; Franke et al., 2001; Garet et al., 2001; Martin & Hand, 2009; Putnam & Borko, 2000; K. J. Roth et al., 2011). Thus, cogenerative dialogues served as an activity structure through which to facilitate and sustain shifts in Kami's classroom practices.

Cogenerative dialogues usually occurred following a lesson and involved reflecting on the goals of the lesson, Kami's assessment of whether the lesson went well, and what she might do differently. After discussing Kami's concerns, I might also raise anecdotes from the classroom observations or show video excerpts from previous observations that would prompt a conversation around an issue related to the meaningfulness of her students' engagement in scientific practices. Engaging in cogenerative dialogues was helpful from a professional development perspective, because it allowed Kami the opportunity to reflect on her own practice without having to immediately react and discuss alternative ways to respond to classroom issues with support (Borko et al., 2010; Fennema et al., 1996; Franke et al., 2001; Jacobs et al., 2010; Santagata, 2011; M. G. Sherin, 2007). Mason (2011) noted the effectiveness of *retrospective noticing* on improving teacher practice and student learning because it sensitizes teachers to what they should notice in the future and how they should respond.

During these "cycles of experimentation and reflection" (Borko et al., 2010), the analytical lenses provided a framework for reflecting on the meaningfulness of her students' engagement in scientific practices and co-developing solutions to identified problems. Any proposed solution was informed by our joint interpretation of classroom events and our proposed means for addressing the issues, yet the teacher had the ultimate authority to make decisions related to implementing any proposed solutions. Thus, teacher agency was protected throughout the intervention with the intent of promoting meaningful shifts in Kami's classroom practices so that she understood what she was doing and why. Subsequent cogenerative dialogues would reflect on the success of these interventions and leverage what we had learned to inform future decisions.

To be effective, W.-M. Roth and Lee (2007) argued that participants need to identify common ground and language and have mutual respect for the variety of experiences, competencies, and structural positions that each participant brings to the discussion. For example, teachers might bring their knowledge of their classroom practices, students, and contexts (Borko et al., 2010), while the researcher might bring an outside perspective and help teachers notice an overlooked event or idea or provide an alternative explanation for identified events (van Es, 2011). Although most cogenerative dialogues occurred between Kami and the researcher, I also involved students to understand how instructional strategies and decisions influenced their learning and to give students the opportunity to voice their own ideas and shape decisions that would enhance the learning of the classroom community.

4.4 Summary.

In summary, there were three stages of the intervention: 1) analyzing the classroom enactment, 2) understanding the teacher's underlying considerations and commitments, and 3) to help Kami reflect on and enhance the meaningfulness of her students' use of scientific practices. Although I identified three distinct stages of the intervention, each stage of the intervention informed the other. For example, my interpretation of on-going classroom events informed the classroom video that I chose for Kami to watch or the classroom events that I raised for discussion.

5. Research Design

In this section, I explain the research methods and collected data used to identify shifts in Kami's instructional practices from Year 1 to Year 2. I used the methods described in Chapter 5 to track how issues related to the analytical lenses changed over the course of the intervention in Year 2.

5.1 Pre-Intervention Data

Table 8.1 shows the observed lessons and interviews that I conducted during Year 1 in Kami's classroom. I analyzed six multi-day lessons over 12 days during which students constructed, evaluated, or revised scientific models either individually, in small groups, or as a whole-class.

Table 8.1
Kami Data Collection 2011-12

			Interviews	
Lesson	**Class Periods**	**Time (hours)**	**Teacher**	**Students**
Physics				
7	3	2.5	2	1
Chemistry				
1	1	0.6	2	
4	2	1.0		
5	2*	1.0		
6	3*	1.5		2
16	3	1.9	1	2
Total	**12**	**9.7**	**4**	**5**

This table shows the number of observed class periods, duration of instruction, and number of interviews for each lesson. I used asterisks (*) to indicate lessons where there was overlap with another lesson on the same day. The total observed class periods accounts for this overlap.

I chose five chemistry lessons that involved developing and using models to explain the anchoring odor phenomenon. During Lesson 1, the students experienced the anchoring phenomenon and constructed and shared their initial explanatory models with the class. During Lessons 4-6, students tested and revised their model's ability to explain contrasting behaviors.

By the conclusion of this lesson sequence, students should have enough evidence to support a particle model of matter. During Lesson 16, students consider their model's ability to explain other related situations. In addition, I analyzed Lesson 7 of the physics unit, in which students constructed models to explain the different ways that light interacts with opaque, transparent, and translucent objects. I chose this lesson because this activity involved small-group modeling work and served as a contrast to the whole-class participant structures that dominated the unit's activities.

Using the Study 1 interview protocols (see Chapter 4, Section 5.2), I triangulated interpretations of classroom events with semi-structured teacher and student interviews. I interviewed Kami on four occasions at the beginning of data collection (n=2) and at the beginning and end of the chemistry unit. I interviewed students at the beginning, middle, and end of Year 1.

5.2 Intervention Data

Table 8.2
Kami Data Collection 2012-13

			Interviews		
Lesson	**Class Periods**	**Time (hours)**	**Teacher**	**Students**	**T & S**
6P 10.5	1	1.3		2	
6C(Pre)			1		
1	3*	1.8	1		
2	5*	4.0	1[V]		
3	4*	3.3	2	3[V]	
4	1	0.6			
5	2*	1.3			
6	1	1.2			
Consensus	6	6.2	4[V]	3[V]	3[V]
7-13			4		
Phase Change	5	4.6	8[V]	3[V]	
16	1	0.7		2	
6C(Post)			2		
Total	**23**	**25.0**	**23**	**13**	**3**

This table shows the number of observed class periods, duration of instruction, and number of interviews for each lesson. * - Lesson that occurred on day with multiple lessons. The total observed class periods accounts for this overlap. v – Watched classroom video.

During Year 2, I observed each chemistry unit lesson over 39 days to monitor effects of the intervention over time (see Table 8.2). The school adopted a modified block schedule in which students were in science for two, 90-minute periods and one 40-minute period each week. Thus, it was possible for multiple curricular lessons to occur within a given class period. For example, students finished Lesson 2 on the same day in which they started material from Lesson 3. To allow Year 1 and 2 comparisons, I listed the amount of time in hours devoted to a given curricular lesson in Table 8.2. I used data from the conclusion of the physic unit through Lesson 2 as baseline data to assess whether issues identified during Year 1 persisted in Year 2. I commenced work to shift Kami's classroom practice after Lesson 2, in which students designed and conducted investigations to figure out that odors are matter (L2) and are in the gaseous state (L3). Kami and I co-designed a series of phase change lessons, in which students developed general models of how matter changes phase in the context of explaining three complex situations: the appearance of condensation on the outside of a cup of ice water, the solidification of lead, and the sublimation of dry ice. Pre/post interviews and cogenerative dialogues occurred throughout the intervention, often following the end of a lesson. I labeled lessons during which I used video to help teachers and students reflect on the classroom enactments.

Chapter 9: Illustrative shifts in Kami's classroom

In this chapter, I document two noticing shifts that prompted changes that enhanced student agency and the meaningfulness of students' engagement in scientific practices. By noticing shift, I mean that Kami responded to a reinterpretation of a classroom event or a noticing of one or more aspects of classroom practice that supported or hindered students' engagement in scientific practices. The first noticing shift involved helping Kami recognize the existing ways in which her students attempted to use their ideas to make sense of phenomena and notice her role in hindering their participation. This noticing led Kami to reconsider the opportunities that students had to engage with and use one another's ideas to reach consensus.

The second noticing shift involved reinterpreting the rationale for students' attempts to exert epistemic authority and reinterpreting evidence of student understanding. This noticing led Kami to re-consider "what counts" as evidence of student understanding and the role that students' participation in the coordination of claims with evidence and reconciliation of competing ideas had for helping students become convinced of a given claim. In what follows, I describe the steps taken to help Kami notice and respond to these identified issues related to supporting students' meaningful engagement in scientific practices.

1. Shift 1: Helping Kami notice how she responded to and used students' ideas during instruction

During the first chemistry lesson, students proposed initial explanations for how they could detect odors from a distance. Many students used the term "molecules" to describe the odor or air, whereas others had more in-depth ideas about the particle nature of matter. Over the next four days, students extended their model during Lesson 2 to investigate the mechanism by which odors could leave the odor source and enter the air. One student, Zachary, asked Kami how odors moved through the air, “When the odor travels, does it travel by like, the singular odor molecules? Like, [do] they go […] close to each other, and they stick together, and they travel together, or they travel separately?” (Kami Observation, 1/30/13). His question considered the nature of the odor and whether it moved as singular entities or whether they aggregated together through the air. Of Zachary’s ideas, Kami attended to his use of the term “odor molecule” and questioned whether he had evidence to support the molecular basis of matter.

Turn	Type	Interactional Units
1	T-S	T: What’s an odor molecule?
2	T-S	ZACHARY: Like, what makes odor. The molecules.
3	T-S	T: Do you know that’s what makes odor?
4	T-S	ZACHARY: I’m pretty sure.
5	T-S	T: Yeah?
6	T-S	T: Do you have evidence? Cause if that’s like the answer, then we can skip ahead of all… Do we have evidence for that?
7	T-S	S: No, but like…
8	T-S	T: Well, we know we all come in — all of us come in with a lot of different knowledge, and odor molecules might be the answer to, I don’t know what question we’re asking.
9	T-S	ZACHARY: [I don't know, I was just wondering how they travel around.
10	T-S	T: No, that’s a good, that’s a good topic to keep in our minds.

(Kami Observation, 2/4/13)

Kami’s response seemed dismissive of Zachary’s claims about odors being in the form of molecules. As discussed in Study 1, the chemistry unit’s content goal involved students using evidence from the unit to develop a model of matter in which matter is the form of molecules with particle-like properties. Consideration of this long-termed epistemic aim could explain Kami’s response that the class could “skip ahead” if they had evidence to support the molecular basis of odors (turn 6). However, Kami’s response to Zachary’s use of “molecules” came at the expense of attending to the underlying rationale for his question, which he repeated. However, once he restated his idea without using the term "molecule," Kami was more receptive to the relevance of his question, "No, that's a good, that's a good topic to keep in our minds" (turn 10).

Similar reactions to the use of the term molecules continued during Lesson 2. For example, Kami wanted to show students a demonstration that would prove to students that air had volume. The flask had a stopper with two holes: one attached to a funnel, while the other was attached to a clear tube (see Figure 9.1). She asked her students to predict what would happen if she poured water into a flask "filled with air." When the tube was open, the water would be able to enter the flask because it would be able to displace some of the air taking up space inside the flask. However, when the tube was closed, none of the air filling the flask could be displaced, thus preventing the water from entering the flask.

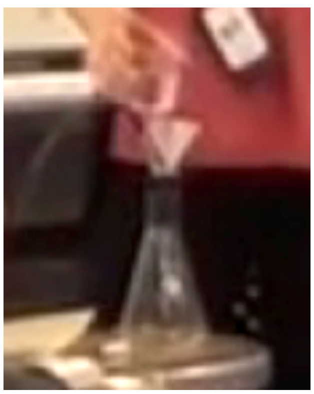

Figure 9.1. Flask and Water Demo. The flask had a rubber stopper with two holes: one for the funnel and another with a clear tube. Students were asked to predict what would happen if she poured water into the funnel.

Some students applied the idea that the air had volume to correctly predict that the water would not be able to enter the flask if the tube was closed, whereas other students used the term "molecules" in their explanations. For example, Connor explained that the air might find a way out of the flask because air was in the form of small air molecules.

Turn	Type	Interactional Units
1	T-S	T: So what do you think will happen?
2	T-S	CONNOR: The air will find its way through.
3	T-S	T: The air will figure out a way to get out?
4	T-S	CONNOR: No. Well, I think the *air molecules* are so small and that hole can only…
5	T-S	T: What's an *air molecule*?
6	T-S	CHASE: [Sighs] Not this again.
7	T-S	CONNOR: I don't know.
8	T-S	T: We gotta have… This is science we gotta have evidence for what we're talking about.
9	S-T	JULIANNA: But we haven't learned that yet, so that's (inaudible).
10	S-T	T: No, no, no. I'm just saying. If we're talking about something we gotta have evidence for it. So, I don't really have evidence for that yet.

(Kami Observation, 2/4/13)

Kami interrupted Connor, because she argued that students could not use a concept for which the students did not have evidence, "If we're talking about something we gotta have evidence for it. So, I don't really have evidence for that yet" (turn 10). Kami reacted in a similar way to Lance's explanation, which involved the water compressing the air inside the flask.

Turn	Type	Interactional Units
11	T-S	T: So, we know air is matter, we know that. OK?
12	T-S	S: No...
13	S-T	LANCE: I think the air molecules are just gonna get tightly packed together.
		T: Uh-huh.
14	S-T	LANCE: I mean if it was like a less... If it was maybe a balloon, it would
15	S-T	probably pop the balloon 'cause it would be-- the air would be too compressed.
16	T-S	T: Okay I'm gonna… What do you… What's an air molecule?
17	T-S	Ss: [sigh]
18	T-S	LANCE: Like a bunch of atoms.
19	T-S	T: Who knows? I think we're, I mean it's an interesting idea, but I think we need to stick with what we
20	T-S	S: know?
21	T-S	T: have evidence for. Right?

(Kami Observation, 2/4/13)

In response to Kami's question, "What's an air molecule?", Lance claimed that molecules were "a bunch of atoms," which, by definition, was correct. However, Kami dismissed Lance's "interesting idea," because students should only use concepts for which students had existing evidence.

When analyzing this episode, I identified several issues that influenced students' position as epistemic agents. The epistemic aim involved predicting what would happen when the teacher poured water into the flask. In response, students not only stated what they thought would happen, but also attempted to justify their claims by proposing plausible mechanisms for what might be happening in the flask at the non-visible level. Kami required students to convince her that they had evidence to support their claims that air was in the form of molecules before they could use that idea in their explanations. In doing so, there was a shift in the epistemic aim guiding the students' and the teacher's work from evaluating plausible explanations for the phenomenon to persuading the teacher that they had sufficient understanding of what molecules were and evidence to be able to use the concept. From a student agency perspective, Kami limited the scope of what ideas or resources students could leverage to make sense of the phenomenon. Rather than probing students' ideas to see what they meant by "molecule" and how they sought to use it in the context of their explanation, the teacher prevented the student's ideas from contributing to the consensus knowledge of the classroom. In addition, the teacher, rather than the students, determined "what counted" as a valid, scientific idea and sufficient evidence. Interestingly, student ideas that did not involve "molecules," such as air being in the form of "clouds" or "strings," did not receive the same scrutiny despite being incorrect.

1.1 Choosing video as representation of practice

Given her pre-intervention concerns about her students not wanting to be participate in the knowledge-building work, I wanted to see whether Kami might have considered how her response to her students' ideas could have a negative impact on students' future willingness to participate. To do so, I chose an 11-minute video clip as a *representation of practice* that made visible her students' attempts to predict what would happen during the flask activity and her responses to her students' ideas. The intent was to understand the rationales for her decisions and to identify what aspects of the classroom interactions were noteworthy to her rather than influence her interpretation of classroom events or jointly construct solutions to identified problems.

1.2 Watching classroom video

We watched the video clip together after the next lesson. I framed the activity as a *video club*, which is a group of teachers who participated in a facilitated discussion about one another's video excerpts (M. G. Sherin, 2004, p. 15), because I wanted to introduce an activity structure whereby the teacher, researcher, and later students could watch classroom video clips and co-construct understandings of what they observed (see Figure 9.2).

Figure 9.2. Kami watching video of her classroom.

After providing some context for the video clip, I asked Kami to pause the video when she found a moment that was "interesting" to her (c.f., Russ & Luna, 2013; M. G. Sherin, 2007; M. G. Sherin & van Es, 2005; van Es & Sherin, 2002) and explain why she identified that moment. The intent was to allow Kami room to interpret what constituted an "interesting moment" to her when watching the video. In response to Kami's request for clarification about what constituted an "interesting moment," I prompted her to think about reactions to her own actions ("I wonder why I did that?") or her students' ideas or actions ("I wonder what the kids [were] thinking?" or "Oh, I really like this point. This is how I built upon it here.") (Kami Interview, 2/8/13). This guidance provided her some examples of what she could respond to without biasing her towards any aspect of the classroom activity. We used the software, Inqscribe, to watch the classroom video and create timestamps moments that were noteworthy to her (see Figure 9.3). After watching the entire video, I asked Kami her general impressions about what she had watched and what she might have done differently.

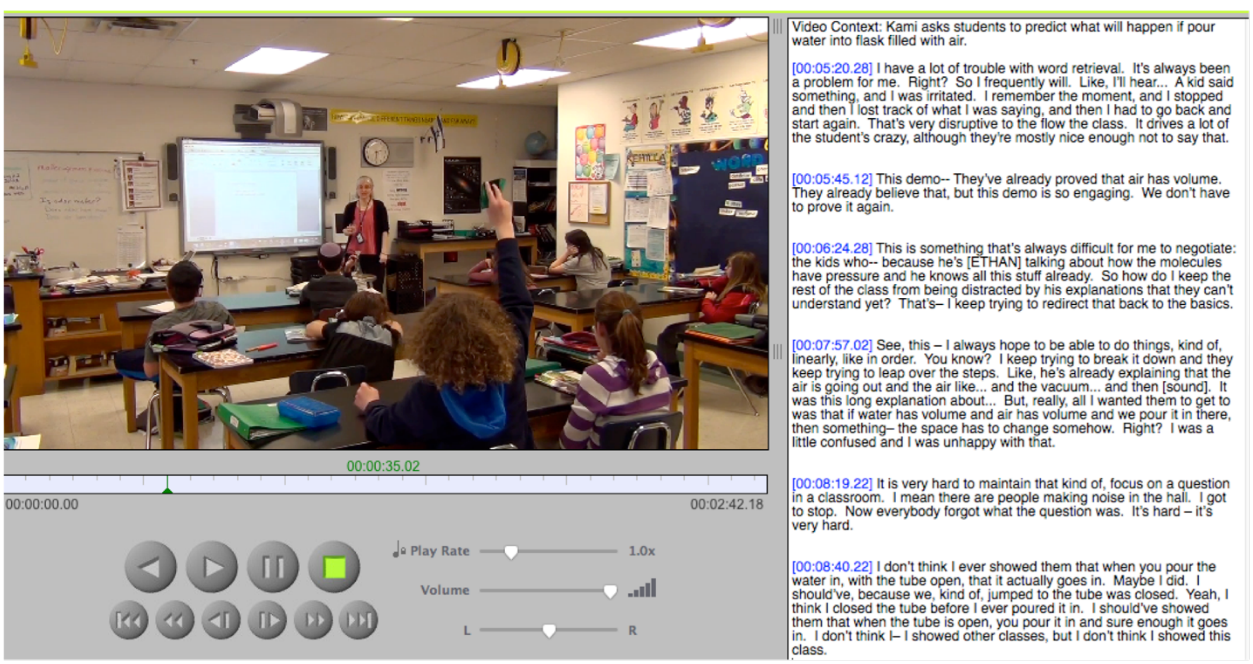

Figure 9.3. Inqscribe screenshot. Screenshot shows timestamps and transcribed comments about noteworthy moments

1.3 Analysis: What did Kami notice?

During the 11-minute clip, Kami paused the video 21 times. I transcribed her response to what she found noteworthy and embedded her comments within the classroom video transcript to facilitate interpretation of Kami's statements. For example, in the following example, Kami stopped the video after the word volume. Her response to that moment is transcribed below the classroom transcript.

WATCH VIDEO TILL [00:05:45.12]
T: This is a rubber stopper and it's got two holes. In one hole there's a funnel, okay? And in the other hole there's this tube, alright? And so, I'm gonna put this [stopper] in here. Now we said we believe that air has mass and volume, okay? So, if we really believe that air has volume
MOMENT 2
T: Oh, can I just stop for a second? I: Yeah. T: This demo… They've already proved that air has volume. They already believe that, but this demo is so engaging. We don't have to prove it again. This is a way to prove it, but it's so engaging that… And, it creates such an emotional memory for them that I decided to do it anyway even though we've already gotten to the scientific proof that air has mass and air has volume.

(Kami Interview, 2/8/13)

Using the three analytical lenses as a framework, I inductively coded Kami's statements regarding each noteworthy moment to identify any themes in what considerations or commitments might have guided Kami's decisions. For example, Kami justified the activity's epistemic value, which involved using an engaging phenomenon to prove that air had volume. I identified three themes: 1) students' and teachers' interpretation of the epistemic aim (n=4); 2) the alignment of students' ideas with her desired trajectory for achieving the epistemic aim (n=10); and 3) students' level of interest or engagement during the discussion (n=7).

1.3.1 Students and teachers' interpretation of epistemic aim. Four of the moments involved Kami explaining her intended epistemic aim guiding this activity and the frustrations that arose when her students' framing of the task did not align with her own. Kami paused the video during the explanation of the activity to explain to me her intended rationale for using this demonstration. Since students had already concluded that air had volume, she did not intend for students to use this phenomenon as an opportunity to develop a new model idea; rather her goal was for students to confirm what they already knew.

> This is a way to prove it, but it's so engaging that — and it creates such an emotional memory for them that I decided to do it anyway even though we've already gotten to the scientific proof that air has mass and air has volume. (Moment 2, 2/8/13)

Thus, Kami's framing, or interpretation of what the students were going to be up to (e.g.,Berland & Hammer, 2012), involved students unproblematically applying model ideas that they had already developed. Kami reinforced this *confirmation frame,* as she explained how students' prior knowledge of air having volume (see italicized text) might be relevant for making predictions about and explaining the phenomenon.

> *So, if we really believe that air has volume, then* I want us to make some predictions about this system. […] *If air is filling up this flask, and the air has volume, it actually takes up space.* If I pour this water in here, in the funnel, what's gonna happen? (Kami Observation, 2/4/13)

Despite desiring students to use the phenomenon to confirm what students knew, students showed evidence of adopting a *sensemaking frame*, in which they sought to construct a plausible explanatory account to justify their predictions rather than apply a known principle in an unproblematic way. For example, Clay justified his idea that the water would enter the flask by drawing analogies between people of unequal weights jumping on a trampoline and water and air.

Turn	Interactional Units
1	CLAY: Air's gonna come out from the tube, because if air is right now taking up all of the space in there. So, if you pour something in to occupy the space that's heavier than that, it's kinda like if you, like if you are jumping on the trampoline with two people. So, the air goes up. It doesn't keep pushing.
2	T: So, so as I pour this water in you'd predict that it would go right in there and that's because the air goes out of here [hole in flask]?
3	CLAY: No, no, I'm saying that it's more-- It's because the water is going in there, that's why the air. It's like if two people are jumping on a trampoline and one person's standing and the other person's sitting,
4	T: Yeah.
5	CLAY: Then the person sitting is gonna go up and down because the heavier the person weighs it makes more of an impact, they're gonna go up.

(Kami Observation, 2/4/13)

Clay cited water's heavier weight as an important factor for why the water could displace the air inside the flask and used a trampoline analogy to justify his response. When watching the video clip, Kami expressed frustration at the length and complexity of the student's explanation.

> He's [Clay's] already explaining that the air is going out, and the air like, and the vacuum — it was this long explanation. But, really, all I wanted them to get to was that if water has volume and air has volume and you pour it in there then something – the space has to change somehow. Right? I was a little confused and was unhappy with that. (Moment 4, 2/8/13)

I argue that Kami's frustration was grounded in differences in the knowledge-building frames adopted by the students and teacher and Kami reflecting on how the question that she used to frame the knowledge-building work might have contributed to these differences in interpretation, "I feel like I'm still trying to define the question so we can take two seconds and answer it" (Moment 8, 2/8/13). Thus, the students' and teachers' framing influenced what epistemic considerations were deemed relevant for achieving the desired epistemic aim.

1.3.2 Alignment of students' ideas with her desired trajectory for achieving the epistemic aim. The second category of moments involved the teacher's responses to students' ideas and her interpretation of whether students' ideas should be taken up or discussed. Thus, this theme foregrounds issues related to epistemic agency. Many of the moments involved Kami's desire to redirect students' comments from using the term "molecules."

> See me thinking? How am I going to get out of this? How am I going to get out of this? I don't want to go into atoms. I don't want to go into molecules. […] It's hard. It's frustrating. So again, trying to redirect them away in a way that doesn't deny the knowledge that the kids come in with, but also doesn't get off-track from what we're trying to (accomplish). (Moment 8, 2/8/13)

Kami wanted her students to apply the model idea that air had volume rather than using terms such as "atoms" or "molecules" Students' comments suggest that they had moved beyond macro-level properties of matter, such as air having volume, to examining the micro-level interactions that explain these properties, such as air being in the form of particles that move and spread out in all directions to occupy the space of the container (Wilensky & Resnick, 1999). Kami claimed that students' moves got the class "off-track from what we're trying to accomplish."

Since the molecular basis of matter is a key part of the intended explanatory model, why was Kami trying to redirect students away from these ideas? Kami recognized the fundamental importance of the particle nature of matter for explaining phenomena, "That concept of nothing, with particles in it, I think is really fundamental to understanding everything about matter: how it interacts, you know, everything about it. Phase changes the whole deal" (Kami Interview, 5/3/12). At the same time, she recognized how challenging this concept is for students.

> It's one of those concepts that they'll tell me one day in class, and the next day in class, they can't reproduce that understanding. […] And it's not just the kids who have recall issues. […] They think this [desk] is solid. Right? So how can there be nothing in that? (Kami Interview, 5/3/12)

Considering the disciplinary importance of this idea and the non-intuitive nature of this idea for students, Kami felt it was important for her students to have opportunities to figure this concept on their own for them to understand it. To do so, students needed to systematically collect evidence to support claims about the particle nature of matter, "See, this – I always hope to be able to do things, kind of, linearly, like in order. You know? I keep trying to break it down and they keep trying to leap over the steps" (Moment 4, 2/8/13). Thus, Kami recognized how the planned sequence of instruction was designed to help students collect this evidence. Kami's response to students using the term molecules was motivated by the desire to prevent confusion and protect students' opportunities to develop this idea using the planned sequence of instruction.

> There are kids in the class who need to see what I'm going to show them in order to really understand that air is a thing that takes up space, and that's critical to their understanding about what a gas is and that's critical to their understanding about what matter is and particulate motion, and all everything… It's a really basic concept they need to be able to grasp, and there are kids in the class who don't have that concept yet, and I don't want them to be confused. (Moment 12, 2/8/13)

1.3.3 Students' level of interest or engagement during the discussion. Kami identified seven moments that involved her interpretation of the students' level of engagement with the activity and the class discussion. In other words, this theme was related to students' interpretation of the epistemic value of the epistemic aim. Kami chose this activity because it was an engaging phenomenon that would create an "emotional memory" for students (Moment 2, 2/8/13). However, she identified students who she claimed were not engaged or interested during the class discussion.

> I feel like these kids, who really just want to see what's going to happen in the demo, are gone by now. I don't know that, but that's my sense. […] I don't know if it's […] not engaging for them what their friends think... Maybe. I'm not sure if they just don't follow [the discussion] so they've checked out. That's my guess, I think. (Moment 12, 2/8/13)

During these reflections, Kami cited several potential explanations for students' lack of engagement: 1) inability to "follow" the discussion, which she attributed to lack of prior knowledge about molecules, or 2) not recognizing the epistemic value of the discussion about students' ideas.

1.3.4 Summary. In summary, Kami's desire to preserve students' opportunities to develop understandings about the particle nature of matter on their own motivated her response to students' ideas about molecules. However, this attention to student agency was not consistently applied to all students, as ideas related to molecules were treated as potential obstacles rather than ideas that could be tested in subsequent investigations or useful for pushing the consensus knowledge of the classroom forward. In addition, Kami's perception of the linear trajectory for developing this knowledge prevented her from probing students' ideas about molecules to clarify the meaning that students applied to this term and even whether students had a coherent understanding about molecules.

1.4 Kami's response

Watching the classroom video prompted Kami to reflect on the challenges of managing the range of student ideas that were raised during the discussion and how her decisions for what ideas had access to the conversational floor and her responses to those ideas affected her students.

> I didn't manage the discussion very effectively, because I kind of let it go off in those directions. It's always a tough balance for me: what to include, what to leave out, you know? Can I validate their thinking and wondering at the expense of boring and disengaging the other kids in the class? How to manage that whole thing? It's a balancing act. I'm not sure this was the right balance. […] I think I sacrificed a lot of kids' thinking for the patterning of discussion and validating of the people who want to share things. And, I don't think that was a good sacrifice to make after watching this. (Kami Interview, 2/8/13)

In this excerpt, watching the classroom video prompted Kami to consider the pedagogical challenges involved in helping students achieve a common epistemic aim when students had different levels of prior knowledge. She attributed students' lack of engagement to students' inability to understand advanced ideas, yet she also acknowledged the desire to validate all students' ideas. Thus, she recognized how her responses to student ideas influenced her students' opportunities to learn and their ability to participate in the knowledge-building work. These tensions led Kami to consider alternative activity structures that would allow students individual sensemaking opportunities to use "their level of knowledge at wherever they were" (Moment 15, 2/8/13) to construct coherent accounts of the phenomenon. In doing so, it would allow all students to participate in the sensemaking work, rather than limiting these opportunities to those who participated during whole-class discussions. In addition, Kami hoped students might be able to think more deeply about the ideas of others and how they related to their own.

> In a general discussion like this, my hope is always that the kids who are not involved in the discussion will be going, "Molecules? What's a molecule? Atom? What's an atom? What are they talking about? What's a particle? What's string theory? Hmm, does that have anything to do with this? Why are we talking about it?" (Kami Interview, 2/8/13).

While this potential future action would still not resolve issues related to the complexity of managing student ideas during whole-class discussions, Kami's reflections showed evidence that engaging in retrospective noticing (Mason, 2011) sensitized her to issues related to epistemic agency and prompted her to think about creating additional opportunities for her students to participate in the intellectual work, both individually and by sharing their ideas in small groups.

> I could have broken them into small groups, maybe, to have a quick discussion about what they thought was going on. Some way that everybody got a chance to articulate what they were thinking rather than just a few people in great detail. (Kami Interview, 2/8/13)

From a professional development perspective, using video to reflect on one's practice made visible Kami's commitment to valuing students' ideas and creating opportunities for students to participate in the knowledge-building work — commitments that we revisited during future cogenerative dialogues as we considered how to use students' ideas more productively and enhance student agency in the classroom. In addition, there was a shift in Kami's noticing from attending to moments related to the teacher's decisions to noticing her students' responses to her actions and considering how to make decisions to enhance student learning. M. G. Sherin and van Es (2005) found similar shifts in teachers' focus on pedagogy to focusing more on attending to students' thinking.

2. Shift 2: Helping Kami notice students' attempts to exert epistemic authority in the classroom

The second noticing shift involved Kami noticing evidence of students needing to exercise epistemic authority and considering what students need to be convinced of a given claim. During Lesson 3, students continued to develop their model by testing Zachary's hypothesis that odors traveled through the air in the form of a gas. To generate evidence to support the gaseous state of odors, groups of students sorted objects and inductively generated a list of characteristics for solids, liquids, and gases. Students would use what they had figured out to make conclusions about odor's state of matter.

Kami projected a characteristics list (see Figure 9.4) that she claimed synthesized each group's ideas, "OK, take a look up here. Look it — this is the consensus. Almost every one of you had all of these things on your list. Some of you had some of them. Some of you had others. OK?" (Kami Observation, 2/11/13).

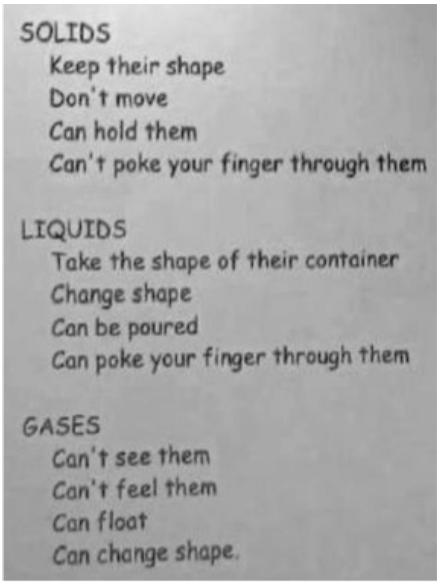

Figure 9.4. Consensus list of characteristics

As Kami reviewed each characteristic, some students voiced their disagreement and constructed arguments to revise the list. For example, one student argued that there were examples of solids, such as Jell-O, through which they could poke their fingers. However, students' efforts to question the validity of these characteristics were ineffective, as Kami argued that the characteristics list represented the class consensus, "The consensus of your classmates is that a solid: you can't poke your fingertips without breaking it" (Kami Observation, 2/11/13). Kami then shifted the conversation to use the list to answer the initial question about odor's state of matter, which Zachary claimed was a gas (turn 2).

Turn	**Discourse**
1	T: So, let's go back to our first question of the day, "What's an odor?" Zachary.
2	ZACHARY: It's a material in a gas state, gaseous state.
3	T: It's a material in a gaseous state. Now we know the answer to your question. That's excellent. Okay?
4	T: I'll entertain objections later. This is the consensus that everybody came up with. Alright? There might be a few exceptions on some of these possibly. Those of you who want to talk about exceptions to these, we will meet after class and talk about exceptions. So, make a note. Okay? It'll only take a minute. All right.

(Kami Observation, 2/11/13)

Kami's actions reinforced the teacher's traditional role as a source of epistemic authority, as she quickly validated Zachary's idea, without pushing for further justification, and denied students who questioned the list's validity further access to the conversational floor.

By the beginning of Day 2 of Lesson 3, Kami wanted to add students' conclusion that odors were gases to the class' principles list, a public document that reflected the classroom's consensus knowledge, "We asked that question and we came up with an answer. That's what you guys said, 'Odor is gas.' Is there anyone who disagrees with that statement?" (Kami Observation, 2/13/13). However, students questioned the validity of the evidence used to support this claim. First, students question the sufficiency of a homework reading as evidence for why odors were gases because it did not "really explain it" (Kami Observation, 2/13/13). Second, when Kami presented the consensus characteristics list as evidence, students questioned its authenticity and authorship.

Turn	Discourse
1	T: Hang on. We know this about gases, right? We figured this stuff [points to list of gas characteristics] out ourselves.
2	CHASE: No, no, not true.
3	T: We figured these things out ourselves.
4	CHASE: Not true.
5	T: We figured these things. It's not an arguable point. This is our list that we came up with as a class.
6	Ss: No.
7	DAVID: It was already there.
8	CHASE: No, there was a problem with the gases.
9	T: No. This I what we came up with in our class. I put this list together for your class.

(Kami Observation, 2/13/13)

Students claimed that Kami compiled the list with little student involvement, "[The list] was already there" (turn 7), and met resistance when they sought to challenge the list's validity. For example, Chase used steam and smoke as examples of visible gases and cited his ability to see steam when they heated ice and menthol to support their argument.

Turn	Discourse
10	CHASE: You know how you're saying that you cannot see gases? Well, there is evidence against that.
11	T: Yeah?
12	CHASE: Hence the menthol experiment. When the menthol and the ice actually... When we melt them, and they turn to liquid, and they [inaudible], you said look at the steam coming up, which was a gas, which we saw, so you can see gases. Certain gases you can see and are visible.
13	T: Here's the thing. You're assuming that the things that you've always thought were true are true. And they might be some of them. But scientists, rather than believing what they've always believed, they look really closely at the evidence and they let the evidence talk to them.
	[…]
37	CHASE: Can you change the characteristic of gas?
38	T: If you want to say, "Can't see most of them or some of them," we can do that if you think that's true. I'm not sure that we can't see.

(Kami Observation, 2/13/13)

Rather than recognizing Chase's attempts to use evidence from the phenomena, Kami seeded doubt in Chase's argument ("You're assuming the things that you've always thought were true are true") and refused Chase's request to qualify the characteristic on the consensus list to account for Chase's concerns. It is unlikely that Chase knew that visible steam is actually small liquid water droplets suspended in the air, as steam looks visibly different from liquid water in a cup.

In summary, there were several issues related to epistemic agency and considerations that influenced students' ability to exercise epistemic authority to assess the sufficiency and validity of the evidence and shape the class consensus knowledge. Kami's resistance to revising the list to account for students' concerns maintained her institutional authority over "what counts" as knowledge. Consequently, there was an unintended shift away from the intended epistemic aim of deciding odor's state of matter to persuading the teacher that the consensus list required revision.

2.1 Post-Lesson Cogenerative dialogue

I conducted a cogenerative dialogue after the lesson to provide Kami with the opportunity to reflect on the lesson, which largely involved discussing her frustration that students could articulate an argument for why odors were gases, yet not believe it, "What troubles me is that they [students] can rationally explain to me why something is true and not believe it" (Kami Interview, 2/13/13). From an outside perspective, it was not surprising that some students were not convinced that odors were gases because students were dissatisfied with the validity and persuasiveness of the available evidence and there was no explicit discussion about the justification used to support Zachary's claim (Kami Observation, 2/11/13). Thus, my goal, from a professional development perspective, involved helping Kami articulate her frustrations and consider potential explanations for why her students were not convinced.

2.1.1 Why weren't her students convinced that odors were gases? I asked Kami to clarify what she meant by a rational argument, which she described as a "rationally-arrived-at" conclusion "made up of evidence that can't be explained any other way" (Kami Interview, 2/13/13). Using her model of a rational argument, I asked Kami to revisit a specific student's argument that she described as rationale to consider why he still might not be convinced that odors were gases.

Turn	Discourse
1	I: So you're saying Clay could go from A to B to C and conclude that odors are gases, but he's missing why -- he's still not convince that this link is true.
2	T: Right. It's like he's not. The rational process doesn't affect his understanding.
3	I: And why is his thought process "irrational"?
4	T: Why is his thought process irrational? Because it's not based on evidence.
5	I: So... What could you help Clay to then do to be more convinced that odors are gases?
6	T: Have him put together the evidence.

(Kami Interview, 2/13/13)

A teacher might interpret a rational argument as evidence of student understanding, because he or she might already know the answer. However, the students' actions suggest that they were critically assessing their understanding and the evidence used to support the proposed claims. From a professional development perspective, my goal was to help her shift the locus of epistemic authority by focusing less on why she believed Clay's argument was rational to considering why Clay and other students might not have been convinced and what they might have needed to be convinced of the claim's validity (turn 5). In doing so, it enhanced the students' epistemic authority because students were positioned as the agents responsible for evaluating the validity of scientific knowledge in the classroom.

2.1.2 Noticing alignment between students' actions and desired knowledge-building roles. In addition to using the epistemic considerations and agency lens to understand why her students were not convinced that odors were gases, it was also important for Kami to recognize that her students were not simply trying to challenge her authority; rather, their actions demonstrated a desire to exercise epistemic agency and contribute to shaping the classroom consensus knowledge (c.f., Candela, 1999). To do so, I referred to Kami's written vision statement that articulated her ideal student role to help her notice the ways in which her students' efforts to critically evaluate the evidence was consistent with her desire for her students to be "critical consumers of one's knowledge" (Kami Vision Statement, 2/4/13).

Turn	Discourse
1	I: If you looked at your vision statement about what you want these kids to learn, so much about what being critical consumers of one's knowledge, being able to evaluate thinking.
2	T: Yeah, I know.
3	I: Um, having confidence in their ability to think and figure things out, to be better readers and writers.
4	T: Yeah.
5	I: Hope that they learn how to critically assess other people's ideas, and more importantly their own ideas, and to discuss it and make improvements and additions to their own thinking. This seems very fundamental to like... It seems very aligned with=
6	T: =It does, doesn't it?

(Kami Interview, 2/13/13)

Her students were "critical consumers of one's knowledge" (turn 1) who "critically assess[ed] other people's ideas" (turn 5) by questioning the validity of the consensus characteristics list and the evidence used to support those ideas. Furthermore, Michelle's reluctance to use a reading as evidence aligned with reasoning that Kami used earlier to object to her students' use of the term molecules. Kami believed that her students used authoritative sources, like textbooks or the internet, to justify their knowledge about molecules rather than critically assessing the justification used to derive read claims, "I want when they read, 'All matter is made up of molecules,' I want them to go, 'Really? How do we know that?' Like, I don't want them to swallow a fact just because somebody tells them" (Kami Interview, 2/13/13). It is possible that Kami's persistent requests for her students to articulate the evidence used to support their claims about the molecular basis of matter sensitized her students to consider the appropriateness and sufficiency of their evidence and the detailed mechanisms used to justify student's predictions about what might happen in the flask demonstration.

In summary, engaging in this cogenerative dialogue helped Kami take seriously students' concerns about the validity of the evidence used to support the claim that odors were gases and recognize that students need the opportunity to coordinate their claims with evidence to construct robust understandings about phenomena.

2.2 Creating opportunities for students to assess the validity and sufficiency of evidence.

Since the gaseous nature of odors was an important component of the model explaining why odors could travel across the room, Kami and I decided that it was important to use what we had figured out during the cogenerative dialogue to address students' concerns. To do so, we discussed an activity that would create an opportunity for students to evaluate the validity of the available evidence to support or refute the gaseous nature of odor and use this evidence to construct an argument for whether odors were gases. Consistent with the cogenerative nature of our discussions, Kami and I discussed the goals and principles that would guide the activity's design, yet it was the teacher's responsibility to operationalize our ideas both in the actual activity design and the enactment. In what follows, I explain the principles guiding the activity's design using evidence from the observation and the post-enactment cogenerative dialogue.

2.2.1 Created opportunities for students to coordinate claims with evidence. During the cogenerative dialogue, Kami recognized that providing students with the opportunity to "put together the evidence" (Kami Interview, 2/13/13) might help students be convinced that odors were gases. Kami constructed a handout (see Figure 9.5) for each student to record their opinion about whether odors were gases. Student would then work in small groups to systematically document the evidence for why odors were or were not gases. Students would then use the evidence to reconcile competing ideas and construct an argument for whether odors were gases.

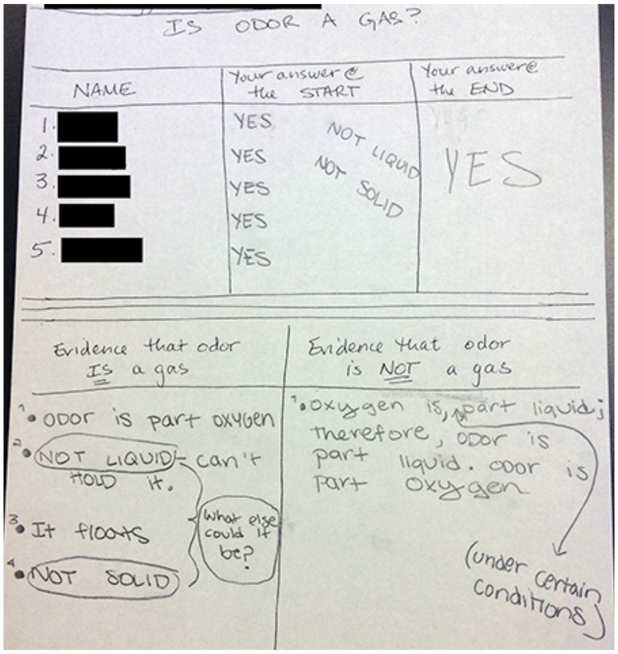

Figure 9.5. "Is odor a gas?" activity sheet.

Kami decided not to provide students with the constructed characteristics list due to the controversy surrounding its development. Thus, she left the task open to see what evidence the students would identify to support their claims (Kami Interview, 2/20/13). Kami argued that it was important for her students to have the opportunity to reach their own conclusions to "own" their knowledge, "I wanted them to own it, and I wanted them to, very explicitly, connect evidence to making a decision — coming to an answer … answering a question" (Kami Interview, 2/20/13). Kami expressed a similar epistemic stance when explaining the rationale for her responses to students' ideas about the particle nature of matter.

2.2.2 Designed groups to ensure that students could access conversational floor. To support students' opportunities to exercise epistemic authority, each student was expected to share their opinion before and after the discussion and consider how their ideas might change in response to the presented evidence. Thus, students in the group had the opportunity to build on or engage with one another's ideas. To ensure that students had access to the conversational floor, Kami designed the groups to spread out 1) students "who would argue about anything" and were strongly committed to their prior knowledge and 2) students who were "typically" quiet. In addition, she paired students who could press one another to clearly express and justify their ideas, "I put Zachary with Chase, because he's really good at kind of marshaling the evidence and thinking clearly about it" (Kami Interview, 2/20/13).

2.2.3 Students have epistemic authority to influence trajectory of the classroom learning. Although Kami had previously communicated to her students that their questions and ideas would shape the trajectory of the classroom learning, students realized that the pre-planned instructional sequence influenced what questions were investigated and how, "On the next page, it tells us what we're going to do" (Kami Observation, 1/30/13). Consequently, students did not perceive teacher's efforts to elicit students' ideas to be authentic. To enhance student agency and the authenticity of their role in shaping the classroom knowledge, Kami told her students that their conclusions, regardless of the outcome, would influence the trajectory of the class' learning.

Turn	Discourse
1	ZACHARY: What if we come to a conclusion that all of us agree, but it's the wrong answer?
2	T: The wrong answer?
3	ZACHARY: Like, you know it's the wrong answer, but we think it's the right answer.
4	T: Well, here's the thing about science. If everyone agrees and there's evidence that supports that, that is the right answer. That's how you figure out what the right answer is.
5	ZACHARY: But what if everyone agrees and there's no evidence, but everyone agrees, and we do come to a conclusion? Will we still study…? Like, let's say we think that odor is not gas, but it really is and we (agree with each other). Will we still study gas after that?
6	T: No. If everyone agrees that odor is not a gas, why would we study gasses? We're trying to answer this question. How can I smell different things nearby and far away?

(Kami Observation, 2/20/13)

Kami enhanced the students' position as epistemic agents by noting how the students' consensus decision would influence the trajectory used to achieve the epistemic aim, "If everyone agrees that odor is not a gas, why would we study gases? We're trying to answer this question, 'How can I smell different things nearby and far away?'" (Kami Observation, 2/20/13). Given students' previous unsuccessful attempts to revise and shape the consensus knowledge of the classroom, students were nervous with this new responsibility and the implication of getting the "wrong answer." Normally, the students had a safety net that ensured that the students would learn whether they had the right answer before moving on to the next activity. However, Kami explicitly removed this safety net, which empowered students and ensure that they would take this task seriously. To facilitate this shift in epistemic authority, Kami explained the epistemic criteria that should guide the evaluation of students' claims, such as its fit with the evidence and its ability to persuade others (turn 4).

2.3 Cogenerative dialogue after enactment.

During the cogenerative dialogue, Kami could reflect on the activity's enactment and articulate what she had learned about how to support her students' engagement in scientific practices.

2.3.1 Reflecting on students' use of evidence. At the basic level, Kami was surprised that all groups came to agreement that odors were gases without the need for more argument (Kami Interview, 2/20/13). However, there was no whole-class discussion of each group's justification for why they agreed that odors were gases. Thus, it was not clear what reasoning each group leveraged to draw their conclusions or how students used the evidence to revise their ideas. Nevertheless, Kami was confident that all students had a justified rationale for their conclusion, as evidenced by what she heard while walking around during small group discussions.

Using evidence from the activity sheets, Kami observed that students cited some of the characteristics present from the consensus list, which she indicates was evidence that some of the students "internalized" and agreed with some of the list's characteristics because they used them as evidence to support their claims (Kami Interview, 2/20/13). Thus, she learned to notice that this use of evidence was more meaningful because students were choosing what evidence they believed helped to justify each side of the argument. When reflecting on what she would do differently, Kami explained that she would have asked each student to list the evidence used to support their initial claims about the states of odors. In doing so, students' articulation of the evidence would be used in the context of justifying their own claims rather than compiling a list of evidence for arguments that might not align with their beliefs.

2.3.2 Reconsidering what is needed to support student understanding. From a professional development perspective, the iterative cycle of reflection and co-planning prompted Kami to question her assumptions about what students understood and to think deeply about what it means for students to meaningfully construct robust scientific knowledge. At first, Kami considered students' ability to construct a rational argument as evidence of understanding, yet after teasing apart why her students might not be convinced, Kami recognized that her students needed the opportunity to coordinate claims with evidence.

> My first thought was they just forgot. […] And it would've been smart at that point to say, 'OK, you need to argue? Let's figure this out and do something like this [activity]. Of course, they need to own the material and understand how evidence affects decision-making in science and that kind of thing, and a small group discussion format is a really good way to do that. (Kami Interview, 2/20/13)

At the same time, Kami recognized the intellectual challenges involved in designing activities to support student agency.

> I think it takes more prep time to let the kids do more of the work in the classroom. […] You know, time, where I can just sit and think through the lesson, like: What are the main concepts that I'd like to get to? How can I structure it -- not do it, but structure it so that there's an opportunity for them to arrive at those places? And it's very hard to find that time. (Kami Interview, 2/20/13)

2.3.3 Reflecting on students' roles as epistemic agents. Kami reported that she was pleased that Zachary raised concerns about their role in shaping the class consensus knowledge, "I wanted them to feel like it was their decision-making process" (Kami Interview, 2/20/13). At the same time, she was nervous about what exactly her next steps would be if the entire class believed that odors were not gases, "My blood pressure went up. I don't know if my face flushed, you'll have to look at the film. I was like, 'Oh my god. What am I gonna do then?'" (Kami Interview, 2/20/13). Kami's reflection revealed some of the struggles that teachers might go through as they seek to enhance student agency to shape the trajectory of the classroom learning, yet still make progress towards developing the target model. Like Laura, who considered how she would use evidence to help students develop a particle model of matter, Kami was able to articulate a pathway using evidence to help students figure out that odors are gases, "I would have said, 'OK. Odors are not gases,' which gets us back to, 'What are they? So, what are they?'" (Kami Interview, 2/20/13). Thus, our cogenerative dialogue not only led Kami to create opportunities for students to exercise epistemic authority to make decisions about whether odors were gases, but the teacher considered how she would continue to support student agency beyond this activity to help students achieve the desired epistemic aim.

Chapter 10: Discussion of Noticing Shifts

The previous chapter presented findings from an intervention that helped Kami notice and account for epistemic issues that could enhance her students' position as epistemic agents and meaningful users of scientific practices. Looking across both studies, I considered how the Kami's noticing shifts and learning could address some of the successes and challenges identified in Study 1.

1. Teachers need clarity on how their role is complementary to, yet distinct from, students' knowledge-building role

The study's findings suggest challenges for teachers when interpreting what their roles should be when redistributing knowledge-building responsibilities from the teacher to the students. Kami's role as the teacher was much more explicit than her students' knowledge-building role. Kami felt that it was her job to design a sequence of instruction that would help students construct robust conceptual understandings. Within this vision, the teacher, rather than the students, were the agents responsible for inducing conceptual change, "I feel like it's my job to, in teaching them science specifically, to open up their minds a little bit to the possibility that there's a way they haven't yet imagined that things might work" (Kami Interview, 2/13/13).

Beyond acknowledging that students ought to participate more in class, her vision for her students' role was less developed, "The piece about what I want, what's the student's job in my classroom, I had never thought about before. And I have ideas, clearly, about what the students' job is in my classroom, like what's the student doing here" (Kami Interview, 2/13/13). Her discussion of her students' role was often in the context of describing their affective response to her planned activities or whether students had made decisions to engage in the learning.

> They're sucking in information from their environment all the time, but sort of an attitude of, "I'm here, ready to be a part of what's gonna happen," I feel like that's something they have to get to, even if it's not a conscious thing in their brain. That's something they have to get to before effective learning can take place. (Kami Interview, 2/13/13)

However, there was less clarity on the role that students would playing in supporting "effective learning" or the role that teachers might play in facilitating that work. Unclear roles and expectations could lead teachers, like John, to fall back to more traditional knowledge-building roles.

2. Teachers' instruction needs to be responsive to students' developing ideas and questions.

Building on prior work documenting the challenges involved in the planning units that were responsive to students' ideas and questions (Lo et al., 2014), this study highlighted the challenges that teachers faced with managing a range of student ideas and questions that might differ from their planned sequence of instruction. A strict enactment of the planned instructional sequence might hinder student agency, as the curriculum, rather than students' questions, would drive the curriculum. In addition, students who might have more advanced knowledge might not gain access to the conversational floor, which would have a negative influence on students' ability to shape the consensus knowledge. Thus, the study's findings note the importance of noticing *whose* questions and ideas were driving the instruction and *who* was the agent responsible for testing, revising, and reconciling competing ideas to reach consensus. In response, teachers need to understand each activity's role in addressing one or more aspects of the explanatory model so that they could be used in a more flexible, yet coherent ways.

One of the reasons for a rigid enactment of the curriculum involves teachers lacking trust that a responsive instructional approach would help students reach the desired conclusions on their own. For example, Kami believed that students would be confused or not develop a robust particle model of matter unless they participated in her planned sequence of instruction. However, noticing the effect of her decisions on her students' learning compelled her to recognize the importance of students exercising epistemic authority and consider alternative pathways that would respond to students' conclusions and help them make progress towards developing a canonical model. Rather than assess the correctness of students' ideas, teachers should provide students with the opportunity to use additional phenomena or activities to test or revise their ideas. Both Kami and Laura articulated potential ways in which they might use activities to test and revise students' ideas. In doing so, the teacher facilitates student learning, while preserving students' opportunities to shape their own learning. Teachers with less experience might not have a deep understanding of the curriculum or the content to be able to respond to student's ideas. However, with experience and curricular supports, teachers might be able to articulate with increasing specificity the moves they might use to shape students' learning, yet preserve student agency.

For the learning to be responsive to students' learning, students should have a role in determining what counts as scientific knowledge and whether their posed questions have been adequately addressed. Both studies demonstrated the ways in which teachers' attempts to communicate reform-minded student roles and responsibilities could fall short if not supported through appropriate norms and routines. For example, Kami would often remind students that they were the drivers of the curriculum, yet in practice the teacher or the curriculum determined the direction of what students would do next. Noticing the misalignment between her desired vision and actual classroom practices, Kami took steps to shift the epistemic authority from the teacher to the students. For example, Kami pledged to use the students' decisions about whether odors were gases to guide subsequent instructional decisions as long as they used evidence to support their answers. Similarly, Laura used similar moves to assess whether students were satisfied with responses to questions of interest.

3. Teachers need to create a space for individual sensemaking.

In addition, there were challenges involving what ideas were worth taking up and discussing as a whole-class.   When students discussed ideas related to the molecular basis of matter, Kami worried about how those ideas might be perceived by students without this prior knowledge and its effect on their ability to make sense of the phenomenon. Kami's initial response involved questioning the sufficiency of the evidence used to support students' prior knowledge. However, she later noticed how her decisions hindered students' ability to use their ideas to shape the classroom knowledge and prompted her to consider alternative ways for students to construct their models. Both studies showed that creating opportunities for students to engage in individual student sensemaking, rather than co-constructing explanations as a class, could enhance student participation during whole-class discussions. However, this approach requires classroom norms that give students equitable access to the conversational floor to share their constructed ideas with others.

4. Teachers need to create opportunities for students to coordinate claims with evidence and reconcile competing ideas.

For teachers to successfully shift the epistemic authority from the teachers to the students, teachers need to give students the opportunity use evidence and epistemic criteria to evaluate, test, and revise one another's ideas. Building on prior work by Sandoval & Millwood (2005), this study suggests that creating opportunities for students to coordinate claims with evidence and reconcile competing ideas was important for facilitating robust disciplinary understanding. It was not surprising that students were not convinced that odors were gases given that the conclusion was reached by a single student in the context of a whole-class discussion with little discussion about what evidence was used to support the student's claim. In addition, there were concerns about the validity of the evidence used by the teacher to support the claim. For this work to occur, students need the opportunity to use evidence and argument to reconcile competing ideas so that students understand how and why their model is valid compared to potential alternatives. In addition, students need to have the epistemic authority evaluate their claims and the sufficiency of the evidence used to justify their claims about odor's state of matter.

Chapter 11: Conclusion

This dissertation put forward a vision for how using an activity structure, characterized by students presenting one's ideas to others and using evidence and argument to evaluate and reconcile competing ideas to reaching consensus, could be useful for realizing the reform vision called for in NGSS. By attending to aspects of classroom practice important for supporting meaningful student learning, teachers could use their interpretations to enhance the meaning that students apply to their learning and the robustness of their conceptual understanding.

To promote these shifts in classroom practice, I presented an analytical framework composed of three epistemic lenses that embrace important issues for teachers and students to attend to when constructing, evaluating, and revising scientific knowledge: epistemic aims, considerations, and agency. Using the three analytical lenses of epistemic aims, considerations, and agency, Study 1 examined the successes and challenges involved in using the activity structure designed to position students as epistemic agents responsible for constructing and evaluating scientific knowledge in meaningful ways. The findings from this research used classroom evidence to justify how and why each of these epistemic issues are important for teachers to attend to and account for to support student learning. In addition, these findings demonstrate how synergistic attention to each of these components is necessary for supporting students' engagement in scientific practices. Each Study 1 teacher showed evidence of one or more epistemic lenses guiding their decisions: Kami foregrounded the use of disciplinary norms and practices (epistemic considerations), John foregrounded achievement of the content goal (epistemic aim), while Laura foregrounded the students' role in constructing knowledge (agency). However, meaningful scientific learning involves joint attention to all three epistemic issues.

The episodes discussed in this dissertation research make visible the multitude of factors that teachers must attend to when supporting students' engagement in scientific practices. In response, Study 2 considered strategies for helping teachers to notice these epistemic aspects of classroom practice and how they influence students' engagement in scientific practices.

Given the prevalence of teacher-focused noticing (M. G. Sherin & van Es, 2005), this study demonstrates the utility of using video excerpts or discussing classroom events as representations of practice to help teachers acknowledge their blind spots and refine their professional vision by noticing how their decisions affect student sensemaking and meaning-making and leveraging their interpretations to enhance student agency. This case study of Kami's classroom demonstrated the complex challenges that teachers face when they attempt to support students' engagement in scientific practices. Kami considered and posed to students the question, "Why should we care?", to enhance the epistemic value applied to classroom activities. She was attentive to the need for students to use evidence from a sequence of instruction to develop important disciplinary understandings. While promoting these important shifts, she took steps that hindered other students' engagement in scientific practices, such as preventing students from posing plausible ideas that she felt might distract students from developing the target understanding using her preferred trajectory. Through watching the classroom video, she noticed how her response to student ideas hindered student agency and responded by considering alternative activity structures for students to use and build on one another's ideas to make sense of phenomena. The study's findings suggest that the three analytical lenses could provide teachers with a useful framework for motivating shifts in classroom practice, reflecting on the effectiveness of these decisions, and informing subsequent moves in service of enhancing the meaningfulness of students' engagement in scientific practices.

These findings reinforce the importance of giving teachers the time to reflect and co-plan with others. Simply giving Kami more time to reflect would not have led her to notice her use of student ideas or recognize the underlying issues that prevented her students from being convinced that odors were gases. However, intentional discussions to help Kami notice these important features of meaningful practice were important for helping Kami to understand why these epistemic issues were important and how to leverage them to inform her decision-making. Sustained efforts to notice these aspects of classroom practice enhanced Kami's ability to notice what her students were thinking and account for her interpretations in her classroom (c.f.,M. G. Sherin, Russ, & Colestock, 2011).

The design-based intervention used to help teachers to notice these issues in the context of their classroom practice could offer theoretical and generalizable contributions to our field's understanding of how teachers come to understand the instructional shifts required to accommodate an authentic, practices-centered instructional approach and appreciate the complexity of the task required to implement these shifts from the perspectives of the teacher, students, and professional developer (Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003).

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Appendix A: Teacher Modeling Interview

Purpose of the interview: The questions will address the purpose of modeling and characteristics of good models from both the student and teacher's perspective.

1) How are your students doing with modeling?

2) General Modeling Questions - from teacher and students' perspectives
   a) What is the purpose for modeling in your classroom?
   b) Do your students think that modeling is useful?
   c) What describes a good scientific model?
      - Ask for rationale for each of the criteria.

3) Discuss student model.
   a) What was the purpose for drawing this model?
   b) What do you think this student understands about X idea? How do you know?
   c) Do you think this is a good model? Why or why not?
      - Consider model's alignment with criteria mentioned in 2c

Appendix B: Sample Embedded Assessment

Examining Your Model of How Odors Move Across the Room

6th Grade Chemistry, Activity 6.2

1. Draw your consensus model that shows how odor moves across the room.

2. [NATURE OF ACCOUNT]: Does this model explain how people are able to smell odors from across the room?
   - **If so,** what parts or features of the model were most important for explaining this?

Detailed Description of Feature	How does this feature help you show how you can smell odors from across the room?

3. [NATURE OF ACCOUNT]: Looking at your model, are there changes that you may want to include in the future to improve how your model explains how you can smell odors from across the room? If so, please describe them here.

Detailed Description of Change	How does this change improve your model?

4. [NATURE OF ACCOUNT]: Look at the consensus model that you drew on p. 1. What are the key differences between your current model and your older one?

Detailed Description of Differences	What have you learned that helped you realize that you needed to change your older models?

5. [GENERALITY]: Can you use your model to **explain other, related situations,** such as how the indicator paper turned blue when your teacher placed it in a flask with a small amount of liquid ammonia?
   - **If so,** describe how your model explains this and maybe other, related situations.
   - **If not,** how could you change it so that it could explain other, related situations?

6. [JUSTIFICATION]: Think about the various activities that you or your group did in class that helped you to come up with this model. For example, the experiments you may have done, the discussions that you had with your classmates or teacher, the readings you may have read, etc.
   a. What was the most important activity that you or your group did that helped you decide what to include in this model? Please be specific.
   b. Can you describe how that activity helped you decide what to include in your model?

c. How did you know if the information that you used to construct your model was correct and accurate?

7. [AUDIENCE]: Imagine that a classmate thought that you could smell odors because the smell was like a cloud that grew and moved away from the source. You want to use your model to convince your classmate that you can detect the smell because an odor is made up of particles that move away from the source. Can you do this with your current model?

If so, explain how you would use **specific** parts of your model to help convince your classmate.

If not, how would you change your model to help convince your classmate of this?

Appendix C: Student Interview Protocol

Purpose: For each embedded assessment, the students draw a diagrammatic model or construct a written explanation to explain a given phenomenon. The purpose of this interview is to understand from the student's perspective: 1) the purpose for drawing models, 2) the epistemic criteria used to guide the students' decisions as they constructed their models, 3) the evidentiary basis for the explanatory ideas in the students' models, and 4) the students' beliefs about the utility of their models.

1. General Modeling Questions
    a. What is the purpose for drawing models?
    b. Audience: Who are these models for?
2. What was the reason for drawing this model?
3. **Nature of Account and Audience**: Can you walk me through your model and show me how your model helps to explain [how and why [X] happens] or [the stated purpose for drawing model]?
    a. Probe about the significance of the idea
        I. Why is this idea important?
        ii. **Justification**: Where did you learn about this idea?
    b. Probe about the representational choices
        I. What does this mean?
        ii. Why did you decide to show this idea in this way?
    c. Repeat back to the student your interpretation of the student's model to ensure that understand it.
4. **Audience**
    a. If someone who wasn't in Dr. K's class picked up your model, do you think that they would be able to understand [x idea]?
    b. Are there any ideas might be confusing about this topic? How might you use your model to help them?
    c. What happens if someone thought that [common misconception]? How would you use your model to convince them of [correct idea]?
5. **Generality**
    a. Do you think you could use this model to help you understand another situation or do you think it only helps you to understand [the targeted situation]? Why?
        I. Ask for specific examples and ask how the model could be used to explain it.
        ii. If student is unable to come up with an example, suggest one.
6. Reflecting on Model
    a. If you were to do this model again, is there anything that you would do differently?
    b. Lesson 6 and 16 Odor Models: How did this model differ from earlier versions of the model?
7. Consensus Process
    a. Did everyone in your group agree with the ideas that were found in this model?
    b. What ideas did people disagree with? How were those disagreements resolved?

Appendix D: Transcript Chunking Example (Laura Observation, 1/27/12)

The bold headings (e.g., Bell Work: Review Properties of Gases) indicate the different episodes of the activity. In the right column, I identified the type of modeling activity and whether it involved students working individually, in small groups, or as a whole-class. I used italics to identify some of the relevant features that I examined related to meaningful scientific practice.

Transcript	Activity
Bell Work: Review Properties of Gases	**Whole-class, model construction**
T: Alright, here we go. See if you could read the directions. […] [Projects bell work] So, all the vocab goes away, just the bell work. [Kids putting stuff away, taking bell work out] T: It's a good review.	*Reviewing properties of air that could be leveraged in students' air models*
T: Ok, so what would we say for #1? [...] ERIC: Odors are matter in the gaseous state. T: Excellent. I like how you said gaseous too. Because a lot of people just use 'gas' but it kind of goes with it as gaseous. G-A-S-E-O-U-S. It's in the gaseous states odors are matter in the gaseous-- […] T: Ok #2. [hands go up] I'm looking at Rhianna... Help us out. RHIANNA: Air is matter in the gas state. T: There you go. Same thing. Same thing. So, odor is as a gas, air is a gas. T: Alexandra, #3. ALEXANDRA: Odors float through the air. T: Oh, good. T: Any other words besides "float?" I'm trying to think what I would say for that... Sally? SALLY: Float, I mean, not "float." Travel. T: Travel. T: Anything else, Jacob? JACOB: Move? T: Move. Good. T: All of those could work. So, odors are moving, it's doing something through the air. T: #4...Henry. HENRY: Air has matter because it has mass and volume.	

T: Good. Mass and volume.
T: So, we have proven, we have evidence that air is matter, has mass, has volume.

T: Last part. Jeremy?
JEREMY: Air takes the space of its container.
T: Good.

T: Yeah?
S: I wrote air takes the shape of the container.
T: Ok, good so it takes the space of the container. Space of it, shape of it. Yup, that works.

T: So, if you're talking about the question about gas definition, we could say it takes the shape of the container, right? So, it's matter, it has mass, it has volume.

T: If we all agree with all of this?
Ss': Yeah.
T: Right? So, if we agree with it and air is something, right, it's not nothing, it has mass, it has volume.

Activity 4.1 — **Whole-class model construction**

T: […] On the first page 9, there was a model that you drew of air. You see your model? OK. We're going to try it again. Put that away though cause we're looking at pg. 9. — Framing of Activity 4.1

T: And now go to pg. 45, cause that's where we are today. 45.
S: [Turning to page.]

T: Ok, on 45 it says, "How can I model the things gases do?"
T: I need all of your help today. People were telling me earlier that this kind of hurts your head. So that's ok. You have a lot of thinking to do, right Ariana? Yeah.

T: So, here's what I need you to do. It says, "How can I model the things gases do?"

T: Purpose. Everyone point to the purpose. Purpose says, “You will examine the two characteristics of air. You will also create models of what you would see if you could look at the smallest parts of air in three different situations.” So, we're going to create models.	*Epistemic aim*
T: “If we had a special instrument that would allow us to see the smallest parts of air, what would it look like if you could focus on one tiny spot inside the flask?” T: So, if you turn to the page to 46, there are three circles. We're only going to do the first circle and it says, “Model 1: Air in a flask.”	*Epistemic considerations: consider non-visible components of phenomenon*
Show flask of air	**Whole-class, model construction**
T: So, let's say, oh, I could do this, here's this is the stopper and the stopper makes it so that the air that's inside here can't get out. Right, so I'm going to fill this with air [moves flask back and forth]. There you go. Fill it with air. Alright then. Stopper on. S: That's funny. T: Would you all agree that I have filled this with air? Ss: Yes. T: Ok is air something, according to what we said? Ss: Yes. T: OK, there's something-- it has mass, it has volume, it has matter.	- Show “phenomenon” Reaching consensus on what is to be explained
Students construct initial air model	**Individual model construction**
T: If I were to take a tiny part from the middle of the flask in that picture and I were to look at it under a special microscope, special instrument...for extra credit find out where you could find one of these... to look at a special microscope, what would I see? Ss: [construct models]	Framing of task for students to construct individual air models
T: There's no right or wrong right now. Right, we're just kind of trying to figure out what it is. What would we see? [Projects lesson goals]	*Norms to promote academic risk-taking*
T: What does air look like under the special microscope if I could see the air. I know I can't see it. But if you could see it, what, because we put it under this really special microscope, what would we see? T: And label the parts cause then we're going to put it over here by the document camera and you could explain it to everybody else.	*Epistemic considerations: include non-visible components; use labels to clearly communicate ideas to others.*

Transition to Whole Class Presentation of Models	**Whole-class model sharing/evaluation**
T: So, Becky, let's see what you have. Yep, bring up your book. BECKY: [comes to the board] Ss: Ooh, I wanted to go up.	
S: We're only supposed to do the first one [referring to the first of 3 models.] […] T: Just the first one, cause we're going to keep adding to it.	
T: Ok, so let me explain Becky's job and your job.	Activity Framing
T: So, her job is going to be to explain to you what she thinks it looks like under the special microscope. So, maybe here we can figure out where to get one of those, right?	*Articulation of students' role*
T: And, your [referring to class] job is going to be to ask S: [Questions. T: [personal questions that would help us, because we want to come up with a consensus. We want to try to figure out really what does air look like, do we think, without even having this special microscope. Or what we could do?	*Explanation of how students' work will contribute to achieving desired epistemic aim*
T: So, try to listen to what she's got and then I'm listening for your questions to see if we could get some...help in.	
T: Okay.	*Articulation of students' role*

Student #1: Becky	**Whole-class model sharing/evaluation**
BECKY: Well what I did was (represent air as) the dots and said since air is a gas, um there are so many different particles in the air. And then the squiggly lines here are probably gas.	*Student's presentation (SP-X)*
[Becky points to Jeremy who has his hand raised.]	*Student Q & A*
JEREMY: Um, is there any like any (water vapor) particles, um... BECKY: Only air. […] S: Isn't air just the gas itself so...? BECKY: Not necessarily. There might be more gases.	
BECKY: Genevieve?	

GENEVIEVE: Does like the gas separate sometimes if, I mean, does the particles separate if like, the gas is like, together?

BECKY: Mm hmm. [nods head affirmatively]

JEREMY: Which one's the particles and which one's the gas?

BECKY: The dots are the particles and the (gas are the) squiggly lines.

BECKY: Hillary?

HILLARY: Is the only stuff you like think that are in the air (is from what we breathe out is like particles of gas or do you think it's carbon dioxide)?

BECKY: Carbon dioxide I think...

S: Would you put the carbon dioxide in the (air)?
(phone rings)

S: I think it's a gas.=

T: =So where would you put the carbon dioxide?

BECKY: Um, I would put it somewhere along the...

S: I think that's the gas particles...

BECKY: Kevin? Kevin? You had something to say.

KEVIN: Are you sure it has those lines?

S: That's just a gas.

S: That's the gas.

ERIC: Kinda, like he said, like, if they're both gases, why don't they just look the same?

[inaudible murmuring]

T: Tricky. Isn't it?

T: Between one particle and another particle, what's in-between those two particles? BECKY: Carbon dioxide. T: A little what? BECKY: Carbon dioxide. [Ms. B looks pensively at the model.] [inaudible Ss comments] T: You did a great job, very good. [applause] First one going.	*Teacher asks questions about what is between air*
T: I do want you to record discussion questions, discussion is very important. So, if you've raised your hand, been called on, you might want to take note, because you might forget next week. So, make sure you remember what you're doing, because I want everyone to be part of it all here. T: Okay, Lindsey, why don't you go ahead? S: Can I go after Lindsey? T: I'll try to get... If I don't get to you today, through all of these different models at some point, everyone will have a chance. S: Good job! T: Good job trying to ask... We learned a lot from asking questions. T: That was great, Becky! […]	Framing to reinforce expectations of students' participation and why it is important.
T: Ok hang on. Do we have an answer yet? Ss: No. T: We gotta keep on going.	Students assess progress towards achieving desired epistemic aim

Appendix E: Presentation of Becky's Model Analysis

Summary of Initial Air Model
Recognizes that air is a type of a gas, but represents them as separate entities. Represents air particles (dots) and "other gases" (wavy lines) as being separate entities

Nature of Account (Descriptive): Components
Becky's attention to nature of account is describing the components of the air rather than elements that contribute to a how and why explanation, such as the behavior of the gases or the air particles

Clarity of Communication with Little Attention to Justification
Simply telling the audience what everything means

Questions about Becky's model

1. Jeremy: Water vapor in air?
Becky responds and says that there's only air particles in her model. She does not justify her claim nor consider why Jeremy's idea may or may not be viable.

Coherence between other students' models
We also see students considering coherence between other students' models. For example, Jeremy asked Becky about whether she thinks that water vapor is present in her model. We find that later, the presence of water vapor is an important idea in his model. Thus, he's not only thinking about comparing Becky's ideas, but also to his own ideas about what's going on inside of the flask.

2. S1: Aren't air and gases the same thing?
Justification/Nature of Account (Descriptive)
Becky responds that there may be other gases present, but she doesn't explain how this notion of "other gases" supports the need to distinguish between air and gases in the air. Thus, the potential for other gases that may or may not be part of the air is the reason for this distinction?

3. Genevieve: Do the gases/particles separate?
Nature of Account (Explanatory) - looking at behavior of component
She may be considering the implication of gases' behavior considering what she knows about how particles move. This is also more mechanistic because she's not only thinking about the presence of a feature, but she's also thinking about what's going on with those components within the air.

4. Jeremy: Tries to distinguish between the (air) particles and the gases in the representation.
Clarity of Communication/Meaning of Representation
The student asks for clarification about what's the air and gas in the model. So, these types of questions not only ask for clarity of what the student presenter's idea was, but also as a means of clarifying the mechanistic distinction that was being attempted. The context of this question was

also in the middle of a sequence discussing whether there should be a distinction between air particles and gas, so perhaps it was used to clarify the significance of the idea.

5. Hillary: Is "what we breathe out" part of the gas or CO2?

Nature of Account (Explanatory)

Throughout this episode, Hillary is trying to tease apart the terms air, particles of gas, and carbon dioxide, as it appears that she thinks they are the same thing. She's testing Becky's model to see what she would call what we breathe out. Thus, she's testing her model to see how it accounts for what we know. Becky responds by saying that she would give it the specific name, CO2.

Hillary is noting some aspect of cause and effect, as she's noting how the product of what we breathe out adds to what's found in the air. Thus, she's trying to think about where those components get featured in the model.

Hillary's question prompts the audience to think about this dual nature of air particles and gases and specifically where carbon dioxide would be found in her model.

Nature of Account (Explanatory)

She also provides a process that gives rise to the carbon dioxide in the model.

6. Student 2: Is carbon dioxide part of the air or the separate gases?

Use of model to identify contradictions in explanatory, mental model

This episode also indicates how this attention to the mechanism is closely tied to the ability for the representation to communicate one's ideas and help to bring to light contradictions perhaps in the explanatory, mental model.

Nature of Account (/Clarity of Communication (Representation)

Becky doesn't fully address what she thinks, but other students think that it's a gas.

Although Becky agrees that carbon dioxide is something that we breathe out and goes into the air, she has yet to claim about what the nature is and whether she would classify or represent them differently in her model. It's not clear whether Becky recognizes that having air and gases as separate entities may be contradictory.

7. Kevin: Are you sure about the wavy lines?

Transition from Understanding Becky's Ideas towards Persuasion

Prior to this point, the students were more neutral in tone about the nature of the gas and where carbon dioxide would be in the model. Their stance was more about where their answers would be.

However, Kevin now asks about whether she's sure that the model has the wavy lines (meaning the distinction between the air and gases. In his question, he is attentive to persuasion because he's trying push Becky to defend her idea for the distinction.
Two other students do not seem to understand the intent behind Kevin's question and responds to what the lines represent, the gas, rather than trying to justify the distinction.

Based on the discourse, it's not clear the exact reason for why Kevin's bringing up the concern, so it's not clear whether we think it's because he doesn't think that there should be a distinction between air and gases. He just asks about whether Becky really wants to include the wavy lines.

8. Eric: Why aren't the air and gas represented the same way?
Nature of Account: Coherence among presented ideas
Eric continues to push this distinction and asks why the air and gas are represented differently. This refers to his interpretation of Kevin's question about why the wavy lines are needed.

Clarity: Representation behind mechanism
These two speakers also further indicate the use

Audience
Although Lisa responds by saying that it was a "tricky" question, she doesn't push on Becky to respond to the other students' concerns.

8. T: What's in between one particle and another particle?
When asked about what's in between the (air) particles, Becky responds that it's carbon dioxide.

Nature of Account: Coherence among proposed ideas
T is confused, as Becky doesn't resolve the contradiction in her ideas. However, it does make sense if Becky thinks that the carbon dioxide is a gas. In that sense, then it would not be contradictory, because the air particles are this entity in which the other gases (like CO2 and others) flow in the gas. Thus, maybe she's thinking about air as being a separate entity.

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Students Participating

Initiating: Jeremy, Genevieve, Hillary, Kevin, Eric, Student 1/2, T
Responding: Becky, other students,

Overall Use of Epistemic Considerations

The students are trying to understand the students' ideas by asking questions about the various components and ideas. In their quest to understand the ideas, they consider the implications for the various ideas and their alignment with what they already know (breathe out carbon dioxide and behavior of gases and their ability to spread out like particles). In doing so, they recognize that some ideas do not match with what they know (distinction between air and gases).

At the beginning, the feeling is generally neutral - trying to understand the ideas, but then they are considering more about the persuasion EC, as they find it problematic about this distinction and are trying to persuade her that they are the same.

Perhaps one of the reasons why it did not prove problematic for Becky is because she was not able to communicate her ideas well to her audience. One could imagine, based on her responses, that she has a model in which gases exist within this entity of air particles. The students instead push on this idea of the particle nature of gases, whereas Becky has not. Although they are scientifically correct, they are unable to fully convince Becky because they are unable to justify why their idea is incorrect, nor do they fully understand Becky's model.

In addition, Becky was not attentive to her audience to recognize perhaps the rationale behind her critiquer's questions nor did she provide substantive justification for her claims. It seems that she was simply trying to communicate her ideas without having to persuade others of the validity of her claims or justify her claims to her audience.

So, high attention to mechanism, mixed attention to clarity of communication, high attention to persuasion, little attention to justification, and no attention to generality.

Appendix F: Vision Statement Prompt

You have the opportunity to cast a vision for what you think science teaching should be like at [school] and more specifically in your classroom.

Without considering the limitations or constraints for what you can do, how would YOU *ideally* like to see teaching and learning taking place in your classroom? In your response, consider the following things:

1. What is your role in this classroom? Why is this role important?
2. What is the students' role in your classroom? Why is this role important?
3. What would your students be learning? Why are those ideas important? What do you envision the learning process to be like?

What do you want your students to have learned and accomplished by the time they have left your classroom at the end of the year?

Abraham S. Lo, PhD

EDUCATION

Northwestern University, School of Education and Social Policy Evanston, IL, USA
PhD, Learning Sciences 2010-2017

- **Dissertation:** *Epistemic aims, considerations, and agency: Lenses for helping teachers analyze and support students' meaningful engagement in scientific practices*
- **Committee:** Brian J. Reiser, PhD (chair), Christina V. Schwarz, PhD, Miriam G. Sherin, PhD, Bruce L. Sherin, PhD

University of Pennsylvania, Graduate School of Education Philadelphia, PA, USA
Master of Science in Education, Secondary Education 2002-2003

- **Master's Thesis**: *Creating a Meaningful Learning Environment by Incorporating Students' Sociocultural Capital*
- **Advisors:** Kenneth Tobin, Ed.D.; Sonya Martin, PhD; Sarah-Kate Lavan, PhD

University of Pennsylvania, College of Arts and Sciences Philadelphia, PA, USA
Bachelor of Arts in Biology, cum laude 1998-2002

PROFESSIONAL APPOINTMENTS

Biological Science Curriculum Study (BSCS) Colorado Springs, CO, USA
Science Educator 2017-Present

University of California, Davis, School of Education Davis, CA, USA
Postdoctoral Scholar 2015-2016

- **Advisor:** Cynthia Passmore, PhD

AWARDS & HONORS

- AERA Minority Dissertation Fellowship in Education Research, 2014-15
- Institute of Education Sciences Pre-Doctoral Training Fellowship, 2011-2014
- International Conference for the Learning Sciences Doctoral Consortium, 2014
- AERA 2015 Division C Graduate Student Seminar Participant, 2015
- Dean's Urban Teacher Education Scholar, University of Pennsylvania, 2002-2003
- University Fellowship, Northwestern University, 2010-2011
- Conference Travel Grant, Northwestern University, 2014, 2016

RESEARCH EXPERIENCE

University of California, Davis, School of Education Davis, CA, USA
Initiative for Innovations in STEM Teaching, Achievement, and Research (I-STAR) 2015-2016

- **Project Goal**: Develop online resource to help K-12 math and science teachers understand the reasoning practices found in the CCSS and NGSS
- Developed video-based resources to help teachers notice students' use of math and science practices to develop disciplinary ideas: http://www.practices-resource.com/video-cases
- Coordinated development of resources and tools to help teachers understand the pedagogical and epistemological shifts involved in supporting practices-centered instruction and facilitate students' use of modeling and argumentation in math and science classrooms.

Modeling Scientific Practice in High School Biology: A Next Generation Instructional Resource

- **Project Goal**: Design and investigate an integrated online resource (curricular, pedagogical, and professional supports) to support high school biology teachers' enactment and understanding of a year-long model-based instructional sequence
- Developed strategies for data collection, data analysis, curriculum development, and professional development for participating teachers
- Observed and provided professional support for three high school biology teachers' implementation of *Model Based Education Resource (MBER): Biology* curriculum
- Developed methodologies to understand teachers' decision making and planning

Northwestern University, School of Education and Social Policy Evanston, IL, USA
Supporting Scientific Practices in Elementary and Middle School Classrooms 2011-2015

- **Project Goal**: Develop a learning progression to characterize how learners' meaningful use of scientific practices can become increasingly more sophisticated over time through instructional, curricular, and professional development supports
- Co-designed research protocol and research instruments for investigating how teachers perceive the changes involved in bringing NGSS into science classrooms and how they adapt their teaching approaches to support their students in scientific practices
- Conducted teacher and student interviews about their understanding and use of scientific practices
- Designed and analyzed assessments used to assess students' understanding and use of scientific practices
- Coordinated data collection at five research sites and supervise undergraduate research assistants

Clark University Worcester, MA, USA
Next Generation Science Exemplar System for Professional Development (NGSX) 2013-2014

- **Project Goal**: Develop web-based professional development system to help teachers engage with the major ideas within the NRC's Framework for K-12 Science Education and Next Generation Science Standards.
- Assisted in the design of a middle-school pathway examining students' use of modeling and teacher strategies to support argumentation in classrooms
- Analyzed pre and post-intervention surveys to ascertain changes in participants' understanding of scientific practices and the effectiveness of the NGSX platform

PUBLICATIONS AND PRESENTATIONS

Berland, L. K., Schwarz, C. V., Krist, C., Kenyon, L., **Lo, A. S.**, & Reiser, B. J. (2016). Epistemologies in practice: Making scientific practices meaningful for students. Journal of Research in Science Teaching, 53(7), 1082-1112. doi: 10.1002/tea.21257

Lo, A. S. (2016). *Epistemic aims, considerations, and agency: Lenses for helping teachers analyze and enhance students' meaningful engagement in scientific practices*. Paper presented at the NARST 2016 Annual International Conference, Baltimore, MD.

Lo, A.S., & Lewis, E. (2017) *A District's Approach to Implementing the CA-NGSS Integrated Model in Grades 6-8*. Presentation at 2017 California Science Education Conference, Sacramento, CA.

Lewis, E., & **Lo, A.S.** (2017) *Toolkit for Science Pedagogy: Supporting SFUSD Teachers with the NGSS Shifts*. Presentation at 2017 California Science Education Conference, Sacramento, CA.

Griesemer, C. D., & **Lo, A. S.** (2016). *Successes and challenges in promoting student sense making in modeling classrooms*. Paper presented at the NARST 2016 Annual International Conference, Baltimore, MD.

Lo, A. S. (2015). *Learning to Notice: Supporting students as epistemic agents and meaningful participants in scientific modeling*. Poster presented at invited session *Promising Scholarship in Education: Dissertation Fellows and Their Research* at the 2015 Annual Meeting of the American Educational Research Association, Chicago, IL.

Lo, A. S. (2015). *Supporting students as epistemic agents and the meaningfulness of their engagement in modeling*. Paper presented at the NARST 2015 Annual International Conference, Chicago, IL.

Lo, A. S., Krist, C., Reiser, B. J., & Novak, M. (2014). *Examining shifts in teachers' understanding of NGSS and their impact on planned instruction*. Paper presented at the NARST 2014 Annual International Conference, Pittsburgh, PA.

Lo, A. S. (2014). *Learning to notice: Supporting students' meaningful engagement in scientific practices*. In J. L. Polman, E. A. Kyza, D. K. O'Neill, I. Tabak, W. R. Penuel, A. S. Jurow, K. O'Connor, T. Lee & L. D'Amico (Eds.), Learning and becoming in practice: The international conference of the learning sciences (ICLS) 2014 (Vol. 3, pp. 1754). Boulder, CO: International Society of the Learning Sciences.

Lo, A. S. (2013). *Understanding differences in student participation in persuasive discourse while engaged in scientific modeling*. Paper presented at the NARST 2013 Annual International Conference, San Juan, Puerto Rico.

Lo, A. S. (2013). *Examining student attention to epistemologies in practice while evaluating scientific models*. Paper presented at the 2013 Annual Meeting of the American Educational Research Association, San Francisco, CA.

Reiser, B. J., **Lo, A. S.**, Draney, K., Sussman, J., & Toyama, Y. (2013). *Using assessments to capture students' understanding of epistemologies in practice across content area and time*. Paper presented at the 2013 Annual Meeting of the American Educational Research Association, San Francisco, CA.

Reiser, B. J., & **Lo, A. S.** (2012). *A framework for supporting and assessing scientific practices*. Paper presented at the NARST 2012 Annual International Conference, Indianapolis, IN.

Baker, R., Blatt, E., Hurwitz, J., **Lo, A. S.** (2003). *How school environment influences students' learning: A look at two magnet schools in the Philadelphia School System*. Paper presented at the 24th Annual Ethnography in Education Research Forum, Philadelphia, PA.

PROFESSIONAL DEVELOPMENT EXPERIENCE

San Francisco Unified School District San Francisco, CA
Middle School Content Specialist and Instructional Coach 2017-Present

- Design and enact district-wide professional development for 6th, 7th, and 8th grade teachers to support the development, implementation, and revision of NGSS-aligned science curriculum
- Co-design professional development for all secondary teacher leaders and science teachers to use video and student artifacts to cultivate cultures of reflective practice and develop strategies for organizing productive classroom discourse
- Collaborate with curriculum writers from SFUSD and Stanford to revise curriculum materials
- Instructional coach for science teachers in high-need middle schools

- Co-designed research instruments used to assess the effectiveness of curriculum materials and professional development

Northwestern University, School of Education and Social Policy Evanston, IL, USA
Teaching Assistant 2013-2014

- Courses
  - *MSED 451: Teaching K-12 Science with the Next Generation Science Standards* (Summer, 2013)
  - *LS 435: New Approaches to Science Teaching* (Winter, 2014)
- Involved in all aspects of course design, instruction, planning, and assessment of student work
- Coordinated the recruitment and enrollment of 31 teachers and administrators for Summer NGSS Course

Supporting Scientific Practices in Elementary and Middle School Classrooms 2011-2015

- Instructional coach for teachers implementing a NGSS-aligned, middle school science curriculum, *Investigating and Questioning Our World through Science and Technology* (IQWST)
- Designed professional development and instructional interventions to support students' meaningful engagement in scientific practices

Instructor, NU-TEACH: Alternative Certification Program 2011-2013

- Conducted professional development sessions with elementary and secondary teachers to refine their attention to student thinking and help their students engage in authentic scientific inquiry
- Observed and evaluated intern lessons and teaching portfolios
- Facilitated video clubs using video from interns' classrooms

Antioch and Lakes Community High Schools, District 117 January, 2015

- Led district wide professional development for two high schools (24 teachers) to help teachers understand the shifts required for implementing NGSS and design NGSS-aligned instructional units

Wissahickon School District 2005-2007

- Designed and conducted school-wide professional development sessions to help teachers redesign
  science labs for inquiry and integrate SmartBoard technology into their instructional practice
- Facilitated roundtable discussions to improve the implementation of inclusion in regular education science classrooms

University of Pennsylvania, Graduate School of Education Philadelphia, PA, USA
Consultant, Fieldwork Seminar (EDUC-555) 2005-2008

- Facilitated discussions and provided resource materials for student teachers
- Hosted classroom management and routines workshop for student teachers, June 2006

CURRICULUM DESIGN EXPERIENCE

- Middle School Core Science Curriculum, San Francisco Unified School District
- Model Based Education Resource: Biology, University of California, Davis
- Honors Physical Science, Wissahickon High School
- Earth Science I, High Tech High (Mastery Charter High School)

TEACHER CERTIFICATIONS

- Pennsylvania Instructional II Certification (Biology, Chemistry, & General Science 7-12
- California Single-Subject Teaching Credential (Biological Sciences and Chemistry)
- Qualified Teacher Status with exemption from induction, General Teaching Council for England

K-12 TEACHING EXPERIENCE

Wycombe High School High Wycombe, Buckinghamshire, UK
Teacher of Science 2008-2010

- **Courses Taught**: Key Stage 3 Science; GCSE Biology, Chemistry, and Physics; and AS Biology
- **Pastoral and Classroom Mentor** for 3 PGCE (teacher education) students
- **Evaluation**: Lesson observations rated "outstanding" by internal and external assessors

Sixth Form Tutor

- Provided pastoral, academic, and interpersonal advice for 18 students attending post-compulsory education
- Reviewed students' personal statements and wrote university references

Wissahickon High School Ambler, PA, USA
Teacher, Biology and Physical Science 2004-2008

- **Course Taught:** Honors, Academic (college-prep), and Inclusion Biology; Honors Physical Science
- **Leadership:** E-Classroom Pilot Teacher and Trainer
- **Faculty Sponsor**: Student Council, Future Teachers of America, Pennsylvania Junior Academy of Science, Montgomery County Science Research Competition, Delaware Valley Science Fair, and student graduation projects
- Designed department quarterly progress assessments and website

Franklin Towne Charter High School Philadelphia, PA, USA
Teacher, Biology and Physics 2003-2004

High Tech High Philadelphia Charter School (Mastery Charter High School) Philadelphia, PA, USA
Student Teacher, Earth Science 2002-2003

- Co-designed inquiry-based and technology-infused Earth Science I curriculum
- Mentored eight students through Guardian Angel program, co-sponsored school choir, taught study skills elective
- Designed and maintained science department resource website

TEACHING HONORS & AWARDS

- Certificate of Achievement, Buckinghamshire Children and Young People's Services, July 2010
- Recognized by National Honor Society, Wissahickon High School, March 2008
- Staff Member of the Month, Wissahickon High School, March 2005

PROFESSIONAL AFFILIATIONS

- National Association for Research in Science Teaching
- International Society for the Learning Sciences
- American Educational Research Association
- California Science Teachers Association

PROFESSIONAL SERVICE

- Reviewer, Journal of Science Education and Technology
- Reviewer, National Association for Research in Science Teaching
- David B. Brownlee Fellow for School of Arts and Sciences Advising, University of Pennsylvania, 2002-2003
- Alumni Admissions Interviewer, University of Pennsylvania, 2006, 2014-2015