Scientific Practices Through Students' Eyes: How Sixth Grade Students Enact and Describe Purposes for Scientific Modeling Activities Over Time

Christina Krist and Brian J. Reiser, Northwestern University, Evanston, IL
Email: ckrist@u.northwestern.edu, reiser@northwestern.edu

Abstract: Recent reforms in science education emphasize engaging students in *scientific practices* (NRC, 2011). These reforms aim to not only have students *doing* things scientists do, but to have them doing them *with the similar goal* of constructing explanatory accounts of the natural world in principled, consistent ways. In this case study, we used a communities-of-practice framework to analyze how students' perceptions of the epistemological purposes of several classroom activities change over time. We found that students used their everyday experiences in ways that allowed them to engage in and describe modeling practices that contributed to their classroom's knowledge building goal. In addition, we found that students' articulations of that goal became more epistemologically sophisticated over time. Our analysis provides insights on how students productively use everyday experiences in scientific practices and offers suggestions for how to rethink learning progressions to account for students' perceptions of their modeling practices.

Recent reforms in science education emphasize scientific practices as the means by which students develop scientific ideas (NRC, 2011; Achieve, Inc., 2013). These practices, such as constructing scientific explanations, arguing from evidence, and developing models, are the ways in which scientists build knowledge about the natural world. Thus, the goal in engaging students in scientific practices is to have students doing things that scientists do *driven by a similar epistemological purpose:* to construct explanatory accounts of the natural world in principled ways. As such, classroom scientific practices must connect classroom activities to larger science ideas and principles in ways that help students to make progress in constructing larger scientific ideas themselves *and* in understanding the principled ways in which those ideas were constructed (Duschl, Schweingruber, & Shouse, 2007; Sandoval & Reiser, 2004).

Despite the best efforts of curriculum designers and teachers, students will not be engaged in scientific practices unless they see their activity as *meaningful for their knowledge building*—that is, as connected to their classroom's epistemological goal (Barron, et al., 1998; Duschl, et al., 2007; Sandoval, 2005). However, engaging students in building scientific knowledge requires that most classrooms make significant shifts in how both teachers and students think about the work they do. These shifts, transforming classrooms from places where teachers communicate the ideas of science to students to places where students and teacher work together to build those ideas through scientific practices, take time. As such, classrooms are designed communities that are in the process of *developing* shared epistemological goals and related practices.

Because we want to know how students come to see their classroom activities as meaningful practices rather than routines, we investigated *how students' enactments and perceptions of the epistemological purposes of classroom activities developed over the course of a unit.* In particular, we focused on activities designed to engage students in the practice of developing and using scientific models. In this case study of a classroom working to establish scientific knowledge building practices, we found that students' engagement in and descriptions of modeling activities shifted from using and describing diagrammatic models as *displays of ideas* to using and describing diagrammatic models as *tools for working out ideas*. In addition, students began to recognize peers' roles in working towards their classroom's epistemological goal.

Participation in Scientific Practices in Classroom Communities

The call to engage students in the practices of scientists is not new. However, engaging students in activities that meaningfully contribute to scientific knowledge building is difficult. Hands-on investigations and labs, if not connected to a larger knowledge building goal, do little more than teach students the immediate practical skills necessary for the routine (Barron, et al., 1998). In other words, they gain neither deep content understanding nor a justification for doing the "steps" in the first place. So how do teachers and students work to develop knowledge-building goals and engage in practices that meaningfully contribute to those goals?

Studies of classrooms in which researchers and teachers carefully designed the substance and structure of the context to engage students in scientific practices have found that students successfully engaged in knowledge-building practices when the discourse framing and supporting inquiry emphasized the goal of developing shared knowledge (Herrenkohl, 2006; Rosenberg, Hammer, & Phelan, 2006; Schwarz, et al., 2009). In addition, students developed rich understandings of the incremental building of evidence-based scientific explanations during *sustained engagement* (6 years) with teaching designed to support students' epistemological thinking (Smith, et al., 2000), suggesting that sophisticated epistemologies take time to develop. Meaningful engagement in scientific practices, then, requires the careful design of sustained sequences of inquiry activities around rich, appropriate content learning goals that are enacted in ways that offer appropriate social supports. Guided by these social supports, students can become active participants in a community that builds knowledge using the tools, social interactions, constructs, epistemological criteria, and discourses of disciplinary science (Ford, 2008). Therefore, viewing science learning as *participation in a classroom community of practice* offers a useful analytical framework for understanding how teachers and students develop knowledge-building goals and learn to engage in meaningful scientific practices.

To examine how classroom communities engage in scientific knowledge building, we interpreted principles about how learning occurs in communities of practice through a lens of epistemological development. In particular, we focused on the *practical epistemologies* that can actively guide the classroom work (Sandoval, 2005), and how those epistemologies develop, or how changes in activation of coherent sets of epistemological resources occur over time (Hammer & Elby, 2002). In this paper, we focused on the characterizing how students' perceptions of *models and modeling activities* changed over time. We anticipated that students could be using models in a variety of ways: to provide a right answer to the teacher; to record his or her own thinking; to explain how and why a phenomenon occurred; or to argue against a competing model (Schwarz, et al., 2009).

However, epistemological development does not happen in isolation. We also wanted to understand how teachers and students used social interactions and shared resources to construct meaning around the modeling work they were doing. We utilized Wenger's (1998) three elements that characterize communities of practice to capture classroom epistemological development holistically. First, a community must establish a *joint enterprise*, or a collectively developed understanding about what their community is about or what they aim to do (Wenger, 1998). Through our epistemological lens, a student will ideally come to understand the epistemological joint enterprise of classroom science—constructing explanatory accounts of the natural world. In other words, students will shift from perceiving inquiry activities as standalone (Barron, et al., 1998), or as serving the purpose of simply propagating knowledge (Hammer & Elby, 2002), to seeing the activity as a means for them to build a larger causal or explanatory story over time (Rosenberg, et al., 2006).

The other two critical elements support the community's joint enterprise. Communities must establish *mutuality,* or norms of interaction and relationship for achieving the joint enterprise (Wenger, 1998). Epistemologically speaking, students will ideally learn to take on important knowledge-building roles that differ from roles afforded by traditional teacher-centered classrooms (Berland & Reiser, 2009). These new roles require that students develop enough trust to be able to both construct and critique each other's knowledge claims (Ford & Ferman, 2006). In addition, communities must support members in using *shared repertoires of resources* in order to accomplish the joint enterprise (Wenger, 1998). In a practices-centered classroom, some of these resources include the discourses, tools, and shared collections of knowledge of scientists. For the purposes of this paper, we focused on a particular set of tangible external resources and their related epistemological resources: those related to the construction and use of diagrammatic models. Students will ideally learn to view diagrammatic models as tools for forming explanatory stories or explanations of phenomenon (Hammer & Elby, 2002; Passmore & Stewart, 2002; Rosenberg, et al., 2006; Schwarz, et al., 2009) rather than as check-your-answer activities, or accumulations and repositories of propagated ideas (Hammer & Elby, 2002).

Based on our framework, as we investigated how students' enactments and perceptions of the epistemological purposes of modeling activities developed over the course of a unit, we expected to see students increasingly: 1. Describing a knowledge-building joint enterprise for their classroom; 2. Describing how classmates' ideas are used in constructing knowledge; and 3. Using and describing diagrammatic models as tools for knowledge building. We found that while students did use models for some of the purposes we expected, they also developed their own epistemological purposes for models that drew on their everyday experiences in ways that contributed to their classroom's knowledge-building enterprise. In addition, we found that they highlighted the importance of peer accountability in knowledge building.

Methods

Research Context

In order to study how students' enactments and descriptions of the epistemological purposes of classroom modeling activities developed, we focused on one classroom using a curriculum designed to engage students in scientific practices (Krajcik, McNeill, & Reiser, 2008). We selected a unit that emphasized the practice of developing and using models to build scientific knowledge because it is a challenging practice for teachers to implement (Schwarz, et al., 2009). This 6^{th} grade classroom is located in a high-achieving middle school in a middle-to-upper-middle-class suburb of a large Midwestern city. The teacher, Mr. H, is an experienced classroom teacher who had taught for 14 years at the time of data collection. However, it was only his second year using this particular curriculum. Although his understanding of scientific practices and pedagogical strategies for engaging students in practices were still developing, he felt that his own orientation to and beliefs about science teaching aligned well with the knowledge-building goals of the curriculum, especially the focus on having students address and challenge their own ideas and questions about the world with evidence from classroom activities (Interview, 3-18-13). Therefore, although he was still learning how to support students in modeling practices, his commitment to engaging students in knowledge building made his classroom a rich context in which to study the development of classroom scientific practices.

Data Collection

The first author observed and video recorded selected lessons in Mr. H's classroom throughout the 2012-2013 school year. The first curricular unit was these students' first introduction to both scientific practices in general and the specific practice of constructing and using scientific models. The data for this paper comes from the second curricular unit, enacted from January-early April 2013. The lessons selected for observation and analysis (Lessons 1, 4, and 6) were those in which students were constructing, presenting, or revising diagrammatic models and therefore had the potential to be activities in which students were engaged in the scientific practice of developing and using scientific models.

In addition to observing and video recording selected lessons, the first author conducted nine semi-structured interviews over the course of the unit with three focus students from this classroom. Focus students were purposefully selected to represent a range of "getting it," based on the classroom teacher's perception, which likely represents some combination of ability, effort, and interest in science. The interviews were designed to elicit students' perceptions on the purposes or goals of specific classroom activities from Lessons 1, 4, 6. These interviews included questions such as, "Why did you draw a model right away at the beginning of the unit?", "Why do you think you presented your models and ask questions about them?", and "What kinds of things were you thinking about when you were drawing [a specific] model?" As a follow-up to each of these questions, we asked if or how the reasons they gave contributed to their learning in order to elicit their perceptions of how each activity was connected to knowledge building. The first set of interviews occurred between Lessons 1 and 4; the second set occurred shortly after Lesson 6; and the third set of interviews occurred after the end of the unit.

Data Analysis

In order to characterize the shifts occurring over the course of the enactment of the unit, we coded transcripts of both the interviews (163 min. in total) and the classroom observation data (370 min. in total) for *epistemological purposes:* rationales for if, how, and why a particular classroom activity contributed to knowledge building. These rationales were relatively straightforward in students' responses to interview questions. In the classroom video, we coded both explicit statements that described a particular epistemological purpose (e.g. "Felix is doing something good here, he's making connections to things we did in the light unit," coded as *Compare to things we've done*) as well as statements that implied or operationalized a particular epistemological purpose (e.g. A student saying, "But there can't be empty space because air has to expand" in response to another student's model, coded as *Compare to things we know*). From the 9 semi-structured interviews, we first generated "in vivo" codes (Miles, Huberman, & Saldana, 2014, p. 74) capturing the epistemological purposes that students described. Drawing on Hammer & Elby's (2002) categories of epistemological resources, we then collapsed our initial list into 19 "epistemological purpose" codes, each representing a particular combination of *epistemological activity + nature/source of knowledge*. These codes included purposes such as, "Make thinking visible," "Public evaluation," and "Shift individual understanding." We then applied these codes both the interview data and the classroom discourse. Applying these codes to the classroom video generated one additional code: *Compare to real life experiences* (see Table 1).

After coding all the data, we eliminated epistemological purpose codes that were not a) included at least twice in the three focus student interviews from the class period of interest, and b) included at least once during the classroom discourse. Although we acknowledge that any classroom activity has multiple overlapping goals and purposes, this reduction was an attempt to focus on the *most salient purposes* at each point of time during the unit as enacted by the teacher and students AND as interpreted by students in interviews.

Characterizing Classroom Enactment and Students' Perceptions of Scientific Practices

We argue that over the course of the unit, students' enactment and descriptions of the purposes of activities related to constructing and using scientific (diagrammatic) models shifted from enacting and describing diagrammatic models as *displays of ideas* to describing and enacting models as *tools for working out ideas*. In the classroom enactment, the class shifted from using their models for displaying or collecting knowledge to using their models as revisable representations of the ideas they were comparing and actively (re)building. This shift in enactment preceded a parallel shift in how students explicitly described the purposes for modeling activities. However, rather than describing models as tools for working out ideas, students instead described the social mechanisms through which they used their models for knowledge-building. Taken together, these shifts suggest that students were developing meaningful ways of participating in scientific modeling practices. In this paper, we characterize these shifts first by looking at classroom activity, supported with data from student interviews. We then analyze student interviews for additional ways in which students developed meaningful modeling practices. Finally, we discuss the implications of these shifts for epistemological development.

Table 1: Epistemological purpose codes.
(These codes were found at least twice in the three focus student interviews and found at least once during classroom discourse.)

"Epistemological Purpose"	***Epistemological Activity + Nature/Source of Knowledge (from Hammer & Elby, 2002)***	**Paraphrased descriptions of the point of the activity**
Make thinking visible	*Displaying + Inherent*	The point is seeing each other's ideas to get a sense of what students think
Record thinking for future use	*Accumulating + Propagated*	The point is to keep track of what we know for use on a test in the future, to prevent myself from getting confused, or to compare later and see how much we've learned
Compare to things we know	*Comparing + Propagated*	The point is to think about the facts we've learned to see if a model or idea matches with them
Compare to real life experiences	*Comparing + Direct Perception*	The point is to think about things we've seen, experienced, or know from real life and see if a model or idea matches with them
Compare to things we've done	*Comparing + Fabricated and/or Direct Perception*	The point is to think about the experiments and discussions we've had in class to see if a model or idea matches with them
Revise representation through peer feedback	*Formation + Fabricated (specific ideas represented)*	The point is to change my model based on the questions and critiques my peers gave me
Learn through collaboration	*Formation + Inherent (in other) and/or Fabricated*	The point is to use peers or teacher as a resources as they ask questions, give critiques, or offer their ideas and understandings
Solve or piece together puzzle	*Formation + Fabricated (big ideas)*	The point was to make another connection (snap another piece in) that moved us closer to solving the overall puzzle/question

Models as Idea Displays: Seeing Ideas and Making Comparisons

During the first lesson of the unit (Jan 10th-11th, 2013), Mr. H had students smell an odor in a film canister and discuss how they thought the odor moved through the air so they could smell it. Students then drew a model illustrating their ideas about what makes up the odor if they were to magnify it. In framing and enacting this lesson, both Mr. H and the focus students explicitly described the purpose of modeling activities as *Making Thinking Visible* (see Table 1). When students began drawing their models during Lesson 1, the teacher emphasized that students were to be drawing "YOUR ideas, not you and your neighbor." He then said that once enough people had something on their paper, they would "take a peek at" each other's models and "share out" their ideas. After giving students a few minutes to draw, he asked if anyone was ready to share their models, stating, "Don't worry, we're not here to judge, especially since none of us has the answers. We're all just getting started with this, so we're curious. We're curious what you think." In framing this activity, Mr. H explicitly denied any evaluative purpose.

In retrospective interviews following Lesson 1, two focus students described the purpose of drawing and presenting these initial models in ways that mirrored Mr. H's framing of the activity. Carly said the purpose was "just to see like what our preference is on it, like what we think it is." Similarly, Ruthie said the purpose of sharing their models was so that they could see what everyone else was thinking. Again, neither of them described an evaluative goal. In and of itself, the epistemological purpose of "making thinking visible" does not suggest any connections or contributions to a joint enterprise; rather, students are each displaying their own inherent ideas. Here, it seems that Mr. H was working to position this activity in contrast to the evaluative purposes that frame most presentation-like school activities.

As students presented their models, however, they did not simply note each other's ideas. Instead, the class began to make comparisons between the previous unit (the "light unit") and the current one (the "smell unit"). Mr. H first connected the two units by guiding students to think more deeply about how they smelled the odor: "Now I know that you guys are pretty careful observers, and you noticed that smelling whatever is in here, that was actually a sort of process. There's a beginning, a middle, and an end. I remember for our light unit we talked about light starts somewhere, goes to an object, bounces off the object, hits our eyes, and we know there's a lot more too with color now. But there's a process, right?" Mr. H made an explicit connection to how they had been working on ideas in the light unit, drawing a parallel to how they would investigate this new question about how odors travel. This connection was his first attempt at establishing a joint enterprise: to figure out the process by which an odor moves across a room. Notably, this enterprise is a knowledge-building one.

During their model presentations, students also made connections to the light unit in ways that contributed to the newly established joint enterprise, suggesting they were at least somewhat bought in to Mr. H's initial framing. Felix, who presented first, used ideas from the light unit to highlight how his ideas about how odor moved contrasted with light: "And then you can see like where the odor moves around in all these different directions. So it doesn't have to, unlike with the light it doesn't really have to travel in straight lines either. So it goes anywhere it wants, really." Lola, the second student to present, also highlighted a difference between the how light and odor travel. She represented odor as a line with a curve in it to indicate "the odor is not like straight lines, but like where the wind takes it and curves it around corners."

In response to Lola's presentation, the class began to bring in ideas from their everyday experiences to justify their comparisons. Mr. H asked the class if they agreed that odor could move around corners. One student said, "You can smell something that's on the other side of the house." The class briefly discussed smelling cookies baking, and then Lola turned to Mr. H and said something inaudible to the camera. He turned to the class and shared her question, saying, "All right, now I don't have any answer for this, because her question was […] asking if temperature has anything to do with this, with odors." Several students responded, all seeming to be in agreement that temperature did have to do with smelling odors. Mr. H said he thought they would need to collect some evidence to decide if temperature was a factor. The class agreed, and Lola wrote her question on a Post-It note.

In these two presentations (and the four that followed), students used their models to display ideas that highlighted contrasts between their new ideas about how odor traveled and their knowledge from the previous unit that light travels in straight lines. So they were both "displaying" ideas, but they were also "comparing" to what they all knew. In addition, to support this epistemological activity of comparison, they began bringing in real life experiences—the experience of smelling food around corners—to help them generate potential factors involved in odor travel and provide initial justifications for whether or not those factors mattered. In other words, students were using their models as a visual platform for making comparisons and generating questions based in their everyday experiences. Importantly, the teacher affirmed these moves and valued questions as important products of the discussion: each time a student made a case for a new potential factor based on a personal experience, he gave the student a Post-It note to record the question and made comments like, "I'm curious too!" and "Good, we're getting somewhere." Through his affirmation, Mr. H established the joint enterprise for the unit and acknowledged that the ways students were engaging in the activity—recording and displaying their ideas and making comparisons to generate questions—contributed to that enterprise.

Models as Thinking Tools: Making Sure Our Ideas Make Sense

As the unit progressed, students continued to draw on their prior knowledge and experiences in modeling activities. In Lesson 4 (Jan 30th, 2013), making comparisons to prior experiences allowed students to initiate the one instance of sustained argumentation between competing ideas that occurred during the smell unit.

By this point in the unit, the class had decided that air was an important factor in how an odor moved and were investigating how air behaved when expanded or compressed. Lesson 4 began with Mr. H adding and removing air from a sealed flask. Students then drew what they thought air looked like in a normal sealed flask, in the flask where air was removed, and in the flask where air was added. After working individually for a few minutes, two students presented their models. The first student, Summer, presented a rather elaborate model explaining that when air was removed from the flask, each individual air particle expanded to fill up the space. Likewise, when more air was pumped into the flask, each individual air particle shrank to allow more particles to fit in (see Figure 1). Students asked her a few questions, including what was in between the particles. She stated that there was more air in between; she just did not have time to draw that many particles.

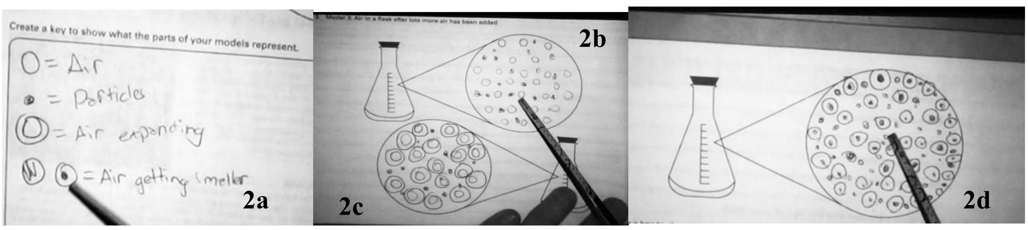

Figure 1. Summer's Models, Lesson 4. 2a: Key. 2b: Normal air. 2c: Air removed. 2d: Air added.

The next student to present, Jared, claimed that there was "nothing" between the particles: when you added air, there was more air and less nothing, and when you removed air, there was less air and more nothing (see Figure 2). Almost immediately, the class erupted into a heated discussion about his idea, arguing that it was not possible to have empty space between particles. Summer stated several times, "there can't be empty space, because air has to expand" because "otherwise it wouldn't be a gas," highlighting a contrast between Jared's model and a principle they had learned in class. Nate tried to imagine[1] what it would mean for there to be empty space. He asked, "Would that mean if I stepped into it, I would shrink or something? If there was no air?"

Jared then attempted to defend his idea by drawing on a real-life experience: he asked, "What about in space?" Summer, supported by many other students, argued that there is air in space, it is just THIN air because the individual particles have each stretched out so much that they are very thin. Robbie and Dexter both added that air in space is like thin air at high elevations, which is why climbers on Mt. Everest need oxygen. Here, the class co-refined Summer's initial idea to make it fit the knowledge they had about places with "thin air."

Jared then tried another tactic to defend his model: he described what having no air between particles would look like on his model. He said, "I think if [their idea] was true then, I think [the models] would all be like the same, like that [*pointing to his first model*]." Mr. H asked, "They would what?" Jared clarified, "They'd all look like that, they'd all be the same. The same amount of particles there. Cuz they're saying that there's air in here? [*pointing to empty space in his model*]." Unfortunately Mr. H did not understand what Jared was trying to say. He asked if that meant all the lines would get fatter, and Jared gave him a confused look. Then another student asked an off-topic question, and Mr. H adjourned the class for the day.

Despite this unsatisfying end to the argument, we want to highlight that rather than models simply displaying ideas, they now display ideas *for a purpose*. Students considered whether or not they were persuaded by another student's model and expressed a need to resolve the discrepancies they saw. In addition, Jared made a move that was, as of yet, unprecedented in this classroom: he attempted to use his model as a tool to rebut a counterargument. His model made his (and Summer's) ideas visible *in order to* determine which idea better explained this phenomenon, based on what they knew to be true about the world. In this episode, students used models as tools to work through and form ideas together about what air looks like so they could figure out how odors move through it. Importantly, the mechanism by which they worked through and formed these ideas was by drawing on and comparing displayed ideas to their prior knowledge and everyday experiences in the world.

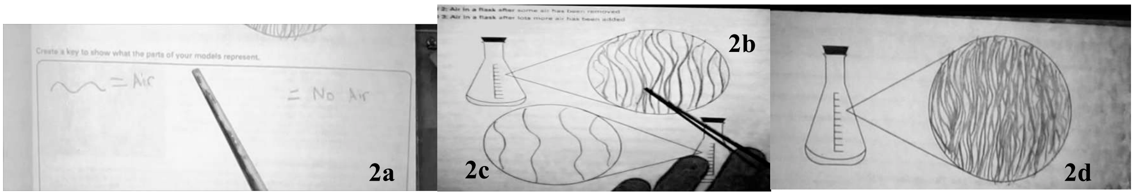

Figure 2. Jared's Models, Lesson 4. 2a: Key. 2b: Normal air. 2c: Air removed. 2d: Air added.

By Lesson 6 (Feb 13th, 2013), the class returned to their original question about how odors move across a room. They saw an animated simulation that showed particles traveling in straight lines until they bounced off of each other. They then worked in small groups to draw a revised model showing what the odor looked like in between the odor source and the nose. In an interview following this activity, Felix explained how he used the activity of drawing his model in Lesson 6 as a tool to help him work through ideas. He described how, as they were drawing, he and his partner wondered about how particles would bounce: "I was also wondering like how it would work, like in what direction would [the particle] go in? Let's say it hits like the exact corner of a wall, directly at the corner, like would it just bounce off, or would it like scatter away, or would it split up? Probably not, but you know I was wondering about that, you know." Here, Felix used the process of drawing the model to help him think through questions he still had and to articulate the specifics of his explanatory account. He later decided that particles would not split apart, and that they needed to hit obstacles placed at different angles in order to spread all around the room. For Felix, the diagrammatic model itself was not the goal; rather, the purpose was to think through his ideas to figure out how the odor was moving

Although Jared and Felix used models as tools for refining ideas in practice, none of the students explicitly stated an idea-refining purpose for models in interviews, such as using models to compare or decide between competing ideas. Instead, of the 15 purposes they did describe, 10 of them were about making comparisons to things they had done or experienced. This is not surprising, given the prevalence of connections they made during Lessons 1 and 4 and the lack of uptake of Jared's use of his model. However, students did describe modeling activities as serving a knowledge-building goal more generally. In doing so, they described how the social aspect of knowledge building helped them to refine their models. Their descriptions suggest that changes in social roles, or establishing *mutuality*, were more salient for students than changes in how they were using models to build knowledge. We turn next to their interviews to illustrate this emphasis.

Describing How Peers Connect Models to the Joint Endeavor

Although students enacted modeling practices in ways that suggested they saw them as meaningfully connected to the joint endeavor, we also wanted to see how students' articulation of the connection developed over time. We found that by midway through the unit (during their second interviews), students explicitly described, in their own words, the joint endeavor of their classroom in ways that involved both metaphors for building ideas and implied a necessarily social process. When asked about drawing models, Ruthie said, “I like how this class is […] sort of like a mystery that you unravel day by day, so *we're* sort of like invested in trying to figure out like what's the big like secret that *we* always like have (*italics added).*” Carly described model drawing in a similar way, saying that when drawing a model *in a group* you can take in *other people's* ideas and perspectives and “piece together the puzzle.” From these statements, we see that these students were beginning to see their modeling activities as tools that allowed them to build knowledge *together*.

Interestingly, students' third interviews at the end of the unit described more articulately how peers influenced their classroom knowledge building during modeling activities. This shift is especially striking, as the interview questions remained the same. Felix described how he considered peers' ideas during model presentations: “I'm paying attention to what I don't have, […] but I would ask like, why would you put this in? And then if it gave me like a good explanation for it, I'd like think about it and try to put it into my [model], if it was like really good.” Here, Felix described a three-step accountability process: he notices differences between the presented model and his own, he asks for the presenter's rationale, and he decides if the rationale is good enough or not. Ruthie also articulated a three-step accountability process when she described how discussing someone else's model helped the presenters: “Because if you're like telling them, […] like, you should probably do this, and then they could, and then the whole class could like join in and see if that's a good idea or a bad idea, because sometimes you have bad ideas, and you share them, but then like the class like keeps you in check.” According to Ruthie's description, a presenter shares an idea, a student offers a suggestion, and the class decides if that suggestion is worthwhile or not. Although these students are not describing *how* they decide if an idea is good or bad, a process for which science has very explicit criteria, they are recognizing that knowledge building in science class requires accountability for ideas. In other words, not only do they recognize that their models and modeling activities are resources they use to contribute to the joint enterprise, but they are also beginning to recognize that there are particular ways to use those resources, and that using them requires that each member contribute. Their participation in modeling activities is not just another classroom routine. Instead, it is a meaningful practice in which they, as a class, build scientific ideas together.

Implications from Students' Enactments and Perceptions of Practices

We have shown how over the course of the unit, this class gradually developed meaningful ways of engaging with scientific models that went beyond simply adding a new school routine. First, they used models simply to make their thinking visible. However, students quickly took up the new joint enterprise—figuring out the process for how odor moves—and began making comparisons to prior knowledge and experiences in order to generate new ideas and questions. In their next modeling activity, students continued to make comparisons to things they knew or had experienced. They used these comparisons to initiate the one instance of extended argumentation that occurred in this classroom during this unit, using their model displays as tools to work through ideas together. Interviews with students suggested that, both individually and in groups, they continued to use their models to work through, rather than simply display, their ideas, and that peer accountability played a salient role in how their knowledge building worked. These shifts suggest that modeling activities in this classroom were developing as instantiations of a meaningful, purposeful scientific practice.

So how did these meaningful epistemological purposes for modeling activities develop over time? In this case study, two important activities afforded students both epistemic authority and epistemic accountability. First, this class engaged frequently in the epistemological activity of *making comparisons*, especially when the knowledge source was students' *shared or everyday experiences in the world.* These students often engaged in “everyday sensemaking” (Warren, et al., 2001) during scientific modeling activities. In this classroom, everyday sensemaking afforded students the epistemic *authority* to construct knowledge and allowed them to argue against a Jared's claim even without deep content knowledge or scientific expertise. Second, students described how their class engaged in a simple form of classroom *accountability* to keep each other “in check.” At least to our focus students, peer accountability was a salient and purposeful part of their knowledge building.

It is important to note that students' forms of everyday sensemaking were valued and even praised by this classroom teacher. The challenge for the teacher here was not learning to make sense of, recognize, and value students' everyday ideas, as was the case in other studies (e.g. Lee, 2001; Warren, et al., 2001). Instead, this teacher struggled to connect students' everyday sensemaking to more disciplinary ways of engaging in those practices—or with balancing students' epistemic authority with *disciplinary* accountability (Ford, 2008), or guidance for students in *how* they decide if an idea is good or bad. Mr. H's difficulty in facilitating argumentation demonstrates the need for explicit guidance or “rules of thumb” for teachers in how to help students engage in more meaningful versions of scientific practices. Learning progressions for practices, then, should help teachers not only in understanding the disciplinary versions of scientific modeling practices but also in how to use moments of sophisticated practice driven by everyday intuitions into more disciplinarily-consistent versions of the practices. In other words, we need tools that help teachers know how to balance epistemic authority and accountability in order to develop students' modeling practices *deeply,* connecting everyday and disciplinary practices at each stage of a learning progression, in conjunction with tools that help teachers move students from simple to more sophisticated versions of scientific practices.

Endnotes

(1) Although Hammer & Elby (2002) list "imagining" as a distinct epistemological activity, we considered the purpose of Nate's move to be parallel to Summer's: testing to see if Jared's idea was compatible with things they knew or had experienced. Therefore, we coded Nate's utterance as an instance of *Comparing to [imagined] real-life experiences.*

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