Model-Based Reasoning: A Framework for Coordinating Authentic Scientific Practice with Science Learning

Julia S. Gouvea, Arash Jamshidi, Cynthia Passmore,
University of California, Davis, One Shields Avenue, Davis, CA, 95616, USA
Email: jmsvoboda@ucdavis.edu, ajamshidi@ucdavis.edu, cpassmore@ucdavis.edu

Abstract: In this paper we explore data from a two-year professional development program intended to help teachers adopt and enact a model-based reasoning view of science instruction. We use a resources framework to explore the teacher learning in this setting. By examining the experience of one teacher, we investigate how the ideas about learning and scientific models this teacher brought to the PD environment were aligned and coordinated over time to result in a change in her self-reported pedagogy by the end of the program. We explore implications of this view of teacher learning for PD in the current reform context.

Introduction

The assumption that science learning should be situated in authentic scientific practice underlies the vision of the recently released *Next Generation Science Standards* (NGSS) in the United States. The important step taken by the new standards framework is that it calls for supporting students to engage with and learn science ideas *through* engagement in authentic scientific practices. In this way the framework puts forward a vision of science learning that brings together constructivist theories of learning with an understanding of science as practice that helps scientists generate and refine knowledge about the world. For many teachers this will mean a radical shift in the character of their classroom instruction. In order to support teachers in enacting this new vision, teacher educators must consider what and how teachers learn (Wilson, 2013).

Much of the scholarship on teacher learning in science has focused on what teachers need to know, and how this knowledge can be brought into better alignment with education reform. In general, this literature tends to treat teacher knowledge and beliefs as deeply held core conceptions that influence how teachers plan and enact their instruction. If these core beliefs do not align with the vision for reform, then they need to be altered or changed through professional development experiences. In this paper we conceptualize teacher cognition in terms of finer-grained knowledge elements, or resources (Hammer et al., 2005a), and model teacher learning in terms of different patterns of activation and coordination of fine-grained knowledge elements. We present a case analysis of a teacher participant chosen because we observed evidence of substantial shifts in the ways in which she described her pedagogy over time in the context of a professional development program that emphasized model-based reasoning as a framework to guide science teaching and learning.

Theoretical Framework

Teacher Knowledge Is Complex and Dynamically Related to Teaching Practice

In the field of teacher learning there exist a number of complex constructs for describing teacher knowledge (attitudes, PCK, beliefs, orientations, core conceptions). What is common across these descriptions is the understanding that teachers bring together a range of different kinds of knowledge to their curricular and instructional decision-making. Researchers have attempted to describe different components and constellations of such knowledge in an effort to guide teacher learning and support professional development. A central aim of this body of work is to describe the kinds of knowledge held by exemplary teachers and how it differs from novice teachers (e.g. Shulman, 1986).

However, the idea that teachers have stable knowledge structures or belief systems that hold in all contexts has been challenged for both theoretical and methodological reasons (Friedrichsen et al., 2011). Mounting empirical evidence suggests that teachers have many different cognitive resources about teaching and learning, and they do not necessarily leverage that knowledge in consistent ways across contexts, or even across moments (Crawford, 2007; Kang and Wallace, 2005; Levin et al., 2009; Markauskaite & Goodyear, 2014). The field is moving towards a conception of teacher knowledge that is more dynamic and context dependent.

This shifting conception of teacher knowledge mirrors the theoretical movement in student learning to describe student knowledge as comprised of sets of interrelated "resources" – fine-grained cognitive elements that are differentially activated with context (diSessa, 2002; Hammer, 1996). Within a resources framework learning need not entail replacing or radically restructuring students' knowledge frameworks. Instead, productive learning can often mean helping students build upon, connect or reorganize existing resources (Hammer, 1996; Hammer et al., 2005b) so that they access and leverage those resources in particular ways in various contexts. When viewed through this lens, it becomes important to understand the ways in which students *use* knowledge in different contexts, and insufficient to simply demonstrate that they *have* correct knowledge.

Applied to teacher learning and PD, a resources framework highlights the need to understand and help teachers refine the knowledge they already have. That is, we want to understand when, how and why particular resources are coordinated in service of pedagogical purpose and action and how to shift these patterns over time. In our case analysis we focus on one teacher, Quinn, who describes her pedagogy as transformed by our PD and ask, how can we make sense of this shift in terms of shifts in this teacher's cognitive ecology? We argue that Quinn developed *coherence* among knowledge resources and pedagogy as demonstrated in her descriptions of her classroom practice and her reflections on her actions. We posit that it is this coordination that is important for lasting change rather than the acquisition of any single particular idea.

Resources for Supporting Students' Engagement in Authentic Scientific Practice

In general, a "resource" can be defined as abstract basic knowledge unit that can be applied across a range of contexts. For example, Markauskaite & Goodyear (2014) propose a number of different knowledge categories from which such resources could be drawn (e.g. resources about *how people learn*, *disciplinary content*, and *student capabilities)*. In this paper we focus specifically on two types of resources that are particularly relevant to the NGSS vision: resources related to (1) *student learning* (2) *the nature and purpose of scientific models*. Separating these two dimensions is important for understanding how teachers make instructional and curricular decisions. Often researchers collapse teachers' views of scientific practice and teaching and learning. For example, teachers' orientations towards "inquiry" tend to combine conceptions of the science as a practice of asking questions about the world and an orientation towards a student-centered classrooms in which students are the ones asking and answering questions. In this paper, we purposely tease apart resources so that we can explore how interactions among these resources changed during her participation in a professional development program that focused on model-based reasoning,.

Methods

Study Context

The Innovations in Science Instruction through Modeling (ISIM) program was designed to engage science teachers in the conceptual work of problematizing current approaches to science instruction and restructuring their curriculum and instruction to include model-based reasoning (MBR) in their classrooms. From 2007 to 2011, two cohorts of 6-12th grade science teachers (N=57) participated in a two-year intensive professional development (PD) program focused on MBR. Here we report on one teacher from the second cohort (N=28).

MBR is an approach to science teaching that involves students in constructing and using models to explain natural phenomena (see Passmore & Stewart, 2002; Stewart, Cartier & Passmore, 2005; Windschitl, Thompson & Braaten, 2008 for more thorough treatment of this approach). Each year of the two-year PD program consisted of a three-week summer institute in which teachers experienced MBR as adult learners to deepen their own content knowledge and analyze their own learning process when introduced to the MBR approach. During the academic years of the program, teachers worked in content- and grade-alike teams to develop and enact curriculum appropriate for their own classroom integrating the MBR approach. Teams met regularly throughout the year to report and reflect on their experiences implementing MBR during afterschool meetings and a day-long retreat in the spring of each year.

Data Collection and Analysis

Over the course of the two-year program, we continually collected data in the form of artifacts from the PD program including approximately 100 written reflections per participant, field notes, video and audio of summer institutes and academic year events, and facilitator notes from lesson study team meetings. Each participant also participated in a small group and individual interviews during which participants discussed and reflected on prepared reflection prompts. All of the data were transcribed and entered into a FilemakerPro database. In this paper we report results from two types of analyses conducting using written prompts and interviews. The first is a pre-post comparison of a single written prompt teachers responded to both upon admission to and exit from the PD The second uses the full set of prompts to track changes in teacher responses over time.

The majority of prompts were generated in an *ad hoc* manner throughout the program in order to provide opportunities for teachers to reflect on their participation in the PD as well as their evolving classroom practice. Because the nature of the prompts changed over time they cannot be used to measure absolute shifts in teachers' responses. However, because all teachers had the opportunity to respond to the same set of prompts, we can use relative differences across teachers as an indicator of the ideas that were most salient to them at different points throughout the program. We conducted a qualitative analysis of written prompts and interview transcripts in order to generate longitudinal descriptions of changing response patterns for the teachers in the second cohort. As a research team we iteratively developed a set of 14 categories to capture teacher statements by first reading through the full datasets for 10 teachers. We then separated statements into these different categories (double-binning was permitted), which made it easier to parse the large dataset for further coding and analysis described in more detail below.

Pre-Post Analysis of Teachers' "Exemplary Lessons"

One of the written prompts asked teachers to "Describe one of your exemplary science lessons and explain your reasoning about the most important things that make it effective." Teachers responded to this prompt on their initial applications to the program (pre-lesson) and again two years later on exiting the program (post-lesson). To analyze specific features of these lessons we created a rubric that we used to score the lesson along two dimensions: attention to student ideas as an overall measure of student-centeredness, and authenticity to scientific practice as an indicator of how science is portrayed in the classroom. Each lesson was given a score ranging from 1 to 5 along each dimension. A score of 1 in the student-centered dimension described primarily lecture-based lessons, whereas a score of 5 signified lessons in which the teacher described giving students the opportunity to both share and reflect on their ideas with responsive feedback from the teacher. A score of 1 in the science dimension indicated lesson descriptions not involving students engaging in scientific thinking or practices, whereas a score of 5 represented lessons in which students combined science ideas and practices in order to make sense of a phenomenon. During scoring, all identifying markers were removed and pre- and post-lessons were randomized. Two researchers scored all lessons with initial reliability of 78%. Through discussion an inter-rater consensus of 100% was achieved.

Longitudinal Analysis of Shifts in Teachers' Instructional Choices and Pedagogical Strategies

One of the 14 categories captured statements about teachers' self-reported *instructional choices and pedagogical strategies*. We established qualitative codes for statements in this category by first reading through the binned dataset for each of the 28 teachers. As a research team we iteratively developed a set of codes drawing on both *a priori* expectations and emergent patterns in the data. The final set of codes were assigned to describe statements that fell into broad instructional strategies: (1) *traditional* approaches to science instruction including both lecture and activities focused on engagement (2) *student-centered* strategies such as group learning making student ideas visible (3) *procedure*-focused strategies including engaging students in laboratory skills (4) sense-making strategies focused on *explaining phenomena* and (5) *modeling* strategies that explicitly referenced involving students in model development or use.

Three researchers participated in the coding process by first coding a subset of the teachers and conducting extensive discussions to normalize code assignments. A single researcher conducted the remainder of the coding. Researchers were blinded to the identities of the teachers during the coding process.

In order to visualize changing patterns in code distribution over time, we divided teachers' responses into five time periods corresponding to the major time periods in the program (1st spring, 1st summer, 1st academic year, 2nd summer, 2nd academic year). We then counted up the number of responses corresponding to each code during each of the five time periods and plotted the percentage of statements made in each category for each teacher (see Fig 1). This provides a visual representation of the relative frequency of specific codes.

Qualitative Analysis of Quinn Focused on Alignment and Interactions Among Resources

We selected Quinn as a case for a more in depth analysis because of the dramatic change in the character of her exemplary lesson as well as the shifting patterns in her prompt responses related to her instructional practice. Because we were interested in the cognitive resources Quinn might be using to make and justify her instructional choices, we conducted a more in depth analysis of two categories of statements we found in the data: teachers' conceptions of *student learning* and views of *scientific models*.

We developed the Quinn case by reading through all statements in each category to first develop a qualitative narrative of how these statements changed over time. We then used the responses collected through the first summer institute to build inferences about the ideas that were most salient to Quinn during her early participation in the program and responses collected during the second summer and academic year to describe the ideas that were most salient to Quinn towards the end of the program. We then took a third pass through the data looking for responses coded for both views of student learning and scientific models to build up an account of how these different ideas were related for Quinn. Finally, we read through Quinn's descriptions of and reflections on the MBR framework to better understand what it meant to her and in what ways it might be influencing the way she thinks about learning and teaching science.

Results: The Case of Quinn

Quinn's Shifting Descriptions of Her Teaching Practice

One indicator of Quinn's perception of her changing teaching practice is given by the comparative analysis of her pre (before entering the PD) and post (upon exiting two years later) exemplary lessons (Table 1). Quinn's first lesson received a score of 2 in both rubric dimensions. In terms of engaging with student ideas, Quinn's pre lesson relied mainly on direct instruction with some time given to allow students to rotate through lab stations, while the scientific aspect of the lesson is dominated by procedural laboratory skills.

Quinn's post lesson received a score of 5 in both dimensions. In it Quinn describes students working in small groups while she played the role of questioning and facilitating whole class discussions. The science component of the lesson involved an exploration into a number of phenomena leveraging ideas about particle movement in response to temperature. Lessons that shifted from a score of less than 3 to a score of 4 or greater in both dimensions were considered to be large shifts. Quinn was one of 11 teachers (42%) whose lessons shifted in this way (N = 4, had smaller shifts, N=4 had high scoring lessons in both pre and post and N=7, had low scoring lessons in both pre and post).

Table 1: Comparison of excerpted sections from Quinn's description of an "exemplary lesson"

	Attending to Student Ideas	Authentic to Scientific Practice
Pre Lesson	**Score: 2** "After providing some direct instruction about elements, the Periodic Table, and chemical bonding, the students partake in a lab activity…"	**Score: 2** "…the students partake in a lab activity where they rotate through nine different stations. …the students perform a task of mixing the chemicals together, heating the chemicals, or some other action."
Post Lesson	**Score: 5** "I then had students respond to a challenge statement …Afterwards, students practiced group norms as they shared in small and large groups." …. "I facilitated and questioned student thinking."	**Score: 5** "We started with discussion about particles of liquids, gases, and solids and how temperature and heat affect it or are affected…" "we examined phenomena and attempted to explain them. Phenomena included: 1. Blue ice melting in warm tap water..."

A second indication of a shift came from examining changes in how Quinn described her teaching over the course of her participation in the PD program as captured by five different types of coded statements (Figure 1). Overall, 110 written or transcribed statements from Quinn were categorized as *instructional choices and pedagogical strategies*. What drew our attention to Quinn was the relative increase in statements about *attending to student thinking* and engaging students in *explaining phenomena* coupled with a decrease in statements coded as *traditional* instruction and *laboratory or procedure-based* instruction. Compare for example the relative frequency of statements made in these categories upon entering the program (1st spring) and near the end of the program (2nd academic year) as depicted in Figure 1.

The final strand of evidence we used to triangulate our account of Quinn is her own descriptions of her teaching. During the first summer institute Quinn described her current teaching practice as "a set of lecture notes of facts that the students should know for the test, lab experiments that only serve to prove the facts already presented, and reinforcement activities of the same rote facts" *(135, 1st sum.)*. Quinn also described attempting to engage her students with "hands-on" activities, but admitted that she often found herself "giving the answer" *(132, 1st sum.)*. Two years later, Quinn recounted the changes she made in her classroom as she discussed her experience in the PD program with her peers in a group interview:

> Labs used to be very cookbook, and, "here, do this, do that, don't do this, don't do that." And now I've given them materials, I say here's some driving questions you might want to think about, what do you think is happening or how do you think it's working or could you design an experiment to test your ideas? *(240, 2nd acad. yr.)*

Quinn also described her shifting role as an instructor in the classroom saying she "eliminated a lot of the direct instruction and lecturing" and was instead "question[ing] student thinking" (*234, 2nd acad. yr.)*. For example, Quinn described beginning each class by asking students to think about "a phenomenon they may have experienced in their everyday lives." *(240, 2nd acad. yr)*. Quinn also drew attention to a in the way she organized her classroom wall space. The information she has displayed on her walls was "no longer posters of this fact or that fact and the periodic table. It's more of what the students' ideas are and how they've changed over the course of the term" (*240, 2nd acad. yr.*). Her approach to assessment also shifted: Quinn described focusing on whether the "reasoning makes sense with the model" when assigning points to her students' work *(240, 2nd acad. yr).*

Overall, the comparison of Quinn's descriptions of exemplary lessons and the quantitative and qualitative analysis of Quinn's descriptions of her instructional approach suggest a shift in emphasis from traditional lecture-based instruction and hands-on laboratory activities to classroom discussions in which students are encouraged to develop their own explanations for phenomena.

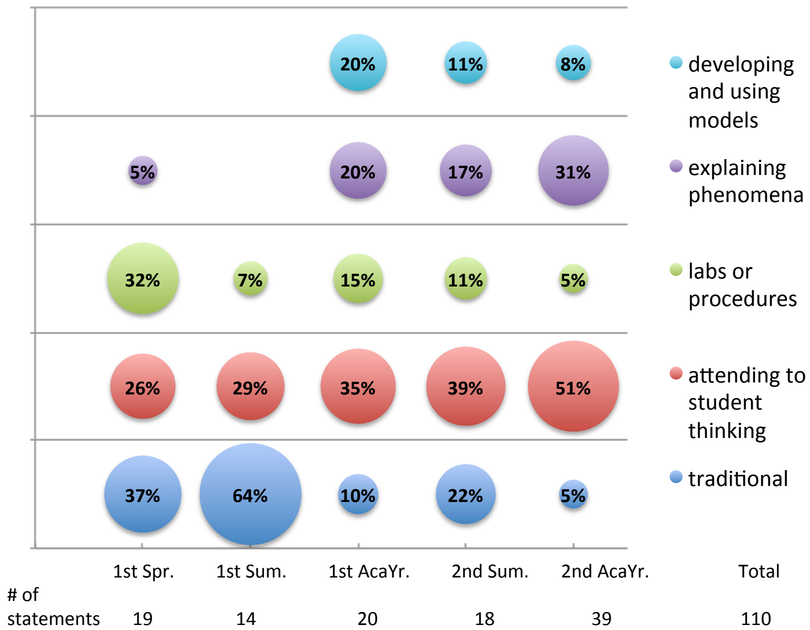

Figure 1. Quinn's self-described *instructional choices and pedagogical strategies* over time. Size of bubbles and number labels indicate percentage of statements assigned to each of the five codes within each time period.

Quinn's Conceptions of Student Learning and Science Teaching

Early in the PD, Quinn's statements about the learning process involve a number of different references to students' prior knowledge. She describes students as having "many misconceptions about science, specifically about chemistry" and that students must be given opportunities to "question what they think that they already know." For example, Quinn described how many students "assume there is only a chemical reaction if the result is an explosion" so she provided them with the chance to observe other kinds of chemical reactions in a series of "hands on" lab stations (*180, 1st spr.*).

She also described the importance of making connections between her instruction and students' prior knowledge. In general, she stated, "throughout lecture/direct instruction, I try to ask questions of students to access their own personal experiences and prior learning" (*155, 1st sum.*). Specifically, Quinn described how "teaching for understanding" in her classroom might happen when "I present the information using analogies to concepts that the students have in their prior knowledge or life experience (like when I compare the molecular movement and energy of solids, liquids, and gases to students in class (solid), at lunch (liquid), and after 3pm (gas)) (*132, 1st spr.*). However, Quinn also expressed dissatisfaction in the way her current practice aligns with her ideas about learning. "My teaching has evolved into something that does not reflect what I do know about prior knowledge and preconceptions," she wrote, stressing the mismatch between her current teaching and her ideas about learning. "Rarely do I find the time to examine students' prior knowledge," *(135, 1st sum.)*.

Towards the end of the program, Quinn still expressed a concern over misconceptions. Her goal was to help students "eliminate all the previous theories," but described this process in a way that emphasized giving students time to think and talk to one another. For example, Quinn indicated that markers of learning for her now included being able to say that during a lesson, "at least they [students] were thinking, at least they were challenging what was being said by their peers, or what they thought themselves…. The kids learn more as opposed to just filling their heads with the facts and not actually committing it into their long-term memory." (*238, 2nd acad. yr.*).

Quinn's Conceptions of Scientific Models and the Role of Models in Science Teaching

Early in the program Quinn's responses reflect a number of different conceptions of the nature and utility of scientific models. Like many teachers Quinn described a model as "a plastic form representing an important structure of process in science i.e. a model of the water cycle or a cell model" (*122, 1st spr*.). She suggested that the role they play in teaching is as, "visual representations of structures that are not readily accessible to students-whether it be due to the lack of equipment necessary (like you can't see a cell without a microscope) or the lack of tangible attributes of a topic (for example, students who live in the suburbs may have difficulty understanding the rock cycle)." (*123, 1st spr*.) At the same time, Quinn stated that, "Models, like theories, are possible explanations for phenomena." (*125, 1st spr*.). In this role she described how models could be used in the classroom to, "Engage students and explore curiosity through understanding the cause-effect of phenomena" as well as to allow, "them to really try to formulate hypotheses and test them!" (*129, 1st. spr*.).

> In a science classroom, we use models everyday to teach students. After all, the models are what make up the ideas that we try to get our students to understand. However, the students and the teachers that often present the curriculum look at the models in the form of facts that are memorized and regurgitated through assessments and projects. This does not demonstrate a thorough UNDERSTANDING of the model, but instead, a memorization of the facts and definitions at hand. (emphasis original, *133, 1st spr.)*

Later Quinn consistently referred to models as things that "allow us to develop explanations for natural phenomena (*196, 1st acad, yr*). A model, she says, is not "just a description," but rather something that is used for "explaining/knowing mechanisms" (*221, 2nd sum*.). What makes models useful in science classrooms is that they allow students "to create their own driving questions make observations, collect data, and develop the model," and, "more importantly, I would like them to reason with their model" (*197, 1st acad. yr*.).

Quinn's "MBR" framework: Coordinating student thinking and explanatory models

Early in the PD, Quinn described MBR as a process that "has participants come to their own conclusions to explain a phenomenon" (129, 1st sum), combining a constructivist ideas about learning with a focus on making sense of phenomena. We see this integration echoed throughout Quinn's responses. For example, at the end of the two-year PD, the teachers were asked to reflect on what they had learned from their participation. Quinn's response once again brings together ideas about learning and the role of models in science.

> I don't need to be the source of information. I learned that I don't have to direct them to a source of information, that a lot of things that students gain through this process are in looking at or experiencing phenomena and reasoning out for themselves that they are the source of knowledge, and that they don't have to go somewhere else to find it, and that they can work together to come to the same answers they would have found in a textbook, and in the process eliminate all the previous theories that used to be presented in coming up with those scientific ideas. (*238, 2nd acad. yr*.)

We posit that it was the refinement and coordination of these ideas that constitute the learning underlying Quinn's described pedagogical shift. We see evidence of this in the way Quinn linked MBR to specific instructional strategies. In describing what it looks like to enact MBR in a science classroom, Quinn described "assessing constantly, to see oh, there's a new misconception, oh, this group is totally on the right path, and then you have another group that's totally on the wrong path, and it's okay, because eventually they'll get there." Quinn described how in her experience as a learner she often had moments of profound confusion, but that she saw these as an integral part of learning within this framework. Quinn stated that in her own classroom, "with my students I almost feel a sense of accomplishment when I leave their group and they seem just as confused as I did." Quinn also described how MBR means focusing her lessons around the following question: what do I want my students to be able to do and explain? (*223, 2nd sum*.)

In summarizing what she saw as the "essential elements" of the MBR approach, Quinn names three instructional heuristics: "1. Don't steal 'ah-hahs' 2. Make thinking visible and making thinking happen, 3. importance of a driving question" *(249, 2nd acad. yr.).* The first refers to the teaching strategy of providing space and time for students to come to their own understanding rather than telling. The second refers to a set of strategies, including asking students to draw and reflect, while prompting them with challenging questions and the third refers to organizing lessons around a central driving question about some phenomenon. Taken together these essential elements combine strategies meant to support student thinking as well as keep that thinking rooted to a scientific question.

Finally, we see evidence of Quinn reflectively applying the MBR framework to her past instruction. At the end of the program Quinn critiques her original lesson (Table 1) noting that while it did "address a preconception," it did not challenge students to "reason, take risks, or thinking deeper" and for this reason she no longer believed it would be effective in changing student thinking. She also noted that the lesson, "asked for answers without explanation" (*253, 2nd acad. yr.)*. In contrast, she described her new lesson as exemplary because it incorporated strategies such as using pictures and words to make students thinking visible and engaging students in explaining a phenomenon. She further described her role in the lesson as "facilitating," not "giving answers" (*252, 2nd acad. yr*.).

Discussion

Using a Resources Framework to Make Sense of Quinn's Shift

This case study relies solely on self-report data as evidence of a shift in how a teacher thinks about her pedagogy. While research has documented that descriptions of practice do not always reflect classroom enactment, we argue that the quality and consistency of the shift we see in Quinn's responses represents an outcome worth exploring. We acknowledge however that more work is needed to see how these self-reports play out in the classroom.

Continuing from the assumption that we have captured a consequential change in how Quinn approaches her teaching, how can we make sense of Quinn's shift over time in the program? One interpretation could have been to evaluate whether she attained the target knowledge about MBR and then attribute shifts to that knowledge acquisition. However, when we actually look at the data they tell a much more complicated story. If we model stable beliefs as mediating instructional practice, then two trajectories are possible: Either Quinn entered the PD with a set of sophisticated beliefs that allowed her to take up the messages of the PD program and change her practice, *or* the PD program was able to change Quinn's core knowledge and beliefs about science teaching and learning. Our analysis of Quinn's statements about student learning and scientific models do not support the interpretation that she had a stable set of core beliefs coming into the program.

A resources framework provides an alternative way to think about teacher learning in terms of building coherence around sets of productive resources. Looking across our analyses we can begin to make sense of the shift we saw in Quinn's descriptions of her teaching. Quinn's evolving understanding of MBR seems to have provided her with a way to coordinate, refine and enact ideas that she brought with her to the program. Quinn's initial inclination to connect to students' prior knowledge was refined into a strategy that allowed her students to make their thinking visible by generating public representations of their ideas. Rather than demonstrating or telling them the correct ideas, as she described doing early in the PD, Quinn described how to her, MBR means giving students more time to think, and allowing for, even valuing, frustration as part of the learning process.

Crucially, MBR also gave her a way to structure this thinking around an authentic scientific aim – to use models to explain natural phenomena. That is, it gave her students something to think *about*. Rather than demonstrating or directly teaching the scientific models to her students, the model ideas became the reasoning tools that her students would use to think about and explain phenomena. For Quinn, ideas about what it means to learn deeply and what it means to engage in authentic scientific reasoning appear to have come together under the MBR framework. That is, she came in with the inclination to attend to student ideas and an intention to engage students in science, but she admitted that she didn't actually do much of that in her day-to-day practice. By the end of the program Quinn demonstrated that she was using MBR as a coherent framework and as a lens through which to view her pedagogy. In reflecting on her past lessons she was critical of both the quality of the science and the nature of her attention to student ideas. In describing her current aspirations, she described the importance of both choosing a phenomenon to investigate and ensuring that her students were the ones doing the thinking, while she played the role of facilitator. In her own analysis of her pedagogy, Quinn seemed to productively bring together and coordinate a number of ideas around student learning and scientific practice.

Implications for Professional Development

This PD program was not explicitly designed with a theoretical commitment to a resources view. Given the success of Quinn, what can we say about PD more broadly? The ISIM PD included many design features of good PD including: engaging teachers as learners in the MBR process, long duration, community building and coordination of theory with professional experimentation (Wilson, 2013). This work does not challenge these design decisions, but rather provides us with a way to reframe the way with think about teacher learning. For example, one of the objectives of the PD was to help teachers take up the MBR framework. We now have a better understanding of the mechanisms that may have led one teacher to take up many of our intended messages and a more robust understanding of what uptake even means. For Quinn it was not about merely acquiring or replacing existing conceptions of teaching and learning. What seems to have mattered to her was that the PD generally and the MBR framework specifically allowed her to coordinate and refine some of her existing ideas about teaching and learning. This work echoes the understanding that PD is situated in a much longer trajectory of teacher's experiences. The PD aim should not be to completely overturn and replace teachers' systems of beliefs. Rather than labeling teachers' knowledge as correct, unproductive or transitional, we can focus more specifically on the kinds of resources teachers have that can be built upon, coordinated and activated in particular contexts while helping them to reflect on their pedagogy and refine their practice.

As we go further into our data analysis and consider the implications for PD more broadly, we will need to also attend to the varied reasons why teachers may not have taken up these ideas. Increasingly, research on teacher learning suggests that merely targeting particular beliefs may not result in changes in classroom practice (Blanchard et al. 2009). Instead, what Franke et al. (1998) call "self-sustaining, generative change" seems to depend on the degree to which teachers have a coherent framework that can be used *flexibly* and thoughtfully to guide action. It is a more thorough understanding of the cognition of teachers in context that will be useful moving forward. More work is needed to understand how to systematically support teachers as they apply wide-ranging sets of cognitive and epistemological resources to the array of contexts in which they find themselves. In particular, the implementation of the Next Generation Science Standards in the U.S. creates the potential for a major perturbation of the status quo in science classrooms. Understanding how teachers develop, activate and cohere their new and existing cognitive resources around learning, teaching and scientific practice in service of aligning classroom practice to the new reform context will be critically important.

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