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Running head: POTENTIAL TEACHERS' PEDAGOGICAL RESOURCES

**Potential Teachers' Appropriate and Inappropriate Application of Pedagogical Resources
in a Model-Based Physics Course: A "Knowledge in Pieces" Perspective on Teacher
Learning**

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Abstract

We used a “knowledge in pieces” perspective on teacher learning to document undergraduates’ pedagogical resources in a model-based physics course for potential teachers. We defined pedagogical resources as small, discrete ideas about teaching science that are applied appropriately or inappropriately in specific contexts. Neither right nor wrong, all pedagogical resources can be used to build toward a more sophisticated pedagogical stance. We collected three kinds of data across this 11-week course: videotapes of class sessions, undergraduates’ written assignments and projects, and individual interviews. We qualitatively analyzed these data for pedagogical resources that undergraduates applied both appropriately and inappropriately to make sense of the large concept of model-based science instruction. We identified four such resources: 1) the teacher’s role is to provide the right answer, 2) guiding students is less certain than telling them (the right answer), 3) a good model includes scientific terms, and 4) children are creative thinkers. We examined the ways potential teachers’ inappropriate application of these four pedagogical resources interfered with their attempts to understand science teaching through modeling. We also explored how seemingly problematic small ideas about teaching were applied appropriately toward a more nuanced description of model-based science instruction. In our discussion and implications, we recommended ways content course instructors and science education researchers can identify and build from potential teachers’ pedagogical resources to help them better understand the large concept of model-based science instruction.

Keywords: potential science teachers, model-based science instruction, learning to teach, pedagogical resources

Potential Teachers' Appropriate and Inappropriate Application of Pedagogical Resources in a Model-Based Physics Course: A "Knowledge in Pieces" Perspective on Teacher Learning

There is a need to recruit more science and mathematics teachers to teach in US public schools. The National Research Council (NRC, 2005, 2010) has called for the annual recruitment of 10,000 new science and mathematics teachers to educate 10 million students. There is also a need to better prepare these new teachers before they enter K-12 classrooms. Authors of a third NRC report (2000) recommended the transformation of college-level science courses to provide potential teachers with deep understanding of content and with models of instruction considered effective in teaching such content to K-12 students. More recently, the National Task Force on Teacher Education in Physics (2010) suggested revising college physics courses in light of research on both student thinking and reform-based instructional approaches. To respond to these needs for more and better prepared secondary science and mathematics teachers, universities across the US, including the one studied here, have created innovative programs for STEM undergraduates interested in pursuing teaching careers (see Mervis, 2007).

At the same time, the science education community has proposed a new vision for what counts as reform-based science teaching and learning. With the recent publication of *A Framework for K-12 Science Education* (NRC, 2012), the teaching and learning of modeling has moved to the center of science education reform. Developing and using models is one of eight essential science and engineering practices. It is also one of four practices that make visible the language-intensive nature of science teaching and learning (Quinn, Lee, & Valdés, 2012). "The interplay between diagrammatic representations of models . . . of a system and the language used to describe these representations both builds students' conceptual understanding of the system in question and refines their ability to talk about it" (pp. 3-4).

To make sense of potential teachers' ideas about teaching that emerged in a model-based physics course, we used a "knowledge in pieces" (diSessa, 1993) perspective on learning. We identified small, discrete ideas about teaching, or pedagogical resources, undergraduates activated in specific contexts to understand the teaching and learning of science through modeling. Pedagogical resources develop from observations and experiences with the teaching and learning process over time and exist prior to formal instruction in how to teach. They can be applied appropriately or inappropriately in a given context to understand a larger instructional concept. Pedagogical resources differ from pedagogical content knowledge (PCK; Shulman, 1986, 1987) in that they are neither pieces of an expert knowledge base nor are they developed through formal instruction. Pedagogical resources are less complex than teaching orientations, which are situated within the PCK construct and defined as "teachers' knowledge and beliefs about the purposes and goals for teaching science at a particular grade level" (Magnusson, Krajcik, & Borko, 1999, p. 97). Pedagogical resources are also more precisely defined than small but amorphous teacher beliefs (Gess-Newsome, 1999).

We offer three reasons a knowledge in pieces approach to teacher learning is a more powerful and productive way to frame our study of potential teachers' ideas than pedagogical content knowledge, teaching orientations, or teacher beliefs. One reason is that a knowledge in pieces approach identifies pedagogical resources that teacher learners bring with them into formal instruction in how to teach. As such, the context of our study, an undergraduate model-based physics course for *potential* teachers, is an ideal place to investigate resources about modeling. A second reason is that each and every resource a teacher learner brings into a course

can and should be *built* upon to generate more sophisticated understandings. Resources are never dismissed as problematic, unlike some teaching orientations (Nargund-Joshi, Park Rogers, & Akerson, 2011) and teacher beliefs (Jones & Carter, 2007; Luft et al., 2011). A third reason is that the construct of teaching orientations has been found problematic: The nine teaching orientations regularly used to categorize science teachers' knowledge and beliefs lack a strong empirical base (Friedrichsen, Van Driel, & Abell, 2011).

The purpose of this paper, then, is to illustrate the use of a knowledge in pieces approach to teacher learning by documenting the pedagogical resources that potential teachers bring to model-based science instruction. Because our study is found at the intersection of these three movements -- recent calls for more and better prepared science teachers, the central science and engineering practice of modeling, and the emerging area of research on teacher learning as resources -- it is novel: It provides new insights into learning to teach science. We posed three research questions to identify resources about teaching science through modeling: What pedagogical resources undergird our undergraduate participants' understanding of science teaching? In which contexts were these resources accessed and applied appropriately and inappropriately? How did these resources support or constrain undergraduates' efforts to learn model-based science instruction? In our discussion and implications, we described ways content course instructors and science education researchers can productively leverage teacher learners' pedagogical resources -- so as to more effectively teach teachers what modeling is and how one implements model-based instruction in classrooms.

Conceptual Framework: The Centrality of Ideas

Mikeska, Anderson, and Schwarz (2009) identified three problems of practice teacher educators must help preservice science teachers understand and address to become well-started beginners¹: (1) engaging students in science, (2) organizing instruction, and (3) understanding students' ideas (p. 678). While these three problems of practice are only a small subset of the skills, knowledge, and beliefs reform-minded teachers must develop (see Davis, Petish, & Smithey, 2006), even limiting science teacher education to these three problems presents a formidable challenge to preservice teachers and to those who educate them. This is especially true at our institution, where teacher candidates spend only one year in their teacher education program. Providing opportunities for potential teachers to grapple with these problems of practice as undergraduates in content courses, prior to entering teacher education, may contribute to the production of well-started beginning science teachers.

We argue that a central reason model-based science instruction is challenging for beginning teachers to learn is because it requires them to *understand students' ideas* in order to *organize instruction*. As such, our study of potential teachers in an undergraduate model-based physics course explored participants' initial ideas found at the intersection of two of the three problems of practice discussed above: problem two about organizing instruction and problem three about understanding students' ideas. We drew from two areas of scholarship to construct our conceptual framework about the centrality of ideas in the teaching and learning of model-based science: a knowledge in pieces approach to teacher learning, and what counts as a sophisticated model-based pedagogical stance. We discuss each piece of our conceptual frame below.

¹ For information about the origin of the term "well-started beginners," see Hollon, Roth, and Anderson (1991).

A Knowledge in Pieces Approach to Teacher Learning

We used a knowledge in pieces perspective to identify and understand ideas articulated by potential teachers in our study, in particular, their notions of how to teach science through modeling. This knowledge in pieces approach to learning was introduced by diSessa (1993), who proposed phenomenological primitives (p-prims) as small cognitive elements that are not formally learned, but that stem from one's interactions with the physical world. P-prims shape the ways an individual interprets an experience. The same p-prim can be cued in multiple contexts. In some cases, it is activated appropriately; in others, inappropriately. For example, a commonly cited p-prim is that "closer is stronger" -- the idea that the closer something is to an object, the stronger that object's influence will be. This idea serves the learner well when activated in the context of describing increasing heat as one gets closer to a fireplace. However, when activated to explain why it is warmer in the summer than in the winter, the learner may incorrectly conclude that the earth is closer to the sun in the summer.

Hammer and Elby (2002), building on diSessa's notion of p-prims, referred to learners' small cognitive elements as resources. They also distinguished between *cognitive resources* associated with explaining scientific concepts and *epistemological resources* associated with one's ideas about knowledge. An example of an epistemological resource is "knowledge as propagated stuff" -- the idea that knowledge can be transferred from a source to a receiver. The epistemological resources that students draw on influence how they interact with and value texts, instructors, peers, evidence, and their own prior ideas when learning science (Hammer & Elby, 2000).

As such, a knowledge in pieces approach views learners' ideas as comprised of small pieces that are cued in both appropriate and inappropriate contexts and that act in concert to understand a large concept. This approach helps to explain persistent challenges in understanding large science concepts: the contextualized nature of ideas, the existence of misconceptions, and the resistance of initial ideas to change (see Strike & Posner, 1992, for a discussion of the tenacity of students' ideas). It also suggests the kinds of student ideas researchers and teachers should attend to. Rather than examine large concepts that need to be confronted and replaced, researchers and teachers should identify the conceptual resources that students bring to bear in a given situation and devise ways to build from these resources to help students broaden and deepen their understanding (Hammer, 2000).

In our study, we used this knowledge in pieces perspective to identify the small ideas potential teachers used when learning the large concept of model-based science instruction. We referred to these pieces of knowledge about teaching as *pedagogical resources* -- to distinguish them from cognitive resources and epistemological resources. A few other researchers (Kali, Goodyear, & Markauskaite, 2011; Phillip, 2011) have similarly extended the knowledge in pieces description of learning to teachers' pedagogical knowledge. Kali, Goodyear, and Markauskaite (2011) drew from diSessa's work to propose pedagogical p-prims, mental resources created when being taught or when teaching and used for pedagogical sense making. They used the notion of pedagogical p-prims to explain why teachers articulated sophisticated pedagogical stances while talking about teaching, but reverted to less sophisticated stances when actually designing instruction. Philip (2011) extended the p-prim notion to explain teachers' ideological sense making about race, which he argued was built on concepts that were "socially shared ways of gaining information about the world" (p. 303). Both of these studies highlight the

contextual dependence of the particular pedagogical resources drawn on by teacher participants. A related construct is Windschitl's (2004) "folk theories" -- ideas about inquiry constructed by teachers through their experiences learning science. Although folk theories are neither as small as resources nor always built upon, they are similar in that they play an important role in sense making, are often tacit, and develop through normal and varied experiences, rather than during formal instruction in how to teach.

We intentionally selected the construct of resources because we think it important to *build* on potential teachers' ideas about teaching, even if these ideas initially appear counter to a sophisticated pedagogical stance. Rather than labeling some ideas as productive and others as problematic, we prefer to discuss small ideas as appropriately applied in some contexts, to support understanding of model-based instruction, and as inappropriately applied in others, leading to misinterpretations of the purposes and/or practices of modeling. Ultimately, we argue that teachers need to learn to integrate these different pedagogical resources into a coherent set of ideas that they can access and use effectively when teaching science through modeling.

Effective Model-Based Science Instruction

The course investigated in this study was designed to help potential teachers think about how to elicit, interpret, and use children's ideas to organize model-based science instruction. So that readers can better understand the type of pedagogical stance our potential teacher participants were expected to develop, we include a description of what effective model-based instruction looks like. We begin by defining a scientific model "as a set of representations, rules, and reasoning structures that allow one to generate predictions and explanations" (Schwarz & White, 2005, p. 166). Such models take many forms, including physical representations, drawings, analogies, and computer simulations. A good model has both explanatory and predictive power: If tests confirm one's predictions, the model gains more credence; if tests contradict predictions, the model is revised and retested. Further, modeling is considered an important aspect of science: "Scientists formulate and test their explanations of nature using observation, experiments, and theoretical and mathematical models" (NRC, 1996, p. 171). Indeed, as stated in our introduction, the recently published *A Framework for K-12 Science Education* (NRC, 2012) includes "developing and using models" as one of eight essential science and engineering practices (p. 56).

In model-based science instruction, teachers guide their students through proposing models, conducting investigations that lead to revised models, constructing explanations, engaging in argument, and using models to unify understanding (Passmore, Stewart, & Cartier, 2009). Engaging students in the process of articulating, testing, and revising models of natural phenomena requires teachers attend to students' ideas. They must learn to plan lessons and modify their in-the-moment classroom instruction to build on students' current ideas and to ask questions that challenge and develop students' understandings of natural phenomena and of the nature of scientific inquiry (Hammer, 2001). Further, Harrison and Treagust (2000) urged teachers to attend to the conceptual demands of different model types (e.g., scale models, iconic and symbolic models, mathematical models, and theoretical models): to "carefully assess the conceptual demands that their teaching models place on their students and [to] carefully negotiate each model with their students" (p. 1014).

Research makes clear, however, that preservice teachers find organizing their instruction to elicit and build from students' ideas difficult. One challenge preservice teachers face is

encouraging students to talk about their ideas. They do not always include the elicitation of children's ideas in their lesson plans (Mellado, 1998; Tabachnick & Zeichner, 1999). Teachers are also challenged to use students' ideas to inform instructional decisions. Otero and Nathan (2008), for example, found that even after eliciting and valuing children's ideas, many preservice teachers did not use these ideas to inform their next steps in instruction. Davis and Smithey (2009) also reported mixed success in helping preservice elementary teachers identify and work with children's science ideas.

Just as it is important for teachers to identify and build on students' ideas when teaching science through modeling, it is important for teacher educators to identify and build on potential teachers' ideas when teaching them about model-based science instruction. Crawford and Cullin (2004) noted that preservice teachers came into their course on model-based instruction thinking solely of models as teaching tool – as something used to explain concepts to others. Similarly, the preservice teachers in Windschitl and Thompson's (2006) study initially thought that “the purpose of scientific models was simply to illustrate ideas, to help one think more clearly about an idea or teach someone else about it.” “Apparently,” Windschitl and Thompson continued, “undergraduate experiences do little to advance the idea of models beyond that of acting as pedagogical props” (p. 820). We intend to contribute to this line of research by using a knowledge in pieces approach to identify small pedagogical ideas that can build towards a sophisticated understanding of using children's ideas in teaching science through modeling.

Research Design and Methods

Context for Study: A Physics for Teaching Course

We conducted our study at a large research university in California in fall 2009. In response to a national shortage of qualified science and mathematics teachers, a small team of university faculty embarked on an interdepartmental initiative to encourage STEM undergraduates to consider careers in secondary science and mathematics teaching. They attempted to develop a set of coherent pre-professional experiences at the undergraduate level as a bridge to entry into a post-baccalaureate teacher education program. (In California, teacher credential candidates must complete an undergraduate degree before entering a teacher education program.) They established an undergraduate minor in science and mathematics education to serve as the linchpin of this initiative. Physics for Teaching, the context of our study, was a content course in this minor.

The purpose of Physics for Teaching was to introduce potential teachers to research-based ideas about the teaching and learning of science before they entered a teacher education program. The course instructor, a science educator and first author of this paper, integrated the teaching of key physics concepts with children's ideas of science and recommendations for model-based instruction. Undergraduates were provided multiple opportunities to engage in the modeling process itself: to propose initial explanations for phenomena, test and revise their explanations, and then share and debate their tentative models with classmates. Undergraduates also examined how to teach science through modeling by analyzing videos of children talking about their ideas of physics-related phenomena and by discussing how they might build from children's ideas when implementing model-based science instruction in actual classrooms.

One can argue that undergraduate science courses specifically designed for potential teachers are integral to the production of reform-minded science teachers (NRC, 2000; National

Task Force on Teacher Education in Physics, 2010). Increased subject matter knowledge has been found to positively impact teaching practices (e.g., Carlsen, 1993; Hashweh, 1987; Hill, Rowan, & Ball, 2005; NRC, 2000; Van Driel, Verloop, & de Vos, 1998). Compared to teachers teaching outside their primary field (e.g., teaching physics when trained in biology), teachers who are comfortable in their subject area ask more complex questions (Carlsen, 1993) and are better able to identify students' alternative ideas (Hashweh, 1987). However, because subject matter knowledge alone is insufficient for teachers to teach well (Zeidler, 2002), researchers have also recommended the integration of pedagogical knowledge with subject matter in courses for potential teachers (Ball & Cohen, 1999; Munby, Russell, & Martin, 2001). In physics and the physical sciences at the undergraduate level, researchers have developed curriculum materials that explicitly address pedagogical issues along with content instruction for potential-to-preservice teachers (e.g., American Association of Physics Teachers, 1996; Goldberg, Robinson, & Otero, 2006; Hrepic et al., 2006; Jackson & Laws, 1997; McDermott, 1996). Physics and Everyday Thinking (PET; Goldberg, Robinson, & Otero, 2006) is one example of this type of curriculum. PET is regularly used with potential, preservice, and/or practicing elementary teachers. The course studied here, Physics for Teaching, implemented a modified version of the PET curriculum.

PET differs from traditional physics courses in its content, pedagogy, and focus on learning about learning. PET's physics content objectives are based on the *National Science Education Standards* (NRC, 1996) and the American Association for the Advancement of Science Project 2061's (1993) *Benchmarks for Science Literacy*. Because both policy documents (NRC, 2000; National Task Force on the Teacher Education in Physics, 2010) and research studies (e.g., Brown & Melear, 2006; Grossman, Smagorinsky, & Valencia, 1999) recommend teachers learn content using the methods they themselves will be expected to implement, PET is taught using model-based instruction. Teacher learners discuss their initial ideas about a particular physics concept, use computer-simulated and/or laboratory experiments to help them develop their understanding of this concept, and discuss their observations and interpretations within their small groups. At the close of each investigation, groups present their explanations, or models, to the rest of the class and reach consensus on a coherent set of evidence-based ideas that explain their observed results. PET also includes Learning about Learning (LAL) activities: Teacher learners watch video clips of elementary school children working through activities similar to those they completed, analyze these children's ideas, and reflect on the relationship between the nature of science and the process of learning science. (For a detailed description of PET design principles, see Goldberg, Otero, & Robinson, 2010.)

The instructor in our study articulated four reasons for adapting PET for the Physics for Teaching course. One, PET was designed for use with potential, preservice, and/or practicing elementary teachers; Physics for Teaching was intended for undergraduates considering secondary teaching as a career. Two, PET was developed as a semester-long course (15 weeks, 60 contact hours) while Physics for Teaching was taught during one quarter (11 weeks, 27.5 contact hours). Three, previous research on PET (Harlow, 2010, 2013) pointed to the need to foreground children's ideas of physics phenomena and to make explicit the decisions used in designing the curriculum if teachers were to learn the pedagogical skills of eliciting students' ideas and designing activities to challenge those ideas. Four, while the nature of learning and the nature of science are important and explicit components of PET, PET's primary goal is the learning of physics content. The primary goals of Physics for Teaching, in contrast, were

twofold: 1) an appreciation for the role of students' ideas in the teaching and learning of science and 2) an introduction to how to teach science through modeling.

For these reasons, then, the course instructor made three substantive modifications to PET for her Physics for Teaching course. One, she increased the proportion of time spent on Learning about Learning (LAL) activities. The 60-hour PET curriculum contains 47.6 hours of class time dedicated to physics content and 4.9 class hours dedicated to LAL (PET Project, 2009). Since the LAL activities were directly related to both course and research goals, she increased the time spent on LAL activities by extending discussions and by including additional LAL activities from similar curricula (e.g., Goldberg, Robinson, Kruse, Otero, & Thompson, 2007; Goldberg, Robinson, Price, Kruse, & Harlow, 2012). To account for the additional time on LAL activities and the smaller number of total contact hours, she reduced physics content to only those activities that directly supported the LAL activities. Content learning was used to reflect on and support undergraduates' analysis of children's ideas and to build an understanding of model-based inquiry. The adapted version resulted in 13.7 hours of content instruction and 10.4 hours of LAL instruction in the 27.5-hour course.

Two, the course instructor added questions about instructional strategies to the LAL activities. After nearly every LAL activity that involved videos of children learning science, the instructor asked undergraduates to discuss what they would do next if they were an elementary school teacher. (We clarify that, although the course was for potential secondary teachers, undergraduates were asked to place themselves in the role of an elementary school teacher because the videos were of elementary school children.) This differs from the PET curriculum in that the PET LAL activities focus exclusively on learning.

Three, the instructor added a series of four homework assignments focused on teaching. In their first homework assignment, for example, undergraduates described what they thought a teacher needed to know about children, science content, and teaching in order to teach science well. The assignment's purpose was to surface undergraduates' initial ideas about what constituted knowledge for teaching. Toward the end of the course, they were asked to revise their initial descriptions into a coherent teaching philosophy (first as a draft and then as a final statement). In place of exams that focused on physics content covered in the course, undergraduates developed both an individual and a group model-based science lesson intended for elementary school students. They were explicitly asked to attend to students' ideas and to draw on aspects of modeling as an instructional strategy in designing their lesson plans.

Finally, the instructor changed the order of the curriculum. The instructor began the Physics for Teaching course with the PET Model of Magnetism unit (unit 4 of PET) to establish modeling as an example both of scientific practices and of an instructional method. These two dimensions of modeling were then referenced throughout the course. Undergraduates first conducted a series of investigations with magnets to arrive at a simplified scientifically accepted model. They then examined video clips of second and third graders explaining their models of magnetism and discussed criteria to use in assessing these children's ideas. The magnetism unit was followed by three additional units on energy, forces, and electricity.

In sum, in the Physics for Teaching course, the instructor described model-based science instruction as engaging students in the iterative process of proposing, testing, and revising their models. The teacher's role was presented as guiding students toward the scientifically accepted model of a phenomenon: first soliciting students' ideas and then providing opportunities for students to collect, interpret, and share evidence to prompt revision of their models. Instructional decisions, the instructor emphasized, should focus on helping students use the criteria of

testability and explanatory power to test, evaluate, and revise their iterative models so as to eventually arrive at a model aligned with the one accepted by the scientific community. Our purpose in investigating this Physics for Teaching course was to examine the pedagogical resources, or small ideas about teaching, that were elicited in this particular instructional context – as undergraduates interpreted their own model-based learning experiences, explored models proposed by elementary children, and considered how they might build on students' ideas to teach science through modeling in the future.

Undergraduate Participants and Researchers

Twenty-seven undergraduates initially enrolled in the Physics for Teaching course. Five did not consent to participate in our research project and two others dropped the course mid-way through the quarter. Our resulting 20 undergraduate participants came from a range of majors: 11 were STEM majors (chemistry, mathematics, physics, environmental studies, or psychology); six were sociology majors; and three were business economics majors. Eleven undergraduates noted an interest in pursuing a career in education: Eight stated they wanted to become a secondary school mathematics or science teacher, and three discussed other careers in education, such as a counselor or curriculum developer. Indeed, eight of our 20 participants enrolled in additional science and mathematics education minor courses – before, during, or after the Physics for Teaching course.

A team of researchers participated in data collection and analysis. The first author, a science education faculty member, both taught and researched this course. To limit her influence on undergraduates' stated views and actions, she did not participate in the data collection phase. The second author is a science education faculty member and the director of the science and mathematics teaching initiative at this university. She participated in the research design and analysis phases. The third and fourth authors, graduate students in science and mathematics education respectively, helped design the study, videotaped all class sessions, interviewed undergraduate participants, transcribed audio and video recordings, and helped analyze the data. Three additional science education graduate students helped film the course and/or transcribe audio and video recordings.

Data Collected

The course instructor and her undergraduate students met for 75 minutes twice each week for 11 weeks. Three types of data were collected. One type of data was video records. We used two video cameras to record each class session. During small group activities, cameras were repositioned to capture small group discussions. All told, we collected 40 hours of videotape during the 27.5 hours of instruction.

Our second type of data included undergraduates' written products: nine individual online discussion responses, four individual homework assignments, and two lesson plans. More specifically, for their online assignments, undergraduates posted a response in a discussion forum each week. Students had a week to respond to each prompt; this means that while a prompt was assigned in a particular week (e.g., "Week 3 prompt"), it is likely that the undergraduates actually wrote their response the following week. Prompts asked undergraduates to describe how children learn science, to reflect on how they themselves learn, and to analyze ideas expressed by children in the LAL videos. (For each week's online discussion prompt, see Table S1 in the

supplementary materials.) As part of two of their four homework assignments, undergraduates wrote a draft and final teaching philosophy (statements ranged in length from one to three typed pages). They also developed two model-based lesson plans for elementary school students. One lesson plan was designed individually and due mid-course; the second was created as a group and due on the last day. Undergraduates were explicitly asked to design a science lesson that foregrounded model-based inquiry: They were instructed to identify children's possible initial ideas, discuss the subject matter knowledge a teacher would need to teach toward the scientifically accepted model, and include tests of models.

As our third type of data, at the end of the course, we purposefully selected and individually interviewed five undergraduate participants. Interviews followed a semi-structured protocol, lasted from 15 to 35 minutes, and were digitally recorded. Interview questions addressed the most and least valuable aspects of the course, the kinds of ideas children might hold about a scientific phenomenon studied in class, how a teacher might use children's ideas to inform instruction, and an example of an effective science lesson for elementary school students. (See supplementary materials for the undergraduate interview protocol.) Table 1 summarizes the data collected for each undergraduate participant.

<< PLACE Table 1 ABOUT HERE >>

Data Analysis

To align our analytic process with our conception of modeling, we drew from Mostyn's (1985) description of qualitative content analysis. Just as children use their scientific model to predict the outcome of a test, we began our analysis by framing a testable hypothesis: Learning physics content through model-based instruction, coupled with explicit reflection on children's ideas of these same concepts, should help undergraduates understand reform-based ideas about the teaching and learning of science. We tested this hypothesis against our data: We were particularly interested in the small ideas undergraduates held about teaching science concepts and practices through modeling.

We completed three cycles of analysis. We began our first analytic cycle by dividing all data among the four researchers. Two researchers independently open coded each piece of data. Disagreements were resolved through discussion. This initial pass through the data yielded two primary categories – undergraduates' ideas about children's ideas and undergraduates' ideas about teaching science – and thirteen subcategories. Successive passes through the data led to the elimination, addition, and/or condensing of subcategories. Resulting categories and subcategories from our first round are listed in Table 2.

<< PLACE TABLE 2 ABOUT HERE >>

In our second cycle of analysis, we attempted to synthesize our data. We identified what Mostyn (1985) called a "key concept" (p. 138): A key concept gives order to the rest of the data; it is an overarching theme to which all other findings relate. In this study, our key concept was undergraduates' concern for the right answer. We used the phrase "the right answer" as shorthand for ideas that are consistent with scientifically accepted concepts and processes – the types of ideas published in science journals and textbooks. We identified three additional themes that both connected to this key concept and retained our focus on children's ideas and model-

based science instruction: 1) interpreting children's initial ideas of scientific phenomena, 2) using instruction to develop children's ideas, and 3) assessing children's ideas in light of both evidence and scientific accuracy.

In our final analytic round, we reexamined our key concept and three additional themes through a knowledge in pieces perspective on teacher learning. To do so, we searched for pedagogical resources, or small ideas about teaching, held by our undergraduate participants and made visible through our previous analyses of the Physics for Teaching course. Recall that pedagogical resources are ideas developed through observations of and participation in the teaching and learning process, rather than ideas that are formally learned in courses on science education. Resources are neither correct nor incorrect in and of themselves, but applied appropriately or inappropriately in a given context. We identified four pedagogical resources that were not explicitly part of the Physics for Teaching curriculum: the teachers' role is to provide the right answer, guiding students is less certain than telling them (the right answer), a good model includes scientific terms, and children are creative thinkers.

Findings: Pedagogical Resources

We begin our presentation of findings by reminding readers of the study's context. The Physics for Teaching course was designed to introduce potential teachers to the teaching and learning of science through modeling and to the central role of students' ideas in the modeling process. Over the weeks of instruction, potential teachers took up the language of modeling as presented in the course. In class discussions and in assignments, they talked and wrote about modeling as eliciting prior knowledge, testing and revising ideas, requiring discussion among students, and explaining phenomena. Equally important, over the course of instruction, potential teachers were encouraged to examine their expectations for and prior experiences with science instruction. Conflicts across expectations, previous science learning experiences, and current instruction in modeling cued and brought forth a number of resources.

As such, we identified four pedagogical resources potential teachers in the Physics for Teaching course held – four small ideas on identifying, developing, and assessing children's ideas – that were integral to their larger understanding of model-based science instruction. These resources, we underscore, were sometimes applied in appropriate contexts and sometimes, in inappropriate ones. In these latter cases, the inappropriate application of pedagogical resources interfered with these potential teachers' attempts to understand how to teach science through modeling. Table 3 summarizes these four resources and the number of participants we identified as drawing on each resource. We elaborate on each pedagogical resource below.

<<PLACE TABLE 3 ABOUT HERE >>

Pedagogical Resource 1: The Teacher's Role Is to Provide the Right Answer

We found that undergraduates in our study consistently drew on the pedagogical resource that it is the teacher's role to provide the right answer. They drew on this "providing right answers" idea when considering how to interpret children's ideas, how to develop children's ideas, and how to assess children's ideas. In some contexts, they inappropriately applied this resource. David serves as a case in point. On Day 1 of the Physics for Teaching course, undergraduates participated first in small group discussions and then in a whole class

conversation about what an “ideal” teacher was and how he or she should teach. When reporting out for his group, David stated that good teachers should be able to provide the answer to each and every student question:

What we thought about [in our small group] was mostly what everyone else said. But I think that teachers should really have a good understanding of the subject because, in some classes, when you ask the teacher a question, they don't really answer the question for you. You just kind of go, “Oh, okay,” but they don't really answer the question. And they should be able to answer the question thoroughly. (Whole Class Discussion, September 24, 2009)

As David himself noted, his small group's view of a good teacher providing the answers to questions resonated with what preceding groups had presented.

Again, in their first homework assignment completed the following week, 12 of 20 undergraduates inappropriately applied the idea that the teacher should provide the right answer when responding to the following question: “What do teachers need to know to teach science?” More specifically, six undergraduates (including David) explicitly stated that it is the teacher's role to answer students' questions. For example, George wrote that teachers “should be able to answer any question for the student in the most clear possible way” (Homework 1, October 1, 2009); Rachel, that teachers need to be able to “explain at least the basics of every science [concept] in case students have questions” (Homework 1, October 1, 2009). Six additional undergraduates placed the teacher in the complementary role of telling students science content. For example, Ingrid equated lecturing to teaching in her description of previous course instructors: “I have come across many teachers in the past who do not know enough about their supposed subject; as a result, they assign reading and homework questions with no lecture or actual ‘teaching’ involved” (Homework 1, October 1, 2009).

As undergraduates in the Physics for Teaching course experienced new teacher and student roles, in some contexts, the pedagogical resource that teachers should provide the right answers was applied in ways that were consistent with the intent of model-based science instruction. In these contexts, undergraduates noted that it is the teacher's responsibility to ensure children understand that not every idea is scientific and that not all ideas are equally valued in science – that a goal of model-based science instruction is to encourage children to arrive at ideas resembling those of scientists. As one example, in his end-of-course interview, Victor aptly described how, when teaching science through modeling, the instructor's role is to provide *students opportunities to construct scientifically accepted* answers rather than to tell the right answers themselves: “Instead of the students expecting the answer from the teacher, you have the teacher expect[ing] the answers from the students” (Interview, November 20, 2009). He contrasted the role of the instructor in his current Physics for Teaching course with those in previous science courses.

[In other courses, the instructor is] giving you all the answers and giving you their ideas or other peoples' ideas. And if somebody says, “Well, I have this idea,” it's like, “Well, this person has this idea, it's in the book, and we don't care what you think really.” (Interview, November 20, 2009)

Although Victor was able to apply the pedagogical resource of providing right answers appropriately in one part of his interview, immediately after describing how much he appreciated the different format of the Physics for Teaching course, he expressed his frustrations with the expectation that the undergraduates, rather than the instructor, would propose scientifically accepted models: “In the end, I'm just waiting for the like, ‘Okay, Professor, what's the correct

answer? Who has the right answer?” (Interview, November 20, 2009)? For Victor, a question on what he liked most about the Physics for Teaching course elicited a response that resonated with model-based talk; a question on what he liked least, a response about the traditional role of the teacher.

As a second example of appropriate application, when asked to assess children's models of magnetism near the close of the magnetism unit, some undergraduates considered that teachers should keep in mind the scientifically accepted model (or what they termed the “right answer” or the “correct answer”) when making assessment decisions. Rachel explained that she considered “closeness to the correct answer” or at least models that could “potentially get the correct answer” important when assessing children's models. She clarified: “Not exactly that they [the children] have the right answer, but that you [as a teacher] could do a couple exercises and they would get progressively closer and closer to the correct answer” (Whole Class Discussion, October 13, 2009). We note that the two sets of statements made by Rachel in this first findings section show how cuing the same resource can lead to descriptions of instruction that are both inconsistent with the purposes and practices of modeling proposed in class (e.g., that teachers provide the answers to students' questions) and consistent with modeling (e.g., that teachers should help students move progressively closer to appropriate conclusions). We continue discussion of undergraduates' ideas on how teachers might move students closer to scientifically accepted models in our next section on guiding versus telling.

Pedagogical Resource 2: Guiding Students Is Less Certain than Telling Them (the Right Answer)

Most undergraduates in the Physics for Teaching course thought that *guiding* students through the process of proposing, testing, and revising models was less certain than *telling* them the scientifically accepted answer. We identified this small idea as a second pedagogical resource. Undergraduates sometimes applied this resource of guiding as uncertain in ways that were inconsistent with the intent of model-based science instruction. In Week 7 of the course, for example, as part of their individual responses to an online instructor prompt, potential teachers discussed the advantages and disadvantages of “not telling students the answer.” (See Table S1 for full prompt.) In their responses, 15 of 20 undergraduates noted that guiding students had the disadvantage of introducing unproductive uncertainty into the teaching and learning process. Undergraduates identified four ways guiding was uncertain; several discussed more than one way in their response. When teaching science using model-based instruction, they clarified, children could leave the class with scientifically inaccurate ideas (stated 8 times); waste time by proceeding down the wrong investigative path (stated 5 times); get hopelessly stuck during their investigation (stated 3 times); and/or experience difficulty when required to change their wrong ideas in future science courses (stated 2 times).

One undergraduate, Evelyn, identified wrong ideas and wrong paths as disadvantages of guiding through model-based instruction – even though she noted that the strategy could be effectively implemented in elementary science classrooms.

Unfortunately it [model-based instruction] can also serve to frustrate students. And if they don't get positive feedback of what they think is the right answer or affirmation that they are on the right track they can get discouraged and not want to try anymore. It is kind of frustrating to go around in circles and not reach a definite conclusion or answer. Also I think it is also kind of dangerous to let kids believe whatever they want instead of

eventually teaching them the right answer. (Online Discussion Response, November 12, 2009)

Another undergraduate, Fabiola, also expressed concern that children could leave the classroom with scientifically inaccurate ideas if guided through modeling – again, even though she thought model-based instruction an effective strategy. Children, she continued, could become resistant to future science instruction as a result: “[Because] they [children] can develop their own answer, students may believe that their answer is right and in the future it could be harder for them to change their belief” (Online Discussion Response, November 13, 2009).

In this context of discussing advantages and disadvantages of model-based instruction, eight undergraduates, including Evelyn and Fabiola, equated the process of guiding students with enabling them to leave the classroom with scientifically inaccurate ideas. They did not view the practice of guiding as requiring teachers to be cognizant of students' current ideas and the desired model to be constructed by them so as to carefully and thoughtfully plan instruction. The instructor in the Physics for Teaching course encouraged undergraduates to articulate ideas that were both consistent and inconsistent with scientific models – to make such ideas part of the public classroom discourse. The instructor made clear, however, that welcoming all ideas into the class conversation did not imply that all models were of equal value: In science, some models can indeed be considered better than others. One way the instructor (and the curriculum) questioned the value of a particular idea was by asking the class to consider whether the idea was consistent with data collected. Ultimately, undergraduates were expected to reach consensus on models that were consistent with scientists' models (or simplified versions of them), even though the instructor did not tell them which of their models was aligned with the scientists' models.

As with the pedagogical resource of teachers providing right answers, on occasion, undergraduates applied the resource of guiding as uncertain in appropriate contexts. For example, in Week 8, as part of a LAL activity on forces, small groups of undergraduates were asked to discuss a video clip of a teacher using questions to prompt her elementary school students' talk about friction. The children explained why they thought a toy car that had been pushed would slow down and eventually stop before and after they experimented with toy cars moving over different surfaces (grades of sand paper). Initially, the children mentioned a lack of batteries, gravity, and bumps as possible explanations for the car slowing. After their investigation, all of the children mentioned the role of the surface in slowing the car. When discussing the video, Karen and Isabelle agreed that guiding children using probing questions was better than simply telling them the right answer. The former approach furthered children's thinking about friction; the latter approach did not.

Isabelle: Just randomly I have a question. Do you think that by [the teacher] pushing [the child], do you think [the teacher] was giving [the child] the answer or do you [the teacher] was letting [the child] develop the answer on her own?

Karen: I would have to say it was sort of probing her [the child].

Isabelle: So do you think that's better than, do you think that's not giving her [the child] the answer but helping her find it?

Karen: I guess you can look at it as like sort of guiding the student in a direction.

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Isabelle: I was just wondering. Something to question.

Karen: Because it's not like the teacher like blatantly says, “Oh it's because of a push.” She was suggesting that that's why, right?

Isabelle: Because I think that if the teacher gives them the answer right away they're going to be dependent upon that and like they're going to think, "Well I don't have to think that hard because she'll tell us the answer anyway."

Karen: Yeah, they might stop.

Isabelle: And they'll wait for it. (Small Group Discussion, November 12, 2009)

We note that in their Week 8 individual online responses about this same friction video (see again Table S1 for the full prompt), Karen continued to argue that guiding was effective. Isabelle, however, clarified that it was difficult for teachers to pose questions that actually furthered children's thinking. Because guiding was uncertain, if a teacher provided too much or too little guidance through questioning, she explained, students would not be encouraged to think for themselves, and thus, would learn little about key scientific concepts like friction. "I do not feel that [the two children in the video] truly learned anything [about friction] because it seemed as though the answers they gave the teacher about their experience were ones that were coaxed by the teacher's questions and replies" (Online Discussion Response, November 24, 2009). Isabelle recommended that teachers first guide children and then tell them the right answer.

Finally, we found evidence that undergraduates tried to reconcile the idea that guiding is less certain than telling with their concern for right answers. Isabelle's conclusion to her online response that teachers first guide and then tell the right answer is one example. As a second example, in their end-of-course lesson plans, five of the eight small groups of undergraduates included instructions to the teacher both to guide children by investigating a phenomenon and to tell children the right answer. More specifically, in four lesson plans, children were invited to observe a demonstration or conduct an activity and to devise explanations for their observations – but then the teacher was to explicitly tell the right answer at the lesson's close. In Alison, Brenda, and Berenice's lesson on electricity, students first constructed a lemon battery, made observations, and drew pictures to explain their observations. However, rather than then inviting students to test, further discuss, and revise their models, the teacher was to "lead a class discussion in which [the teacher] explain[s] to the class how the lemon battery works" (Group Lesson Plan, December 8, 2009). In one other lesson plan, the teacher was to introduce the lesson by presenting genetics content and vocabulary – the right answer – and then to ask students to create Punnett squares and pedigree charts. (The remaining three group lesson plans were more closely aligned to model-based science instruction.)

Pedagogical Resource 3: A Good Model Includes Scientific Terms

A third pedagogical resource held by undergraduates in the Physics for Teaching course was the idea that, in science, a good model includes scientific terms. Across small group conversations, whole class discussions, and weekly online written responses, 12 of our 20 potential teacher participants articulated this pedagogical resource. In the magnetism unit, for example, some undergraduates inappropriately applied this resource when asked to select a best model from among 14 children's ideas of magnetism and to describe the criteria they used to do so. In their small group discussion, David and Christine focused almost exclusively on third grader Harley's use of scientific words like electricity, atoms, and electrons in deciding that his drawing of a model of magnetism was best.

David: This one [Harley's model] has atoms in it. Attractive power!

Christine: Ok, now we have to set up our criteria [for the best model of magnetism].
First of all, [Harley] mentioned atoms.

David: Oh yeah, [inaudible]. I like that one.

Christine: Um.

David: (examining Harley's drawing of his model in the textbook) [He] says, "When it pushes, it just got working." So [he] knows that it's pushing. But that's not another word for it [inaudible].

Christine: And [he] also mentions electricity.

David: Yeah.

Christine: (examining drawing of model) What's that? I wonder what [inaudible]. What's this?

David: (examining drawing of model) What's that say? Atoms, atoms everywhere. Cheetos [a type of potato chip].

Christine: It says electrons.

David: That says electrons? Oh, ok. I thought it said Cheetos.

Christine: (examining drawing of model) What about this? Oh, negative.

David: Oh, [he] knows negatives. And [he] has little plus signs.

Christine: I know. And [he] has a bunch [inaudible].

David: Example of pulling.

Christine: Pulling. Ok, yeah, I like Harley. (Small Group Discussion, October 8, 2009)

We note that Harley drew a magnet divided into sections labeled "atoms everywhere," "negitives (sic)," "metal," "electrons," and "electricity." Across the top, Harley wrote, "I think everything in here works together and makes a magnet. I also think when it pushes it's not working anymore. I think it matters about which way the atoms are pointing." This model is, in fact, aligned with the model developed by the potential teachers and uses several scientific terms; however, the model is neither testable nor connected to evidence collected in class.

As a follow up to these small group conversations, in Week 4, the instructor facilitated a whole class discussion and crafted an online discussion prompt about these 14 children's models of magnetism. She asked undergraduates to describe if their own ideas about the "ideal science student" influenced which child they picked as having the best model. (See Table S1 for full prompt.) Although the undergraduates disagreed over whether their notion of an ideal student influenced their choice of best model, five of them – including David and Christine – noted use of scientific terms as a reason they selected a particular model of magnetism as best. Ingrid explained that Harley's model was best, in part, because he used words like atoms and electricity.

Actually, my ideas do seem to be influenced by the student that I believe sketched the best model. Harley drew on experience from his past science classes to create his model. He listed all possible phenomen[a] (that he knew) that could be causing the magnet to attract other things, such a[s] electricity, "force" and atoms. (Online Discussion Response, October 18, 2009)

The instructor, in contrast, emphasized to undergraduates that models should be evaluated against the criteria of testability and explanatory power.

The absence of scientific vocabulary in many of the children's models signaled to some undergraduates that the teacher was necessary to help children learn to use scientific terms to express their ideas; we argue that this is an appropriate application of the pedagogical resource of a good model including scientific terms. As one example, in her written response to the Week 7 online prompt (see Table S1 for full prompt), Berenice stated that model-based instruction would work well in elementary school classrooms if the teacher helped children articulate their ideas using scientific terms:

[Children] have big ideas. The teacher would just need to help guide them in helping their ideas flow. The teacher should consider that kids this age probably don't know the proper vocabulary but could still be thinking on the right track. (Online Discussion Response, November 12, 2009)

Berenice's views that children need help from their teacher to articulate their ideas using scientific terms and that the learning of such terms is indeed important in the construction and refinement of models were shared by her group members, Karen, Isabelle, and Alison. The four discussed how, in a LAL activity video clip where children investigated friction using toy cars and sand paper, the teacher helped second graders Adriana and Elizabeth articulate their ideas about friction using scientific terms. This small group discussion occurred earlier on the same day that Berenice posted her online Week 7 response; it immediately followed Karen and Isabelle's exchange about the benefits of guiding versus telling presented under Pedagogical Resource 2.

Isabelle: Because their [Adriana and Elizabeth's] vocabulary's not really as developed as much.

Alison: Because they know that it's [the sand paper is] rough, but they just don't know how to put it in words.

Isabelle: In words, right. Because they are saying the right idea, it's just they're not saying it right, you know?

Alison: Yeah.

Karen: But I have to say that I feel the same way even at my age in this class. I don't know how to articulate what is going on.

Isabelle: I know, yeah.

Berenice: Exactly.

Karen: That's, you know, that explains why the teacher sort of guided them in that direction, so that they would have a better understanding of how to articulate what is occurring right in front of them. Right? (Small Group Discussion, November 12, 2009)

As a second example, in his written response to the Week 8 online discussion prompt about these same videos (see Table S1 for full prompt), Steven described at length how some children's explanations can show a high level of conceptual understanding even though they do not include scientific terms. He wrote: "It just proves to us that the kids know what is going on, but it is hard to them to put it in scientific words that would satisfy a scientist." He elaborated:

All in all they [the children] had the right idea that the car would slow down because of the bumps.

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I think Adriana and Elizabeth discovered that the car would go a certain amount of distance, depending on which sandpaper they used. So they figured out that certain sandpaper had more friction, which resulted in the car going a certain distance. This concept educat[ed] them on friction. However they never used the word friction. [T]heir vocabulary [word] that expressed this idea was pushing. "Oh, it's pushing this way (both move their hand in the direction opposite the motion of the car)." They learned that the harder you push something the faster it might go, however if the[re] are bumps or something pushing it away, it might eventually come to a stop. (Online Discussion Response, November 17, 2009)

Pedagogical Resource 4: Children Are Creative Thinkers

The idea that children are creative thinkers is a fourth and final pedagogical resource held by undergraduates in the Physics for Teaching course. Unlike the other three resources presented above, we begin our discussion of this small idea by examining its proper application. For example, in their Week 4 online responses, potential teacher participants were asked about the qualities they associated with an ideal elementary science student. (See Table S1 for full prompt.) Ten potential teachers explicitly stated that they thought creative thinking an important student quality in developing and refining models. (Five additional potential teachers referenced this resource in other contexts.) Alison wrote that “an ideal science student’ . . . [has the] capa[c]ity to think outside the box and be creative in explaining the magnetism model” (Online Discussion Response, October 19, 2009). Douglas stated that “an ideal science student needs to have an open mind that allows for generating multiple ideas when analyzing material” (Online Discussion Response, October, 19, 2009). Carla agreed; she wrote that it is “important to be creative so one can come up with new ways of understanding things” (Online Discussion Response, October 20, 2009).

This pedagogical resource of children as creative thinkers, we underscore, is integrally connected to the two learning goals of the Physics for Teaching course. One course learning goal was that children have ideas that must be elicited and built upon. In the course activities that included watching videos of children talking about science ideas, potential teachers were to identify children’s ideas about phenomena and consider how these ideas could be built upon. A second goal was that creativity is integral to the construction and refinement of a scientifically accepted model. This was supported through readings about the nature of science that included text about the role of creativity, as well as their reflecting on their own development of a model of magnetism and how they had used creative thinking to imagine what might be happening inside the magnet to account for the observed phenomenon. As such, unlike the three resources presented above, this pedagogical resource in and of itself can be understood as an appropriate outcome of the course.

This is not to say that the pedagogical resource of children as creative thinkers was always applied appropriately. At times, we found that this notion led potential teacher participants to draw problematic conclusions. As one example, as part of their Week 7 online response, potential teachers were asked whether the model-based instructional practice of not telling students the answer would be effective with elementary school children (see Table S1 for full prompt). Some potential teachers argued that they would not recommend implementation of model-based instruction in elementary schools precisely *because* children are creative thinkers. For example, Alison did not think model-based instruction an effective way to teach elementary school science because “[elementary students] might have their own imaginary and creative ideas towards [a] scientific topic.” Brenda similarly stated that this tactic would not work because “the answers that [elementary students] come up with tend to be imaginative.”

As a second example, Christine inappropriately applied this pedagogical resource in her discussions of why and how to teach children science. In her final teaching philosophy paper, she argued that children’s creativity should be viewed as valuable, but not necessarily as helpful in constructing scientific models.

In regards to younger children, it is important to allow them to be creative and reach their own conclusions. . . . However, the instructor should always remember to clarify what the correct answers or concepts are at the end. (Teaching Philosophy, December 7, 2009)

Discussion: Using Small Ideas Within the Large Concept of Modeling

The knowledge in pieces perspective “is founded on a manifold ontology of mind, of knowledge and reasoning abilities comprised of many fine-grained resources that may be activated or not in any particular context” (Hammer, Elby, Scherr, & Redish, 2005, p. 92). A shift in thinking from larger conceptions to smaller cognitive elements allows instructors, including university instructors of content courses for potential teachers, to abandon the daunting challenge of trying to confront and replace large concepts in science or science education. Rather, they can facilitate learning by employing the more productive practices of identifying the cognitive, epistemological, and/or pedagogical resources that learners bring to bear in a given situation and of considering how to help learners appropriately apply these resources in developing and deepening their understanding. In our study, we focused on the pedagogical resources potential teachers brought to and applied in an undergraduate model-based physics course.

As argued in our conceptual framework above, effective model-based science instruction requires eliciting and using students' ideas to organize and modify instruction. Part of the reason beginning teachers find learning to teach science through modeling challenging is because they must locate their instruction at the intersection of two of three problems of practice: organizing instruction and understanding students' ideas (see, again, Mikeska et al., 2009). In our findings, we identified four pedagogical resources that potential teachers accessed in their attempts to understand model-based science instruction: that the teachers' role is to provide the right answer, that guiding is less certain than telling, that good models require scientific terms, and that children are creative thinkers. In many instances, we found that our potential teacher participants inappropriately leveraged these pedagogical resources, either individually or in concert, to conclude that the instructional practice of guiding students through developing models to explain phenomena is less effective than the more traditional means of teachers explicitly telling students the correct answers. In fewer cases, these resources were appropriately applied to describe how teachers might use children's ideas to organize science instruction through modeling. The charge for content instructors and teacher educators, then, becomes how to support potential teachers in the correct application of these resources – how to help potential teachers leverage these resources in contexts where the problems of organizing instruction and understanding students' ideas in relation to the teaching of science through modeling can be thoughtfully discussed and better understood.

Our first pedagogical resource of providing right answers does not obviously align with model-based science instruction: This and other reform-based instructional strategies require teachers to release some control of their classroom to their students. In teaching science through modeling, rather than delivering a pre-planned lecture, teachers must actively use students' ideas to make decisions about how the lesson should unfold. Teachers also must be able to draw on content knowledge flexibly to build on the ideas students articulate. Further, they must remain confident that their students will develop deeper conceptual understanding through proposing models, making predictions, and revising ideas in light of new evidence. The pedagogical resource that it is the teacher's role to provide the right answer can serve as a barrier to embracing model-based instruction when inappropriately applied in the context of what counts as effective teaching. In our study, our participants, like those in David's small group, drew on this resource when describing a good teacher: A good teacher is one with deep subject matter

knowledge that can answer any and all students' questions. To better grasp model-based instruction, potential teachers must learn that a good teacher, a teacher with deep subject matter knowledge (Carlsen, 1993), consistently *poses*, rather than answers, questions.

Had we employed a view of teacher learning as the adoption of orientations or as influenced by beliefs, our discussion of how to understand and address potential teachers' notion that the teacher's role is to provide the right answer would end here. In light of the goals and constraints of model-based science instruction, viewing the idea of providing the right answer as part of an orientation or as a belief leads to the conclusion that it must be eliminated. However, because we decided to view teacher learning through a knowledge in pieces perspective, we can continue this discussion: We can explore how content course instructors can productively build upon this pedagogical resource located squarely at the intersection of organizing instruction and understanding students' ideas. More specifically, as we saw in our findings, instructors can leverage this resource to help potential teachers recognize that the ultimate goal of model-based science instruction is for their students to leave the unit or course with a model consistent with one accepted by the scientific community. Not all models generated by students can be considered equally scientific. Instructors can focus on helping potential teachers recognize that, when organizing instruction to build from students' ideas, they should keep the scientifically accepted model in mind and provide opportunities for students to compare their existing models with evidence so as to move closer to the target model. As Victor and Rachel suggested, it is the teacher's responsibility to devise appropriate learning opportunities that will lead students to this "right" model. In short, potential teachers must be encouraged to apply this resource in the appropriate context of designing a series of model-building activities that elicit students' initial ideas and systematically move them towards a scientifically accepted model.

Our second pedagogical resource, that guiding is less certain than telling, can also act as a barrier for potential teachers in using students' ideas to organize appropriate model-based instruction. Reforms in science education call for teachers to adopt the role of guiding students' thinking. This is likely something few potential teachers themselves have experienced as students; most have sat through course after course where they are expected to learn material provided to them through lectures and textbooks (Lortie, 1975). Potential teachers, like Evelyn and Fabiola, must learn that this resource is applied inappropriately when discussing disadvantages of model-based instruction because it necessitates an outdated view of student learning, a view that ignores both the existing ideas students hold and the active role students play in their own learning. The idea that guiding students using model-based instruction is less certain than telling students the right answers through lectures makes sense only if learning is viewed as a simple process of transmitting knowledge from teacher to students – as a process of teachers writing on students' minds as blank slates (Phillips, 1995). More recent constructivist (Driver et al., 1994; Vygotsky, 1978) and situated (Lave & Wenger, 1991) theories of learning make clear that telling is no more certain than guiding in light of students' active participation in what ideas they take up and how they fit those ideas into their existing understandings.

Again, had we viewed teacher learning as orientations or beliefs, our discussion of potential teachers' notion of guiding is less certain than telling would end here. However, when viewed through a knowledge in pieces lens, we see that potential teachers can also be encouraged to appropriately leverage this resource: to view uncertainty as an integral part of the teaching and learning process and to organize instruction in ways that provide guidance as needed to help students systematically move their thinking across time and experiences to more acceptable scientific models. Further, as Isabelle noted, because guiding is uncertain, teachers must

carefully consider the questions they pose and the activities they propose to further children's thinking. Depending on students' existing ideas, if a teacher provides too much or too little guidance, students will not be adequately supported in examining and revising their understanding for themselves. Deciding when, how much, and which kinds of guidance to provide students must be framed as a challenging and uncertain task located at the intersection of the two problems of practice, using students' ideas and organizing instruction.

Third, potential teachers' pedagogical resource of including scientific terminology in good models might be dismissed as associated with a naïve understanding of science – science as a long list of vocabulary words and hard facts (see Achieve, Inc., 2013, for a recent, reform-based description of the nature of science). Certainly, in the context of what counts as reasonable criteria for assessing students' models, potential teachers, like David and Christine, must be encouraged to see this pedagogical resource as inappropriately applied. When assessing students' proposed scientific models, they must learn to replace attention to included scientific terms with notions of testability and alignment with evidence.

Once again, our discussion of the notion that good models include scientific terms would end here had we viewed teacher learning as orientations or beliefs. However, from our knowledge in pieces perspective, we argue that potential teachers do not need to eliminate this resource; instead, they must learn ways to appropriately apply and build on this resource so as to effectively use students' ideas to organize model-based instruction. Some of the potential teachers in our study, like Berenice and Steven, used this resource to suggest teachers help their students move from explanations of phenomena couched in everyday language to ones that included integration of appropriate science vocabulary. As such, while this resource can be a barrier to identifying reasonable criteria for assessing student models, such as testability and alignment with evidence, attention to scientific terminology is needed to closely monitor the kinds of language students use to describe natural phenomena, to explicitly support students in mastering the academic language of science, and to determine if and when students understand core ideas and practices in science (Brown & Ryoo, 2008; Quinn et al., 2012).

Unlike our first three pedagogical resources, the final one we identified, that children are creative thinkers, is *not* an obvious barrier to learning to teach science through model-based instruction. Valuing the creative thinking of children is appropriately applied in the context of goals for science education: Like scientists, children should use their creativity when engaging in science.

One helpful way of understanding the practices of scientists and engineers is to frame them as work that is done in three spheres of activity. . . . In one sphere, the dominant activity is investigation and empirical inquiry. In the second, the essence of work is the construction of explanations or designs using reasoning, creative thinking, and models. And in the third sphere, the ideas, such as the fit of models and explanations to evidence or the appropriateness of product designs, are analyzed, debated, and evaluated. (NRC, 2012, p. 44)

Still, the idea that children are creative thinkers became a barrier in our study when potential teachers inappropriately concluded that reform-based instructional methods would not work well for children *because* they are creative. This inappropriate application would not have been unearthed using an orientations or beliefs perspective. Potential teachers, like Alison, Brenda, and Christine, valued students' creative thinking and yet thought that their creative ideas might lead away from scientific ones. They did not seem to recognize that understanding and valuing students' ideas is an integral part of science instruction – one of three practices

considered central to becoming a well-started beginning teacher. As such, potential teachers should engage in conversations about what to do when unexpected student ideas emerge – on ways to design instruction that is flexible and responsive to students' ideas while continuing to guide them towards intended learning goals. If potential teachers gain an appreciation for and understanding of the role that creativity plays in the scientific enterprise, they might more willingly encourage and embrace the expression of creative ideas in their own students.

We end our discussion by returning to the intersection of two of the three problems of practice beginning science teachers must master if they are to become well-started beginners: organizing instruction and understanding students' ideas. Again, to organize effective model-based instruction, it is imperative that teachers view students as active participants in their own learning and that they elicit and build from students' science ideas as they plan and implement lessons. Three of the pedagogical resources we identified in our study (that the teachers' role is to provide the right answer, that guiding is less certain than telling, and that good models require scientific terms), when applied inappropriately, led our potential teacher participants to narrowly focus on organizing instruction (one problem of practice) around the end content goal; they failed to consider how to use and build on students' ideas (another problem of practice) as part of the instructional process. The final resource (that students are creative thinkers) focused directly on students' ideas, yet like the first three, when applied inappropriately, discouraged many of our potential teacher participants from considering *how* to use students' ideas when organizing instruction. The way our potential teacher participants inappropriately applied pedagogical resources resonates with existing research: The primary obstacle to effective model-based science instruction is not eliciting or interpreting students' ideas, but figuring out how to *use* students' ideas to actually inform instruction (Otero & Nathan, 2008; Schneider & Plasman, 2011).

In contrast, when our potential teacher participants appropriately applied these pedagogical resources, they did so in ways that recognized the integral relationship between understanding students' ideas and organizing instruction in the context of effective model-based instruction. More specifically, they identified ways teachers could use students' ideas to make instructional decisions, in other words, to use instruction to further develop students' ideas. More work is needed to better understand how the identification and leveraging of pedagogical resources can help beginning teachers consistently and appropriately use students' ideas to organize effective model-based instruction.

Implications

Below, we discuss our study's implications for both instructors teaching content courses for potential teachers and researchers investigating teacher learning. Like our discussion above, our two sets of implications are tied together by a common theme: the importance of building from students' ideas when organizing instruction.

Teaching Content Courses for Potential Teachers

We offer two recommendations for ways a knowledge in pieces perspective can improve the teaching and learning of science through modeling in content courses for potential teachers. We remind readers that, from a knowledge in pieces perspective, learning is viewed as a process of changing the resources that are activated in a particular context or of building from resources

to a more stable construct, not of changing or eliminating the resources themselves. As such, our recommendations for content courses are grounded in the need for instructors and their undergraduate students to more closely interrogate and better articulate how to *build* instruction from learners' ideas. Indeed, the notion that students have *good* ideas that must be elicited and built upon is not only a core principle of learning as resources, it is integral to the practice of developing and using models (NRC, 2012) and, as examined at length in our discussion section, considered a central goal of science teacher education (Mikeska et al., 2009) as well.

One recommendation is that content course instructors be aware of and build instruction mindful of the four pedagogical resources we identified in our findings so as to help potential teachers develop a more sophisticated understanding of modeling. Content instructors should plan instruction that elicits these resources and makes them explicit to potential teachers. Instructors should also help potential teachers consider when these resources are being cued and whether the context is appropriate. Further, they should make clear how these resources relate to the problems of practice of organizing instruction and understanding, or more specifically, using students' ideas. As one example, course instructors can encourage potential teachers to consider how the pedagogical resource that the teacher's role is to provide the right answer is relevant when examining why and how to implement model-based science instruction (see NRC, 2012, p. 58), but not when describing an effective, reform-minded teacher. As Victor suggested in our findings above, in the context of model-based instruction, providing right answers can be understood as shorthand for engaging students in iterative opportunities to develop, critique, and refine their models so as to move closer to scientifically accepted representations and explanations of phenomena.

As a second example, content course instructors can build on potential teachers' pedagogical resource that guiding is less certain than telling to help them better understand student learning and the teaching of science through modeling. In the context of model-based science instruction, the less certain nature of guiding is considered integral to the learning process. Struggles to articulate ideas in response to teachers' guiding questions, as our undergraduate participants Isabelle and Karen discussed in our findings above, encourage students to think more deeply about the science they are asked to learn. Telling students the right answer at the beginning or end of a modeling lesson, as five small groups of undergraduates did in their lesson plans, can be understood to short-circuit, rather than ensure, science concepts are understood and retained. Further, as Isabelle underscored, given the uncertain nature of guiding, teachers themselves can find it difficult to pose questions that help prompt students' thinking. As such, course instructors can explicitly discuss with potential teachers how they manage the uncertainty of teaching science through modeling, the principles they follow to pose productive questions, and the ways they use students' ideas to inform their instructional decisions.

A third example is that content instructors can elicit and build on the pedagogical resource that good models include scientific terms. As was discussed in our introduction, modeling is considered a discourse-intensive science practice (Quinn et al., 2012). As was also recognized by some of the potential teachers in our study, like Berenice and Steven, science talk *is* different from everyday talk. Part of a teacher's role when teaching science through modeling, then, is to facilitate discussion among students so that they can compare proposed models and can determine which models best explain existing data. Imprecise language can lead students to misunderstand what is meant by each other's models, and thus, to derail productive discussions. In content courses in which potential teachers propose, debate, and refine models, instructors can point out when potential teachers appear to be using terms differently from one another and to

use these instances as opportunities to consider the role of terminology in scientific models. Course instructors should push potential teachers to recognize that scientific terms themselves are not the model; rather, scientific terms are valuable in clearly articulating a particular set of ideas and in ensuring all understand its meaning.

As our final example, we found that the pedagogical resource of children as creative thinkers led some potential teachers to conclude that model-based instruction would be ineffective in elementary school classrooms because children's ideas were creative rather than scientific. In other words, these potential teachers saw creativity as a distraction from, rather than a generative part of developing and using scientifically accepted models. We see this pedagogical resource as closely tied to potential teachers' concern for the right answer – as cued in concert with the resources that the teacher's role is to provide the right answer and that guiding is less certain than telling. If the ultimate goal of science (or at least science instruction in classrooms) is to arrive at the right answer, creativity seems unnecessary, even problematic. To productively use this resource, instructors can begin by explicitly stating that creative thinking is a goal of science education. Instructors can also engage potential teachers in conversations about what to do when unexpected student ideas come up and how to re/design instruction to guide students toward intended learning goals. Further, instructors should make explicit the role of creativity in the science and engineering practice of developing and using models: One purpose of “models [is to] make it possible to go beyond observables and imagine a world not yet seen” (NRC, 2012, p. 50). Finally, instructors must better articulate the connection between creativity and the nature of science: “An education in science should show that new scientific ideas are acts of imagination, commonly created these days through collaborative efforts of groups of scientists” (NRC, 2012, p. 79).

Our second recommendation for instructors of content courses is to use the construct of resources to more effectively organize their own instruction around their undergraduates' ideas – to model for potential teachers productive approaches located at the intersection of these two problems of practice routinely encountered by beginning science teachers. Instructors can draw explicit connections between their own attempts to elicit and build from potential teachers' pedagogical resources in implementing model-based science instruction and these potential teachers' efforts to solicit and use students' ideas about a natural phenomenon in a model-based science unit. Put in the language of resources, considering both potential teachers' understanding of teaching and students' understanding of natural phenomena as consisting of resources frames the goal of instruction in each context as a process of identifying, appropriately applying, and building from learners' existing small ideas (for a similar argument, see Otero & Nathan, 2008). The process and purpose of both learning to teach science and learning science through modeling can be presented as the same: Learners, whether potential teachers or students, are asked to start from their existing ideas to build coherent, stable constructs accepted by the larger community of science educators or scientists.

Researching Teacher Learning

We also offer a second set of recommendations for researchers of teacher learning. Part of what is needed to facilitate the integration of pedagogical resources into science teacher education is additional systematic research: to identify additional small ideas about teaching held by potential and preservice teachers; to understand the specific contexts that routinely cue these resources; to examine their application across content courses for potential teachers, teacher

education coursework, and K-12 science classrooms; and to explore instructional strategies that might be effective in helping these nascent teachers build from their resources to develop coherent and stable pedagogical stances on model-based science instruction. Our study, we underscore, serves as a mere beginning to this process.

Examination of our study's limitations suggests four avenues other researchers interested in pedagogical resources, in particular, and a knowledge in pieces approach to teacher learning, more generally, could explore. One limitation of our study is its number of participants. As is typical of qualitative studies, we collected a large amount of data on a small number of potential teachers in one particular course. While the resources we identified in this paper were held by the majority of our potential teacher participants, we do not claim that this is the case for all undergraduates considering a career in teaching. Further research on larger numbers of potential teachers across a variety of content courses would be necessary to make claims about how common these resources actually are.

A second related limitation, and hence second fruitful avenue of future research, is connected to the course we studied. Physics for Teaching presented only one approach to science instruction: All activities and assignments were focused on helping undergraduates better understand science teaching through modeling. Research on children's resources for scientific sense making indicates that resource activation is context dependent (Hammer, 2000) — different course content, activities, and assignments may have made different pedagogical resources visible. As such, we do not claim that the four resources described above represent the only pedagogical resources our undergraduate participants held or could draw upon when considering how to use students' ideas to organize science instruction. Research in courses implementing one or more other reform-minded approaches to science instruction (e.g., place based science education, and culturally relevant science instruction) should lead to the identification of additional pedagogical resources.

A third limitation is the short duration of our study: We did not follow our undergraduate participants into a teacher education program to see how pedagogical resources were applied when actually teaching science in classrooms. While some of our data indicate a possible shift in how particular undergraduates used pedagogical resources (see, for example, our discussion of David under Pedagogical Resource 1), we have little sense if such shifts would persist over time or if they would support the effective teaching of science through modeling to K-12 students. Future research should follow potential or preservice teachers who complete a model-based course both over time and into science classrooms (see Bianchini & Cavazos, 2007, for one study that bridged teacher education coursework and K-12 classroom teaching).

A fourth limitation of our study is the failure to complicate our notion of undergraduate participants. We neither looked for nor teased apart differences among undergraduates in the Physics for Teaching course — how pedagogical resources held or applied differed by student demographic characteristics, such as ethnicity, gender, socio-economic status, and/or first language; by disciplinary major, such as the sciences, mathematics, or sociology; or by career aspirations, such as secondary science teacher, elementary teacher, or STEM professional. Certainly, to help better prepare well-started beginners, future research should search for connections across differences in potential and preservice teachers' backgrounds, disciplinary training, and interests; the kinds of pedagogical resources they hold; and when and how they apply these resources in the complex process of learning to teach.

Examination of our study's findings also suggests two additional routes for exploration and research. The notion of right answers is a case in point. Many of the undergraduates in the

Physics for Teaching course viewed the teacher's role as that of providing the right answer and thought that guiding students was less certain than telling them (the right answer). This finding that commitment to right answers interferes with the implementation of reform-based teaching strategies is not new. Lemberger, Hewson, and Park (1999), in their investigation of conceptual change teaching practices, also found that beginning teachers struggled to let go of this need to tell their students the right answers. More recently, Carlone, Haun-Frank, and Webb (2011) described how a teacher who was committed to reform-based science teaching unintentionally marginalized certain groups of students by focusing on right answers and right vocabulary: "The consistent glossing over of students' varied intellectual contributions to privilege the 'right' answer, phrased in the 'right' way, resulted in a somewhat inaccessible definition of legitimate *science knowledge* and *science person*" (p. 475). Systematic research into additional pedagogical resources tied to notions of right answers would help content instructors, teacher educators, and teacher learners move closer toward the goal of reform-based science teaching, including the effective implementation of model-based science instruction.

Looking forward, a final avenue for additional research is for content instructors and teacher educators to provide opportunities for teacher learners to articulate, test, and revise their large concept of science teaching in ways that mirror their K-12 students' efforts to articulate, test, and revise models of parts of the natural world. Potential or, more likely, preservice teachers could act as teacher researchers (Cochran-Smith & Lytle, 2009) to investigate how the application of one or more pedagogical resources plays out over time in a science classroom. They could examine, for example, when and how the small idea that good models include scientific terms is appropriately applied. As a result of their investigation, they might decide to broaden their definition of science talk to include discussions of testability and use of evidence, in addition to scientific terms. They might devise ways to better bridge and mutually reinforce science and everyday talk. They might also identify key points in the teaching-and-learning-by-modeling process where identification and application of key scientific terms is essential to the furthering of student learning. Finally, by testing and revising their own understanding of teaching, potential and preservice teachers might more fully embrace the call (see NRC, 2012) to engage K-12 students in the practices of developing and using models, planning and carrying out investigations, and analyzing and interpreting data – all central components of model-based instruction. In short, teacher learners can develop a more sophisticated pedagogical stance by investigating differences in student learning outcomes generated from the application of particular pedagogical resources in model-based science classrooms.

Concluding Thoughts

In this study, we applied a knowledge in pieces approach to teacher learning to identify four pedagogical resources held by potential teachers in a model-based Physics for Teaching course. We close by underscoring to readers that the notion of pedagogical resources has both theoretical and practical uses. Theoretically, when teacher learning is viewed through a knowledge in pieces lens, the notion of pedagogical resources can provide deeper insight into why learning to teach science in reform-minded ways is a complex and difficult process. A given pedagogical resource can be both generative and constraining. The inappropriate application of a small idea about teaching can be understood to interfere with the construction of a coherent pedagogical stance. In practice, instructors of content courses can explicitly identify and build from potential teachers' pedagogical resources to help them better understand how to use

students' ideas to organize instruction (see, again, Mikeska et al., 2009), in other words, to help these nascent teachers develop a coherent understanding of reform-based science education, in general, and model-based science instruction, in particular.

In states, like California, where teachers do not enroll in teacher education programs until finishing their undergraduate degree, we see facilitating potential teachers' recognition and interrogation of their pedagogical resources in undergraduate content courses like Physics for Teaching a fruitful way to begin the learning to teach process. Potential teachers can become mindful of how various contexts (as learners and teachers) cue individually and in concert their existing pedagogical resources and of how these activated resources can be productively built on to understand the processes of teaching and learning in reform-based science education. They can begin the long and complex process of learning to actually use students' ideas to design and modify their instruction. Research on and teaching about pedagogical resources should help content course instructors and science teacher educators move more closely in concert toward the goal of educating well-started beginning science teachers.

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- Methods Supplement
- Table S1

Table 1

Summary of Data Collected for Each Potential Teacher Participant

Name	M/F	Major	OR (9)	HW (4)	Final Lesson Plan	Video-SG (21)	Interview
Alison	F	Sociology	9	4	B-Circuits	18	
Berenice	F	Sociology	9	4	B-Circuits	8	
Brenda	F	Psychology	9	4	B-Circuits	13	
Carla	F	Psychology	9	4	F-Catalyst	5	
Christine	F	Economics	9	4	F-Catalyst	5	
David	M	Biology	7	4	F-Catalyst	9	Yes
Douglas	M	Env Studies	8	4	C-Boiling	8	
Eric	M	Mathematics	9	4	A-Pastries	8	
Evelyn	F	Chemistry	9	4	G-Freezing	7	Yes
Fabiola	F	Psychology	9	4	D-Pressure	0	
George	M	Psychology	9	4	G-Freezing	1	
Gregory	M	Sociology	9	4	E-Buoyancy	5	
Henry	M	Sociology	9	4	C-Boiling	8	
Ingrid	F	Env Studies	9	4	H-Genetics	12	
Isabelle	F	Sociology	9	4	H-Genetics	13	
Karen	F	Sociology	9	4	H-Genetics	10	Yes
Kyle	M	Economics	9	4	C-Boiling	4	
Rachel	F	Mathematics	9	4	A-Pastries	12	Yes
Steven	M	Psychology	8	4	E-Buoyancy	5	
Victor	M	Economics	7	4	E-Buoyancy	4	Yes

Note: Columns include the potential teachers' (1) pseudonyms, (2) gender, (3) majors, (4) number of Online Responses (OR) turned in out of a total of nine, (5) number of Homework (HW) assignments turned in out of a total of four, (5) Final Lesson Plan group and topic, (6) number of class periods included in the small group (Video-SG) video records out of a possible 21, and (6) whether or not they were interviewed.

Table 2
Categories and Subcategories Used in Round 1 of Analysis

Category	Subcategory	
Undergraduates' Ideas about Children's Ideas	C_PCI	Predictions of what children will think or say
	C_ICI	Identification and/or explanation of children's ideas
	C_ECI	Evaluation of children's ideas
	C_WIMS	Why a child's idea would make sense to that child
Undergraduate's Ideas about Teaching Science	T_SES	What science teaching -- or science education more broadly -- should look like
	T_TTR	What they would say or do if they were a science teacher
	T_PSE	Their own past experiences in science classrooms

Table 3

Four Pedagogical Resources Held by Potential Teachers in the Physics for Teaching Course

Pedagogical Resource	Number of Participants
PR1: The teacher's role is to provide the right answer.	12
PR2: Guiding students is less certain than telling them (the right answer).	15
PR3: A good model includes scientific terms.	12
PR4: Children are creative thinkers.	15