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Model Use Choices of Secondary Teachers in Nanoscale Science and Engineering Education

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In this study we describe secondary teachers' reported practices of model use in nanoscale science and engineering (NSE) education after participating in an NSE professional development program. Participants in this study were primarily high school teachers of chemistry, physics, or biology. After incorporating NSE lessons that included models into their classrooms, four distinct ways teachers used models emerged: Models as: (1) tools for visualization, (2) products of student design, (3) representations for student critique, and (4) means for investigation. As some teachers' natural model use choices in NSE were not for investigation, design, or critique, curricula and professional development experiences must support teachers in using models as more powerful tools than visualization alone.

Keywords: Model Use, Curriculum Design, Professional Development.

1. INTRODUCTION

Models play a central role in science and engineering education at all levels of schooling and beyond. They provide access to realms of science that are difficult or impossible to access otherwise. They offer opportunities to study scientific phenomena from a variety of perspectives—e.g., they can be scaled up or scaled down, they can emphasize certain aspects over others, they can represent function. Models translate ideas into organized products that can focus, develop, and challenge understandings. As advances and discoveries in science and engineering have educational implications, recent advances in nanoscale science and engineering (NSE) prompt questions about the role of models in the education of NSE.

In the last few decades, scientists have begun to measure and control matter on the nanoscale. At the nanoscale, some of the most fundamental principles governing form and function of matter depend on size in a way that is unlike any other scale (DiVentra et al., 2004; Ratner & Ratner, 2003). The prefix "nano" means 10^{-9} and represents a world that is larger than atoms, but still too small to access with a light microscope. An object is considered "nano" if one of its dimensions lies between 1 and 100 nanometers (American Society for Testing and Materials, 2003). The unique principles and properties of the nanoscale have recently motivated new research areas, increased opportunities for technological innovations, and prompted the development of news tools for discovery and manipulation at this scale.

Science curricula should reflect contemporary science. Thus, NSE topics are important to integrate into curricula. As with many chemistry topics, the scale of nano makes it challenging for students to "see" concepts and phenomena, increasing instruction's reliance on models. The process of teachers designing NSE lessons and integrating them into their existing curricula provides the opportunity not only to understand what NSE instruction looks like in secondary schooling, but also what choices teachers make about model use in NSE instruction. Teachers play a central role in students' learning of NSE concepts, thus this study focused on teachers, exploring their reported use of models in the NSE lessons they developed and implemented in their classrooms.

1.1. Defining Models

The literature is replete with ways of defining and characterizing types of models. Gilbert and Boulter (2000) provided an inclusive definition of all types of models by describing them as representations of ideas, objects, events, processes, or systems. This definition of models includes internal models, those not existing as physical representations. External models, on the other hand, are outward representations of objects and phenomena. Harrison and Treagust (2000) defined analogical models as

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one type of external model, which share information with a "target," the target defined as the object, concept, or phenomena to be learned. An analogical model can be simplified or exaggerated from the target. Boulter and Buckley (2000) developed a typology for characterizing external models based on their mode of representation (e.g., visual, concrete) and the attributes of representation (e.g., qualitative versus quantitative, static versus dynamic). In this study, we were interested in teachers' instructional uses of external models (e.g., drawings, computer animations and simulations, 3-D models).

1.2. Model Uses in Instruction

Models can translate abstract ideas to more concrete ones, represent systems or objects that are difficult to see, and summarize information cohesive ways. Models can be used to allow students to see things they otherwise could not, including both scaled-up and scaled down views (Duit, 1991). Models can be extractions of a larger concept or system, highlighting an important aspect (Gilbert, 1993). The use of multiple models can help students realize that models are explanatory tools, not representations of "truth" (Harrison & Treagust, 2000). The act of comparing models to their targets is a way for students to develop deeper understandings. For example, the Teaching-With-Analogies Model (Glynn, 1991) and its revised version (Harrison & Treagust, 1993) were designed to help learners apply six sequential operations to reduce misconceptions resulting from memorizing models as truth.

Models can help students learn about the nature and processes of science by studying the transformations of models over time (Gilbert, 1993). Students can actually engage in the nature and processes of science by developing and revising their own models (Coll et al., 2005; Halloun, 1996). When students translate their mental conceptions to physical representations, they are learning to communicate ideas.

Models can also be used to test theories (Penner et al., 1997). They can prompt questions, and serve as a place to report and hold findings from investigations of those questions (Windschitl & Thompson, 2006). The work by Windschitl and Thompson emphasized the use of models of all types, i.e., mathematical, conceptual, and physical, as foundations for scientific investigations. Hypermodels can also serve as testbeds for investigation. These models are based on data that exist in a computer environment and allow learners to interact and manipulate the models and see a result or response (Horwitz, 1995). These types of models increase student interaction with phenomena that are difficult to interact with and have been developed for a variety of science topics (e.g., Buckley et al., 2004).

The emphasis on model use in the literature seems to be the act of modeling, specifically to support understandings of the nature and processes of science (Clement, 2000; Coll et al., 2005; Crawford & Cullin, 2004; Danusso et al., 2010; Gilbert, 2004; Gilbert, 1999; Harrison & Treagust, 1998; Justi & Gilbert, 2002a; Van Driel & Verloop, 2002), not of science concepts themselves. There is a fair amount of literature related to student misconceptions as a result of memorizing models (e.g., Grosslight et al., 1991) and using model critique as a way to support students in developing accurate conceptions of the target (Glynn, 1991; Harrison & Treagust, 1993). With the exception of Windschitl and Thompson (2006) and hypermodel-based instruction (Horwitz, 1995), few strategies for teaching with models in the science education literature emphasize the need to interact, discover, and investigate with models to learn about target concepts. Even if recommendations for how to use models increases in the literature, there is a lack of documentation that these recommended ways are the ways teachers actually use models. Because of student inaccessibility of the nanoscale world, it is incumbent upon educators to use models in more investigative ways to support student learning of science concepts. The following section reviews the literature on secondary teachers' decisions about model use.

1.3. Research on Science Teacher Uses of Models

In the few studies that investigate the ways teachers choose to use models to teach science concepts, teachers most commonly used them as visual tools (Duit, 1991; Harrison & Treagust, 1996). Their use often included an explanatory component, in which teachers or students would describe what the model represented. Smit and Finegold (1995) found that prospective physical science teachers believed that models were only useful for understanding science when used to explain complex or abstract ideas or to serve as demonstrations of how things work. Van Driel and Verloop (2002) found that teachers rarely mentioned that models can be used in making predictions or used as tools for obtaining information about targets that are inaccessible by direct observation. In interviews with Dutch science teachers, Van Driel (1998) found that biology teachers used models to summarize and make objects and relationships visible, while chemistry teachers used models to show causes and effects of phenomena. Regardless of the disciplinary differences in model use, teachers from both disciplines used models strictly to help students visualize, and did not discuss extensions of visualization that involve student interactions with models. In another study, chemistry teachers emphasized the purpose of models as making the abstract visible (Justi & Gilbert, 2002b). Scale similarities of chemistry to NSE indicate that the idea that models are mainly for showing, not interaction, could exist for teachers who include NSE content in their curricula.

In a study by Justi and Gilbert (2002b), they categorized the contributions teachers felt that models made to science education. These categories included increasing students'

interest, providing a framework for structured explanations, defining a reference to judge student understandings, making abstract ideas and concepts concrete and visual, promoting conceptual change, and providing a connection to the nature of science. Of this list, 90% of the teachers believed one of the primary uses for models in science education was to make abstract concepts concrete and visible, and none of the teachers reported that models could provide a means for students to interact with phenomena.

In the same study (Justi & Gilbert, 2002b), one third of the teacher group implied that the teacher, not the students, uses models. As this was not an explicit question in the interviews that comprised the study, it was unclear what the other two-thirds of the group thought. Four of the seven teachers in another study preferred teacher-focused model activities, and offered little or no opportunities for students to design or interact with models (Van Driel & Verloop, 2002).

While there is evidence in the literature that some teachers use models as more than visual tools, and while there is literature that indicates the need for teachers to engage students in using models in alternative ways (e.g., to frame research questions or to experience the nature of science), we do not know what choices teachers would make in specific content contexts, especially in the NSE content area. This work sought to answer the following research questions in the context of an NSE professional development (PD) program: What choices do teachers make for how to use models in their designed NSE instruction? What purposes do the models have? What reasons do teachers have for their choices?

2. METHODS

This study took place within the context of a yearlong NSE professional development program aimed at enhancing teachers' knowledge and skills for teaching NSE concepts in grades 7–12 (Bryan et al., 2007). The researchers were part of a team of science educators, scientists, and graduate students who designed and implemented a sustained contact PD program in NSE education. The PD program consisted of a two-week summer institute, participants' academic year implementation of program-related lessons in grade 7–12 science classrooms, post-lesson reflective analyses, and an academic year follow-up workshop. The PD program content was selected and organized to represent nanoscale phenomena that aligned with content currently taught in middle- and high-school curricula, and based on seven big ideas governing NSE: (1) size & geometry; (2) size-dependent properties; (3) forces & interactions, (4) self-assembly; (5) science, technology, & society; (6) tools & instrumentation; and (7) models & simulations (Stevens et al., 2009). This study included participants from both the 2007–2008 PD program and the 2008–2009 PD program.

The PD program instructional materials included a suite of twelve NSE lessons, teacher resources, and a teacher content knowledge assessment. During the professional development program, teachers engaged in lessons that included investigations, demonstrations, discussions and reflection activities, as outlined in *Inquiry and the National Science Education Standards* (NRC, 2000). Participants also interacted with nanoscale scientists and engineers and toured visualization and nanofabrication facilities. NSE content lessons were aligned with state academic standards, and pedagogical activities were woven throughout the PD experience.

During the institute, teachers participated in a lesson on the role of models in NSE and NSE instruction. The current version of this lesson is available online (Daly, 2009a). The learning goals of this lesson included facilitating teachers ability to: (a) explain a variety of models types and uses both in the field of NSE and in the classroom, (b) describe the limitations of models and how these limitations can be taken into account when using models to learn (either as students or researchers), and (c) design instruction that uses multiple models of different types representative of their ideas of best practices of model use in NSE education.

In addition to the explicit lesson on models and modeling, most of the PD lessons included models as instructional tools. For example, in a lesson on allotropes of carbon (Sederberg & Bryan, 2009), teachers designed models of a carbon composite space elevator and tested the strength of their models. A self-assembly lesson (Daly, 2009b) included investigations with a computer simulation model, and a design activity in which teachers had to represent the self-assembly process in model form. Activities within a scanning probe microscopy lesson (Hutchinson, 2009a) included the task of designing a model of an atomic force microscope probe to get a detailed scan of a model of a molecular surface and a mapping of a modeled magnetic surface using a functionalized magnetic probe. The lessons were focused on supporting teachers' development of NSE content knowledge, but also served as examples of how models could be used in NSE instruction.

One requirement of the program was to teach at least one NSE lesson that they designed during the academic year. For this study, we collected information on one lesson from each teacher. Teachers were permitted to use any pieces of the lessons in which they participated during the PD as part of their lesson design. Teachers were required to incorporate at least one model into the lesson, and while we encouraged them during the PD experience to use models in interactive ways, there were no specific instructions on how they had to use the model in their lesson plan. Their prompt was to design the lesson in a way that they thought would best support student learning. During lessons and discussion, the PD team did not categorize model uses into types. We incorporated a variety of

model uses into our lessons and let teachers decide how they wanted to use models in their own NSE instruction.

2.1. Participants

Eighteen teachers participated in this study—nine teachers from the 2007–2008 PD program and nine teachers from the 2008–2009 PD program. Of the 18 teachers, one was a middle-school teacher and 17 were high-school teachers. Seventeen teachers identified themselves as Caucasian and one as African American. Nine were male and nine were female. Teachers indicated a range of science disciplines that they taught: general science, chemistry (AP and general), physics (AP and general), biology (AP and general), and engineering. Teachers were from six different states and one was from England. Their years of teaching experience ranged from 2 to 36 years, with an average of 16.5 years. In the findings section, we refer to participating teachers as Teacher A through Teacher R so that no demographic or other identifying information is evident.

2.2. Data Collection

Upon completion of the two-week institute, teachers turned in draft electronic copies of their NSE lesson plans that would be implemented in the upcoming academic year. Upon completion of the lesson in their classrooms, they were asked to update their lesson plans to reflect what they actually implemented. In addition, they provided written explanations of how they used models in their lesson according to a worksheet with questions. The instructions for this assignment may be found in the appendix. Teachers also completed a reflection on their perceptions of how the lesson went in their classroom. One revised lesson plan, their responses to the models questions, and their lesson reflection were collected as data for this study.

2.3. Data Analysis

Data were analyzed using the constant comparative method (Lincoln & Guba, 1985). The written lesson plans, the questions on model use, and teacher reflections on the lesson (all collected post-implementation) were grouped for each teacher and read together. Each model teachers used in their lessons was identified and matched with the explanation teachers provided in the supplemental assignment. Then, each model was coded in terms of how the teacher used it, for example, an artifact to compare to experimental data or a visual aid to supplement instruction. Once descriptions were generated, similar uses of models were grouped together as a category. Groupings were read multiple times and compared to other groupings to determine distinct differences among categories. Categories were finalized once the categories held together through multiple read-throughs. The titles of the categories were generated to describe the unifying link within each category.

Each instance of model use was reanalyzed according to the finalized categories and counted within a category if it was a purpose of the model. A few cases existed in which one model was used for two primary purposes (e.g., design and critique), thus that one model was considered to be used in two different ways and was counted in two categories. Other times, teachers used multiple models within a lesson. If the uses of the multiple models were different, the models used by that single teacher were counted in multiple categories. For example, Teacher E had students design a model, critique a series of models, and generate an explanation from evidence collected from a different model. Thus, he had three different uses of models. If, however, one teacher used four different models in the same way, the models were grouped and only counted once. For example, Teacher D used multiple models of molecules as a visual tool to explain intermolecular forces. Her model use was only counted once. This coding approach was used to avoid weighting a category based on any one teacher who provided multiple models for the same purpose within his or her lesson. To check category reliability, as a team, three members of the PD team who did not participate in defining the categories sorted the raw data according to the emergent categories discovered. They collectively rated the raw data, and their sortings were consistent (100% agreement) with the original sorting.

This study was designed using qualitative research methods to explore details of the ways teachers reported their use of models in their classrooms. Resulting from this type of study is a descriptive understanding of the "how"—how teachers used models for teaching NSE. No other studies that focused on understanding the choices teachers make about models get at these details. There is also no work about decisions teachers make in the context of NSE instruction. This work, as with rigorous qualitative work, aims at transferability, which means that results must be considered and applied with context in mind. It fills a gap by providing an understanding of the details that go into what teachers' model decisions look like in the context of NSE instruction.

3. RESULTS

Four uses of models in NSE instruction emerged from data analysis. They are summarized in Table I. Each of these model roles is discussed in the context of the teachers' NSE lessons and supplemented with excerpts from their lesson plans, explanations, and reflections.

The choices teachers made about how to use models represent some aspects of their beliefs about how models are effectively used in NSE education. Many ways of using models were presented and experienced by teachers during the 2-week program. However, teachers made their own

Table I. Teachers' intended model use for NSE instruction.

Model use in NSE instruction	Description of activity	Number of times used
Tool for visualization	Students see, watch, and/or touch a model.	10
Product of student design	Students translate their ideas, knowledge, and data collected into a physical model form of the nanoscale object, concept, or phenomenon.	5
Representation for student critique	Students compare and contrast features of nanoscale models with their ideas, knowledge, and data known about the nanoscale object, concept, or phenomenon and evaluate the quality of the model.	7
Means for investigation	Students use models of nanoscale objects, concepts or phenomena to collect information, gather data, answer questions, form hypotheses, describe structures, or make predictions.	3

choices, based on their own ideas of best practices with models in NSE, about how they would incorporate models into a lesson of their choice in their own classrooms.

3.1. NSE Model Role: Tool for Visualization

One of the ways that teachers described using models was as a visual tool. Teachers who used models for the purpose of student visualization framed the use of models in their NSE lessons as tools for showing students the features and details related to a nanoscale object, concept, or phenomenon. This also included using models for students to "see" a process that they otherwise would have difficulty accessing. Teachers expressed the idea that models used for visualization would help students create better mental pictures, and therefore, would help them better learn and understand the nanoscale content being taught. Only one teacher who used models for visualization used models in another primary way as well (which was for critique).

For example, Teacher D talked about her plans to use multiple models during a bonding section as part of a larger lesson on self-assembly:

> I use the electron dot diagrams to convey the intramolecular forces that occur... I compare the electron diagram, structural formula, space-filling model, and electron cloud model... One of the key concepts from the lesson on models that I considered was that multiple models often create a more complete understanding of a phenomena since no one model is completely accurate. Consequently, I used multiple models to represent H_2, such as the electron diagram, structural formula, space-filling model and electron cloud model. In future discussions, I will focus more on critiquing the accuracy of models and explaining how models are still useful even with their inaccuracies. (Teacher D).

Teacher D emphasized the role she had in helping students understand models. Her discussion highlighted her role as the teacher in making sure to find multiple models, telling students about the inaccuracies, and explaining to students what the models represented.

Teacher A incorporated a model as a tool for visualization in her lesson on gold nanoparticle biosensors. Gold nanoparticles can be used as biosensors because of their size-dependent optical properties. Teacher A's lesson focused on color changes in gold nanoparticle solutions due to shielding of charges caused by the presence of a chemical of interest. In this lesson, students completed a laboratory experiment (based on McFarland et al., 2004) in which electrolytes caused the gold nanoparticle solution to change color, and non-electrolytes did not cause a change in color. Teacher A chose a diagram of the sensing particle interacting with a substance as the model intended for use in the classroom, shown in Figure 1.

Teacher A explained the role of the model in her lesson as showing details of the process to her students through pictorial representations:

> This model was used to create a visualization of the optical properties experienced by students during the creation of gold nanoparticles and the addition of electrolytes. It was also used to reinforce or reiterate the design of a biosensor. (Teacher A)

She intended the role of this model to help students form a visual idea of the process of biosensing with gold nanoparticles. Teacher A placed an emphasis on the importance of details:

> I selected this model because it pays attention to the detail of base pairing of the oglionucleotides with the targeted sequences of DNA, and it articulates the color of the gold nanoparticles when congregated and dispersed. It even shows specifically where oglionucleotides attach to the spherical gold nanoparticles and leaves very little to imagine on this size scale. (Teacher A)

This emphasis on detail of the model seems related to Teacher A's understanding of the use of models in NSE education. She felt it was the key characteristic for choosing her model, and further elaborated on the importance of using models for visualization in this emerging discipline:

> Models are the crux of nanoscale education simply because it is a group of events and concepts that are difficult to convey without a model. In other words, they are pertinent in generating interest of students, as most things in their lives that have value

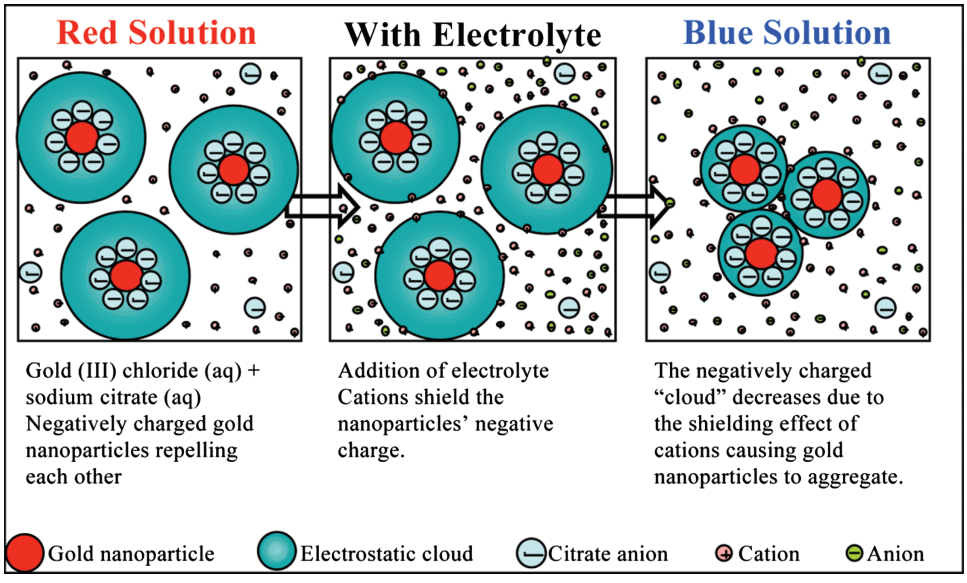

Fig. 1. Two-dimensional model of gold nanoparticle biosensor detection process.

> or interest are in some shape or form is tangible and visible. (Teacher A)

Teacher A felt that the interest of her students in NSE was dependent on the ability for these concepts to be represented in a concrete and visible way. She felt that the way to use models in her lesson on gold nanoparticle biosensors was to allow students to see these visual representations.

Teacher F also used a model for visualization in a lesson about nanoparticle biosensors. Teacher F described her use of a similar diagram to Teacher A, but in a slightly different way:

> The 2nd model was the modified worksheet of the reaction that is taking place in the gold nano-particle lab. The diagram was used as it was made but the words were deleted to have students explain the model . . . The key concept is to understand how agglomeration of nanoparticles causes an observable color change in biosensors. I want students to understand what agglomeration is and what effects agglomeration. (Teacher F)

As with Teacher A, Teacher F's intention was to use the model as a tool for students to visualize the process of gold nanoparticles clumping together based on shielding effects. However, Teacher F's approach entailed students identifying and labeling parts of the diagram, as opposed to simply viewing the diagram. While both teachers' approaches used models as tools for visualization, Teacher F's approach involved some articulation by students of their interpretation of the models.

There were multiple examples from teachers' lesson plans, explanations, and reflections that were focused on using models as tools to help their students visualize concepts and phenomena. Just as Teachers D, A, and F used models strictly for visualization purposes, Teacher N wanted to use a model he created as a visualization of the process of the macroscopic effect of graphite as a lubricant based on its nanoscale properties. After the students investigated the nanoscale composition and properties of graphite, Teacher N provided a demonstration of one of the properties. The following is Teacher N's comments related to this model selected as part of a lesson on allotropes of carbon:

> The model is intended to demonstrate how the allotrope of carbon known as graphite is used as a lubricant . . . The criteria I used most in selecting this model is how well the model would help students to visualize nanoscopic behavior in a way that made sense with their actual observations of the behavior of graphite . . . The strengths of the model are that it is highly visual and the effect . . . is dramatic. (Teacher N)

Teacher N wanted students to see the process of graphite as a lubricant and his demonstration was as a way to represent the macroscopic behavior of one of the allotropes of carbon. He discussed his use of the model in terms of facilitating students' visualization of nanoscale behavior and properties. According to the Boulter and Buckley (2000) typology, Teacher A's and Teacher F's models were visual pictorial static and Teachers D's and N's were concrete material dynamic. Although the modes of representation were different, the purpose of the use was the same.

3.2. Model Role: Product of Student Design

Five teachers incorporated models into their NSE lessons by having students design their own representation of nanoscale objects, concepts, or phenomena. In designing

their own models, teachers allowed students to translate their mental models to visual representations. In addition, the students' models provided a means for teachers to gauge students' understandings of nanoscale objects, concepts, or phenomena. The process of designing the model required students to consider features of the nanoscale object, concept, or phenomenon; create ways to represent those features; and evaluate which features to include and the best way to include them.

For example, Teacher E wanted students to create models as a way for him to gauge their preconceptions and for them to engage in thinking about how small the nanoscale really is:

> Students are introduced to the scale in which they will be learning about with a short paper-tearing activity. One student will take a piece of paper, cut it in half, and pass the half on to another student. That student will also cut the piece of paper in half, and pass the new half on to another student. This continues until the paper cannot be cut in half again. This activity leads to a discussion in which the class will assume that there is a smallest piece of paper possible, even if it cannot be seen. Students are then instructed to draw a representation of what that piece of paper might look like. (Teacher E)

Teacher E wanted students to draw a model of the piece of paper on a scale smaller than could be seen with their eyes. As they had to consider their own ideas to generate this model, it also served to prepare them for the remainder of the lesson, which challenged them to consider other phenomena that occurred on this scale.

In contrast to using models to gauge students' pre-existing ideas, Teacher K had students synthesize their ideas in the form of a model after completing various activities related to the concept. Teacher K used self-assembly as a context for teaching about intra- and intermolecular forces. After the students completed a series of investigations and readings related to intra- and intermolecular forces and self-assembly, they worked with a partner to design a three-dimensional model to represent molecules as they condensed from a gas to liquid state. Students used various craft supplies including Velcro, blocks, balls, and magnets to design their models, and then tested it in a clear or cardboard box. Teacher K specified that the designed model had to include three to five molecules of water and distinguish between covalent and hydrogen bonds. After a series of presentations and model critiques, the class as a whole combined the best components of all of the models and designed a revised model. Teacher K reflected on her reasons for utilizing models in this way:

> There are many reasons why I chose to include this modeling activity. First, I do think it helps to illustrate the concept [of intra and intermolecular forces and self-assembly]. Additionally, I love the idea of students creating and critiquing their own models. I believe this will help them to truly internalize the information learned . . . Students initially make the models to understand the chemistry concepts of bonds and intermolecular forces. We then use that understanding of intermolecular forces as a springboard for understanding the nano concept of self-assembly. (Teacher K)

Teacher K felt it was significant to students' learning experiences to translate the ideas they were forming to concrete representations. Not only did Teacher K include one round of model design, but also after discussion and presentations, the students had the opportunity to take that information and design a refined representation of their ideas.

In these examples of model use as an outcome of student design, models served to help students visualize nanoscale phenomena, but also allowed students to consider their own conceptions and represent it in a two- or three-dimensional form. Students created their own models based on evidence. Model design also provided an opportunity for students to engage in the nature of science and engineering. Just as scientists and engineers use data to build representations, students participated in a similar activity, and could also discuss how models change over time as new or different data were collected. The interaction with models in this way supported students' conceptual ideas on models as well as allowed them to build and construct ideas on nanoscale objects, concepts, and phenomena.

3.3. Model Role: Representation for Student Critique

Seven teachers included opportunities for student to critique models. Students were asked to consider specific aspects of the model as well as the model as a whole and decide how the model did or did not represent what they knew about the nanoscale object, concept, or phenomenon. As students could not ever see the actual nanoscale phenomena, their critiques had to rely on a comparison with their own conceptions. Students critiqued pre-existing science models, traditional models used in science teaching, models they created themselves, or models made by other students. They critiqued multiple models related to the same nanoscale object, concept, or phenomenon, allowing them to realize that multiple models often exist and that no model can be completely accurate.

For example, Teacher Q included a model critique component to his lesson on the structure of matter. His students were instructed to "describe merits and limitations" of a variety of models of the atom based on their pre-existing ideas. This task allowed students to consider their own ideas about atomic structure vis-à-vis the various representations. Students had to describe what aspects of the structure of matter each model represented well and what aspects the model did not accurately present. Because the

models Teacher Q chose to use represented how models of the atom evolved over time, his use of this activity also allowed the opportunity for students to see how the limitations of the earlier models led to the development of the later models.

Unlike Teacher Q, the other teachers who used models for student critique asked students to critique their self-designed NSE models. Both Teachers B and C intended to have students construct models to represent their understanding of various concepts related to nanomagnetism after performing a series of investigations that included the synthesis (Berger, 1999) and investigation of nanomagnetic particles. Teacher B included the following procedure in her lesson plan:

> Given the craft supplies make a model what is happening inside the nail as the current flows through the wire. Include in your model or be able to describe what happens inside the nail when the current (which is providing an external magnetic field) is removed. Each group then collaborates with another to describe their model. The other group will critique the model in light of what was learned through the investigation. (Teacher B)

Teacher C also had students individually construct and critique their own models after they learned more about nanomagnetic particles:

After further discussion of how ferrofluids actually work, the students critique their model . . . [C]ritiquing models is beneficial and the concept that models are useful for conceptualizing behaviors of phenomena that are difficult to observe . . . After the models lesson I decided to add the critique of the models used . . . not only in the context of this lesson, but in many others as well. (Teacher C)

Teachers B and C believed that their students built knowledge of magnetic properties and behavior in their NSE lessons by synthesizing information, building representations, and then critiquing how their own and other students' models represented what they knew and what they found in their investigations. Students' evaluations of the models were essential for them in constructing their ideas of the phenomena.

While teachers B and C stopped the lesson cycle at one critique, teacher K engaged in an iterative design-critique process in her lesson plan:

> Models will be discussed and critiqued. Each pair of students will present/explain their model to the class. After everyone has presented each group will point out what they think the strengths and weaknesses of their models are. As a class we will select the overall best components of the various models . . . (Teacher K)

Teacher K used design and critique hand in hand, as design led to critique, which led to another round of design. This process allowed students opportunities to become aware of their ideas, represent their ideas, evaluate their ideas, and iterate on their first representations.

Teachers' use of models as representations for critique served to engage students in comparing and contrasting with respect to their own ideas, evaluating based on data and their pre-existing knowledge, and suggesting improvements to existing representations. With nanoscale phenomena, students cannot compare a representation to seeing actual phenomena; they can only sometimes see micro- or macroscopic effects. Thus, critiquing models of nanoscale phenomena must be done with respect to students' conceptions of the phenomena, allowing them to reinforce the accurate knowledge they have generated and renegotiate inaccuracies in their conceptions brought about through the evaluation of physical representations.

3.4. Model Role: Means for Investigation

The fourth way that teachers used models in NSE instruction was as a means for their students to investigate nanoscale phenomena. Three teachers used models in their lessons in the form of a guided-inquiry activity, in which students were provided with a question that interactions with a model or models would help them answer. Students could use the models provided to collect information, gather data, and answer questions. Students could view and manipulate models to form hypotheses about nanoscale objects or phenomena, describe structures, or predict properties. Far fewer teachers used models in this way than any other.

Teacher E's lesson exemplifies models as tools for investigation with the multiple models he used in his lesson about "seeing" in the nanoscale world. In his lesson, Teacher E organized a series of activities aimed at helping students build their ideas of NSE-related content, such as the structure of atoms, scanning probe microscopy, and forces and interactions. Teacher E also was trying to improve students' understanding of the nature of science, specifically in the nanoscale world (and smaller), in which scientists and engineers must build models of unseeable phenomena based on data. The lesson began with students' comparing and contrasting models of the atom posed by Democritus, Dalton, Thompson, Rutherford, and Bohr. This activity transitioned into an investigation by students of how Rutherford developed his theory, using a physical model and guided by questions about the open space in an atom and the relative size of an atom's nucleus. The models consisted of unknown objects covered by a square elevated board made of plywood. Marbles represented electrons and were "fired" at the object. Based on their observations of the marbles going through the plywood or bouncing back, students gathered data that they used to draw a representation of the mystery object. Following the activity was a discussion on how scientists investigate objects that cannot be seen.

Teacher E linked the Rutherford model activity into another activity that included investigations with a model of scanning probe microscopy. The model was made of a wooden box with a Lego formation inside that could not be seen through the peg-board covered top. A wooden dowel rod probe modeled the probe tip of a scanning probe microscope, which students used to investigate the shape and size of the Lego formation in the box (See Fig. 2). Students were asked to measure and represent their data of the surface on a three-dimensional graph in Excel. The follow-up to this lesson was a comparison of their results to other groups investigating the same unknown formation as well as a discussion of how results could be improved. Teacher E also asked questions about what was happening on the nanoscale level to allow the probe to "feel" nanoscale objects, leading to a discussion about forces and interactions. Teacher E explained his goals and choices for this lesson:

> It provides a concrete example for the kids to experience . . . I hope the students can realize that we have been making models to try to understand things that we can't see for a long time. These models are based upon observations that we can make and the model reflects what can be observed. The model must change to accommodate better observations. (Teacher E)

Teacher E said his decisions were based on the ability for students to use models to find out information and build understanding about nanoscale concepts. He wanted students to have investigative experiences that helped them build understandings based on data collected. The way he used models for investigation in this lesson also allowed him to connect to nature of science concepts, specifically how scientists learn about objects that cannot be seen and how they must use data and models to develop theories.

Teacher G also used models for investigation in an NSE lesson on nanotubes, buckyballs, and other allotropes of carbon (See Fig. 3). He wanted students to examine the properties of allotropes using 3-D plastic models and pictorial representations. He initiated the investigation by posing questions about the properties of the different allotropes. Questions focused on the composition, number of bonds, and uses of the various allotropes. Teacher G required students to use models to investigate properties of nanoscale materials and predict behavior. He described the role students had in the investigation:

> Based on the appearance and manipulation of the models, students should suggest evidence to support their predictions as to how the physical and chemical properties of the allotropes might compare. (Teacher G)

As Teacher G wanted students to find ways to explore the models, he did not tell them what tests to perform. He asked them a question about properties and had them investigate those properties with the models. For example,

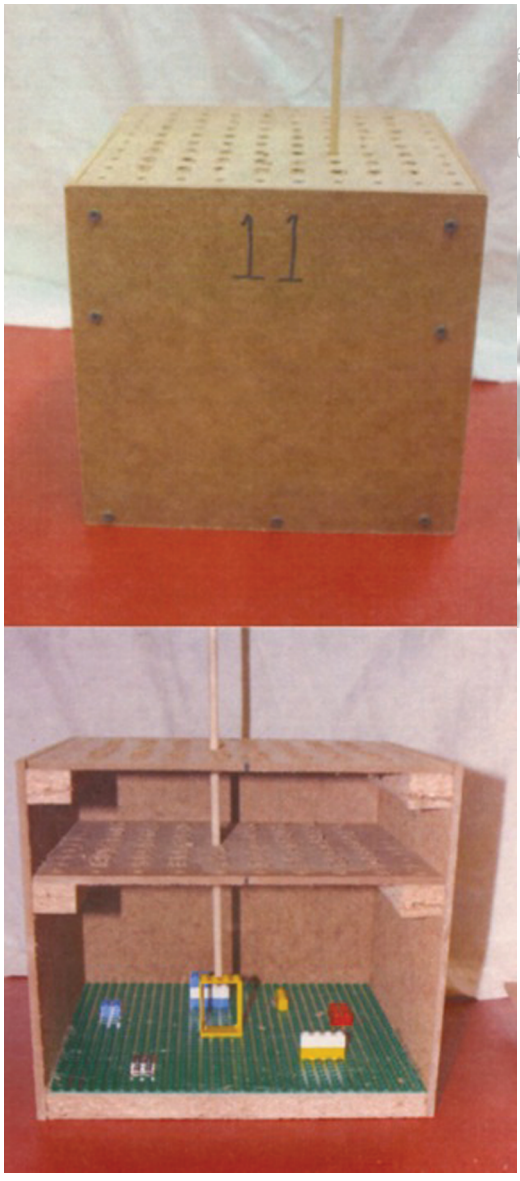

Fig. 2. Model of scanning probe microscopy process.

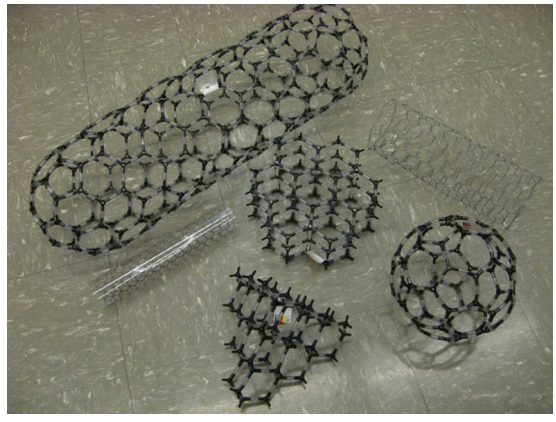

Fig. 3. Models of carbon allotropes.

students were asked questions about strength and structure, and could count bonds, look for bonds that did not complete an octet, and push and pull on the models to see how easily they held weight. Students were asked to consider uses of the different allotropes. They investigated the shapes of the allotropes and how the allotropes interacted with other molecules of the same type. Students often stuck their hand into the middle of the buckyball and realized it could be a cage to hold other particles.

Teacher G discussed his choice of models and their use in his lesson, the associated advantages and disadvantages, and how these choices, advantages, and disadvantages were expected to influence students:

> I chose these models because [they are] easy to manipulate, relevant, and thought provoking. The criteria I considered most was that they can be manipulated in three dimensions, unlike pictures or most computer models. There is some accuracy that is lost or not visible such as the type of hybridization occurring. We can discuss what the model doesn't show or explain clearly. The learner formulates explanations from evidence or at least is guided in the process of formulating explanations from evidence. (Teacher G)

Teacher G focused on how students could actively be involved in their own learning of NSE concepts by using models. This approach was also evident in a lesson Teacher M designed on intermolecular forces. In this lesson, students interacted with animated simulations of molecules. For example, simulations allowed students to investigate temperature and charge effects on the behavior of molecules. Students could increase the temperature of the system and explore how the increase in energy impacted the speed of the molecules and their interactions with other molecules or they could alter the charge and location of the charge on the molecules and gather data about the resulting behavior. Teacher M further explained the choices of models and their strengths:

> I chose these models because they could be manipulated by the students to demonstrate the effects of change in temperature and type of atom on intermolecular forces and how the strength of the forces affects observable properties. The strengths of the model are its dynamic properties and the chance for student interaction. It allows students to explore possibilities as they think of them. (Teacher M)

Teachers who used models as a means for investigation wanted students to be able to "interact" with the nanoscale world. They relied on models to allow students to gather information, collect data, discover properties and processes, and investigate phenomena. Students were required to synthesize data and information gained from interacting with the models as well as to consider how their interactions with the models informed their ideas, answered questions, and guided their predictions.

4. DISCUSSION

Since the establishment of the National Nanotechnology Institute in 2000, there has been a significant increase in educational programs and curriculum materials development on NSE concepts. As materials development continues, and as NSE instruction hinges on the use of models, an opportunity exists for an analysis of choices teachers make about their use of models. This study explored how teachers who participated in an NSE PD program used models within their lessons to facilitate learning about NSE concepts and phenomena. This section reviews the results of the model choices teachers made, considers the four models uses in relation to nature of science concepts and instructional learning objectives (using Bloom's taxonomy and inquiry as lenses), and highlights important considerations of model use in NSE instruction.

4.1. Teacher Model Use Choices

Teachers in this study chose to use models in NSE lessons as tools for visualization, products of student design, representations for student critique, or means for investigation. Previous research documented that teachers have a tendency to think of models as visual tools that can accompany their explanations of concepts (Duit, 1991; Harrison & Treagust, 1996; Justi & Gilbert, 2002b; Smit and Finegold, 1995; Van Driel, 1998), and we saw some evidence of this in our own work. Half of the teachers in this study used models in their lessons only for visualization purposes (the 10th case of a model used for visualization was also used for critique). However, with appropriate PD experiences that included a focus on the use of models in NSE, we were also encouraged by teachers' decisions to use models beyond visualization in their NSE instruction.

The ways teachers discussed the use of models as tools for visualization were teacher-centered and transmission-focused. The language these teachers used indicated that the teacher was the one who would work out all of the details and then would relay that information to students. For example, Teacher A talked about the model as a visual tool to "reinforce" what students should know; the diagram would provide the information and students would receive it. Teacher F included some student involvement by having them fill in the blanks on her prepared model, but most of the cognitive load was on her to prepare the model. Additional indications of a transmission approach are seen in language choices (Prosser & Trigwell, 1999). This was evident in some of the data in the *Models as Tools for Visualization* category; for example, Teacher D's discussion of models used in a lesson on forces and self-assembly was teacher-focused, evident by frequent use of the word "I" and explanations of what she would do with the model in order for her students to be able to visualize and understand the concepts.

Visualization is a natural part of model use and is important student learning. Most of the teachers who talked about models in student-centered ways did not also highlight the idea that models provide ways for students to visualize. However, this is likely because it seems obvious that this is one role of models in education. Research related to the development of the Approaches to Teaching Inventory (Prosser & Trigwell, 1999; Trigwell & Prosser, 2004; Trigwell et al., 2005) proposed a hierarchy of transmission and constructivist teaching approaches, i.e., aspects of transmission-based approaches are built upon and furthered in constructivist approaches. Translating that idea to this work means that teachers understand there is a foundational use of models as visual tools, and additional uses of models build off of visualization. Thus, it is not correct to say that the results of this work imply that teachers should not use models for visualization. Rather, teachers can build on that foundation to engage students in additional ways with models.

The three model uses other than visualization (design, critique, and investigation) were student-centered. Student-centered engagement with models provided opportunities for students to synthesize, evaluate, and convey their own ideas, whether it was through the act of designing a representation of their understanding of an NSE phenomenon (as Teacher K had her students design representations of nanoscale self-assembly) or investigating questions by collecting data from a model (as Teacher E had his students collect topography data of surfaces in a similar way to data collection concerning nanoscale surfaces). Having students critique models may not always be an interactive way of working with models; however, it is student-centered and challenges students to compare and contrast their own ideas with representations.

There were no correlations between teachers' model use and gender, years of experience, or science discipline taught (e.g., biology, chemistry, physics). There was also no apparent relationship between the teachers' model use and the type of the model, as defined by Boulter and Buckley's (2000) typology. For example, teachers did not only use dynamic models for investigation or static models for visualization. While it can be advantageous to have animation- and simulation-based models for investigations, the ways in which models can be used are often easily adaptable, many times without changing the model itself. As in Teacher G's example, he used concrete static models of carbon allotropes. However, instead of simply showing them to his students and explaining their properties, he had his students answer questions and make predictions based on data gathered by interacting with the models. Any of the models that were used as tools for visualization could also include critique. Almost any NSE object, concept, or phenomenon can be modeled; thus, with a limited amount of craft supplies, students can design their own models to represent the nanoscale world. This way of using models captures the importance of student engagement, and is especially pertinent in cases where science and engineering education models do not yet exist, as is the case with many nanoscale phenomena.

4.2. NSE Models and the Nature of Science

Studies have revealed that teachers did not generally show an awareness of the usefulness of models in learning about the nature of science (Justi & Gilbert, 2002b), which is essential to a sophisticated understanding of models (Grosslight et al., 1991; Justi & Gilbert, 2003; Justi & van Driel, 2005; Van Driel & Verloop, 1999). Some model uses have clearer and stronger links to the nature of models in science and engineering. An important consideration is how each way of using models in NSE instruction can facilitate discussions of the nature of science and engineering, an essential aspect of science education (AAAS, 1993; NRC, 2000).

If students are only shown a model and told information about a phenomenon by using that model, it may imply the model is an exact replica of the actual target and the science and engineering community knows all of the information about the phenomenon. This type of model use does not naturally connect to the process of how models come to be or provide examples of how models are used in nanoscale science and engineering beyond as tools for visualization or explanation. It also does not facilitate the addressing of models-related science education standards.

When students use models as products of student design, the process of nanoscale scientists and engineers creating models from ideas, knowledge, and data can be contextualized. This also serves an entry point to further discussions on the process of design in NSE.

Using models as representations for critique provides opportunities to discuss the fact that models are representations and thus carry inaccuracies, but even with these inaccuracies still play a large role in the development of science. It is through a process of critique that understandings can be furthered and the body of science knowledge further developed.

Using models for investigation can be linked to the role that models often have in NSE, that of a research tool—a tangible, concrete way to gather data about phenomena that are impossible to see and with which are difficult to interact. However, this way of model use does not inherently address the lack of accuracy of models and the processes of model design, thus teachers must be aware of this in their discussions with students about the lesson.

4.3. NSE Models and Learning Objectives

The ways teachers used models were also considered with a lens on learning objectives. The Revised Bloom's Taxonomy served as one lens and the National Research Council's (2000) definition of inquiry served as another.

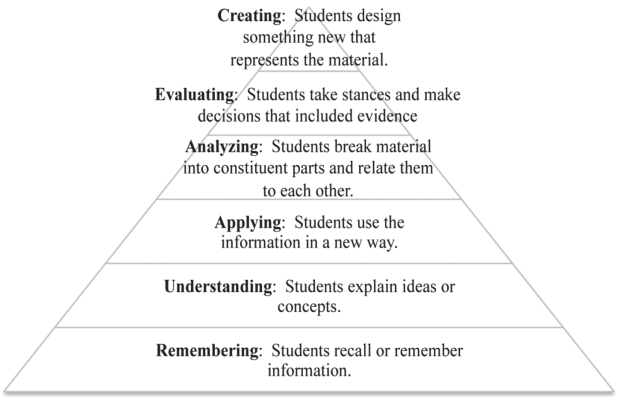

Fig. 4. Revised Bloom's taxonomy.

The Revised Bloom's Taxonomy (Anderson & Krathwohl, 2001) categorizes the types of learning objectives that can be included in educational materials; the pyramid represents increasingly cognitively challenging work (See Fig. 4). Using models as tools for visualization allows students to perform cognitive tasks like defining, duplicating, listing, or memorizing, which require the lowest level of cognitive thought. For example, when Teacher A explained to her students how gold nanoparticles change color according the models, students may have engaged in remembering what substances impact color change or memorizing how the process occurs. Activities in which students design and critique models are categorized as requiring higher levels of cognitive thought. In these situations, students formulate ways to translate their own knowledge and ideas as well as data into representations, and also evaluate the quality of their models by comparing them to other models and scientific data and information. Using models as a means for investigation is an activity that is likely to evoke high levels of cognitive thought for students. Using the language of the taxonomy, students participate in multiple levels of engagement, "analyzing" data, "creating" hypotheses by using evidence to draw conclusions, and "evaluating" their results compared to other resources, as well as judging what their discoveries from interacting with the models reveal about the NSE concept or phenomenon of interest.

The ways in which teachers use models can facilitate or limit the level of inquiry involved in their lessons (NRC, 2000). For example, teachers who used models as tools for visualization were more likely to discuss the role of the model as a way to show and explain aspects of the object, concept, or phenomenon to their students. Thus, students would not use the model to engage in questions and collect evidence. In contrast, instruction in which models are used for investigation facilitates an inquiry environment. The investigations are driven by discovery and data collection, are based on questions to be answered, and the outcomes of these investigations often include an analysis or synthesis of data leading to an explanation of what was learned in the investigation. While there is no guarantee that models used in a particular way will translate to inquiry-based learning, the chances are greater that by using models in interactive ways, students will have a more active role in uncovering information, synthesis data, and formulating their own explanations from evidence.

Both frameworks are useful ways to view the results of this study because they make visible relationships between model uses and modes of learning. Teachers who want to engage students in inquiry and cognitively challenging tasks are able to see from these frameworks ways to use models to achieve these goals.

4.4. Models in the NSE Context

Models are of particular importance in NSE instruction because teachers may rely on models to allow students to "see" the nanoworld. Thus, it is important to view the results of this work with a specific lens on NSE instruction and consider how the results inform NSE education.

Models played a key role in teachers' NSE instruction in this study. While we cannot say what choice teachers would have made had we not required they use models in their lessons, none of the teachers expressed difficulty incorporating at least one model into their lesson. In fact, many teachers used more than one model. Additionally, their uses of models were not "add-ons" to the lesson. Their lessons were often centered on a model or models, and depended on the model(s) to help their students learn the NSE content.

Understanding the reasons that teachers chose to use models only as visual tools in NSE instruction are particularly important. One potential reason for this choice may be due in part to the nature of the scale. As the nanoscale cannot be seen, the idea of "seeing" this scale may be important when teaching about NSE. This is supported by previous work that found that chemistry teachers, more than teachers of other science disciplines, emphasized the need for models to make the abstract visible (Justi & Gilbert, 2002b). The nature of many concepts in chemistry is comparable to NSE, as similar barriers exist in "seeing" these worlds. The nature of the nanoscale may emphasize the advantage of visualization and de-emphasize consideration of student investigations and interactions with models as there are few ways to provide access to this scale. A necessary precaution exists for teachers and teacher educators to combat this potential natural tendency of models in NSE to be seen as merely visual tools.

The choices of teachers to use models as visual tools may also be due to the new content that they were learning. They consider NSE a "new" science. Teachers are more comfortable teaching content in which they are familiar, and are more likely to take a student-centered approach in those situations; teachers are less comfortable with

NSE content because it is new to them, thus they may have a tendency to implement teacher-centered instruction (Hutchinson, 2009b). Giving teachers ideas of how to use NSE models in the classroom as tools for more than visualization will facilitate student-centered instruction, even though they may be less confident in the subject matter. Models are an important part of all science disciplines and across all scales (AAAS, 1993; NRC, 2000), so it is important to make sure that as any new curricula is introduced, models are incorporated in ways to facilitate student engagement.

Model critique also has a unique role in NSE instruction. In NSE, students must critique models compared to their own conceptions. They cannot compare the model to the actual target. They will not have the capability to critique an NSE model without some initial ideas. NSE instruction will need to provide opportunities for students to examine what they think about a phenomenon so that they can use that knowledge in their critiques. Another essential step in using models for critique will be helping students refine their ideas. A potential danger exists in that students could memorize the critiqued model in place of understanding the actual phenomenon (Grosslight et al., 1991). In NSE, it is especially important to engage students in discussions about the role of models and the notion that they are necessarily limited in some ways.

In the case of some nanoscale concepts, instructional models may not be available. Thus, NSE may be more dependent on model design than other scales of science to support students in translating abstract ideas to concrete ones. Similarly, NSE instruction relies on models for investigation. At present, there are limited ways for students to engage directly with NSE phenomena, and limited opportunities for them to access the tools of NSE that allow interaction. Models can provide students access to this scale and allow them to investigate questions and gather data.

This study did not focus on the impact of the professional development experience on teachers' decisions to use models, i.e., we did not characterize their choices before and after an intervention. However, we did study teacher decisions on model use in NSE instruction after participation in a program that required them to incorporate a model in their NSE lesson and that encouraged them to think about ways to help students learn best with models. As some of their choices were to use models for visualization only, it is especially important for future professional development related to model use, and especially model use in NSE, to emphasize and highlight ways that models can be used in addition to visualization. Using the examples in this paper is one way to highlight possibilities for students to engage with models in NSE.

5. CONCLUSIONS

Nanoscale science and engineering represents both the revolutionary and evolutionary nature of science, and if we are to remain contemporary in our curriculum, we must design lessons focused in this area and find ways to successfully integrate this content into curricula. NSE instruction necessitates the use of models, which raises questions about how to use models in ways that will facilitate learning and engage students. As teachers are the ones who make the decisions about how to use models in this emerging field, we must investigate the choices they make and incorporate these data into lesson development and integration strategies. In this study, we found that teachers used models in four ways in the context of NSE instruction. Half of the participants in this study used models primarily in ways other than visualization, which we believe offers more opportunities for more cognitively challenging tasks, inquiry-based learning, and connections to nature of science concepts. The outcomes of this study also provide examples of how each way of model utilization looks in the context of NSE topics, which provides a foundation for continued development of model-based NSE instruction.

As teacher educators, it is not only important to incorporate good practices with models into instruction, but also to demonstrate these good practices when teachers are learning NSE content. We must model the practices we want teachers to implement. Explicit discussions with teachers are also necessary about the use of models and modeling in NSE instruction. Teachers' natural model utilization choices in NSE may not be for investigation, design, or critique, thus we must support them in conceiving of models as more powerful tools than visualization alone. However, as half of the teachers in this PD program used models in student-centered ways, it is possible to impact teacher use of models in this positive way. This study provides evidence that teachers are interested and able to incorporate models in these pedagogically rich ways when they have appropriate support.

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APPENDIX

Instructions for NSE Lesson

(1) List the models you are using in your lesson.
(2) For each model you are using, describe the concept(s) you are trying to help convey with that model.

(3) For each model you are using, describe how you believe it will help students learn about the concept.
(4) For each model you are using, explain why you selected that model for your lesson.
(5) For each model, describe how it will be used within the lesson. What will you do with it? What will students do with it?
(6) Based on how you chose to use models in your lesson, what role do you think models play in nanoscale science and engineering education?

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