# Learning Progression Developed to Support Students in Building a Particle Model of Matter

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## Introduction

The particle nature of matter is a core idea in science. Core ideas are central to the disciplines of science and serve as the building blocks for learning within a discipline (National Research Council [NRC] 2012; Stevens et al. 2009). For example, the particle model of matter serves as the basis for understanding states of matter, phase changes, and properties of substances. In addition to being a core idea of science, understanding particle theory requires students to also understand the scientific practice of modeling. Providing an opportunity for students to develop science content and scientific practices over time is the approach advocated by researchers for the development of common science standards (NRC 2012). Recently, science educators have started to explore learning progressions as a means for understanding how students develop knowledge of complex science content over time (Corcoran et al. 2009).

Learning progressions are depictions of students' increasingly sophisticated ideas about a specific knowledge domain over time (NRC 2007; Smith et al. 2006). Learning progressions are not developmentally inevitable (Stevens et al. 2010) nor are they tied to a particular curriculum but do depend on instruction. However, learning progressions can provide the opportunity to examine how students' ideas evolve over time. The development and application of progress variables is one method that has been suggested as a means for tracking students' knowledge (Wilson 2005, 2009). Progress variables depict students' increasingly sophisticated conceptions over time, regardless of whether it is a matter of weeks or years.

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In addition, progress variables mediate between core ideas and specific concepts and skills being learned and serve as a means for monitoring student understanding during instruction (Wilson 2005, 2009). Once developed, progress variables can be used to provide information to both teachers and students about student development during instruction (Kennedy et al. 2006; Wilson 2005, 2009). Thus, learning progressions and progress variables could be powerful tools for promoting students' understanding of subject matter.

In their review of research on students' understanding of the particle model, Harrison and Treagust (2002) found that traditional curriculum materials present the particle nature of matter as a topic, focusing on the history of the atom. At the middle school level (ages 11–14) in the United States, students are often taught through direct instruction the structure of the atom and that the different states of matter are related to the movement and arrangement of atoms (American Association for the Advancement of Science [AAAS] 1993). This direct instruction assumes that once presented with the particle model, students will accept it as the correct model. For example, at the high school level (ages 14–18), a textbook presents the history the atom beginning with the Greek philosophers and ending with the current quantum model of the atom (Davis et al. 2006).

Moreover, research shows that students find it difficult to learn the particle model using traditional curriculum materials because they present particle concepts to students without helping them to develop these concepts, to take into account their prior knowledge, or to use them as models for explaining phenomena (Harrison and Treagust 2002; Krajcik 1991; Nakhleh 1992; Stevens et al. 2010). Often, students do not develop appropriate ideas because they never apply and reapply these ideas to explain phenomena. In this chapter, we describe a progress variable for the particle model of matter, evidence for this progression, and the importance of building students' ideas over time through key instructional experiences.

## Literature Review of Student Conceptions of the Particle Nature of Matter

The particle nature of matter is a fundamental concept for learning and understanding many physical and chemical processes. Novick and Nussbaum (1978) studied students' ideas about the particle nature of matter as it relates to gases and found that students did not (1) internalize ideas related to the vacuum concept (empty space) and (2) understand the intrinsic motion of particles or the interaction between particles during a chemical change. Other studies have shown that students assign macroscopic properties of substances to the atoms/molecules that compose the substance (Ben-Zvi et al. 1986; Lee et al. 1993; Nakhleh 1992). Moreover, learners and many adults hold nonnormative science ideas regarding the structure of matter and how to explain phenomena. Our position is that student's prior knowledge of matter needs to be used as a resource to build understanding.

The nonnormative science ideas that students possess have been documented (Driver et al. 1985, 1994). For example, students misconstrue mass and size of an

**Table 1** Students' nonnormative conceptions of particle theory

| | |
|---|---|
| Attributing properties of substance to its atoms | Ben-Zvi et al. (1986) |
| Mismatch between the language students use for describing phenomena/matter and students' views of matter | Ben-Zvi et al. (1986), deVos and Verdonk (1996), Driver et al. (1994), Johnson (1998), Lee et al. (1993), Renstrom et al. (1990), and Taber (2003) |
| Language used in discussing the particle model | Ben-Zvi et al. (1986), deVos and Verdonk (1996), Driver et al. (1994), Johnson (1998), Lee et al. (1993), Renstrom et al. (1990), and Taber (2003) |
| Hybrid models | Johnson & Papageorgiou, 2010, Justi and Gilbert (2002), Liu and Lesniak (2006), Renstrom et al. (1990), and Taber (2003) |

object. In other words, students hold the idea that a balled up piece of aluminum has more mass than if that same piece of aluminum foil was flat. In addition, it has been found that students have nonnormative ideas related to the particle nature of matter despite instructional strategies (Driver et al. 1994). Often they hold on to these ideas because they never see how the normative ideas can help explain phenomena they experience in their lives.

Researchers have also suggested that nonnormative ideas related to particle theory are developed during instruction. In some instances, instruction can be enveloped in prior malformed conceptions or learned due to the student's method of learning. As Harrison and Treagust (2002) note, "this practice of providing token evidence and making the assumption that students will accept the new ideas as fact is not an uncommon phenomenon in teaching and learning chemistry" (p. 191). Table 1 shows examples of some studies that have found different nonnormative ideas that students develop.

Students will often attribute properties of a substance to the atoms or molecules of that substance (Ben-Zvi et al. 1986; Lee et al. 1993). Ben-Zvi et al. (1986) designed a comparison study aimed at investigating students' views of matter. They found that although classroom discussions involved the correct terminology (i.e., atoms, molecules), one-third of students still attributed properties of a substance to its atoms. For example, students would come to the conclusion that gold atoms are yellow in color because a gold brick is yellow in color.

Lee et al. (1993) completed a comparison study that also found students were applying observable properties to molecules. In addition, they found that students had no concept of empty space between molecules, viewed molecules as being the same size as tiny objects (i.e., dust, bacteria, cells) and did not think molecules are constantly moving. These studies, as well as others focused on students' understanding of the particle nature of matter, often mention the mismatch between the language that students use for describing phenomena/matter and students' views of matter (Ben-Zvi et al. 1986; deVos and Verdonk 1996; Driver et al. 1994; Johnson 1998; Lee et al. 1993; Renstrom et al. 1990; Taber 2003).

As aforementioned, it is often taken for granted that students will just take up the particle model during instruction. Most curricula in the United States make no mention of alternative models students may hold. The only mention of alternative ideas relates to the delineation of the history of the atom found in many traditional textbooks (Harrison and Treagust 2002). This is a very scientific view of how the particle model developed, focusing on the scientists and the experiments that led to the current quantum model of the atom.

Besides the lack of acknowledgment of alternative student conceptions, there are issues related to the language used in discussing the particle model (Ben-Zvi et al. 1986; deVos and Verdonk 1996; Driver et al. 1994; Johnson 1998; Lee et al. 1993; Renstrom et al. 1990; Taber 2003). The particle model is important for explaining macroscopic phenomena using submicroscopic terms. For example, water boiling is explained as the rapid movement of water molecules from the liquid phase to the gaseous phase. In addition, the terms atom and molecule are often used interchangeably to describe materials on a submicroscopic level, which is often confusing for students and sometimes teachers (Taber 2003). For example, students are taught that elements are made up of atoms. Oxygen is an element that is made up of oxygen atoms, but these atoms are always found as oxygen molecules (two oxygen atoms bonded together). This becomes confusing for many students because they conflate the definition of element with the term atom. As Harrison and Treagust (2002) note, the "…semantic differences between students' and teacher's meanings for commonly used terms in science are a source of alternative conceptions" (p. 525).

Textbooks can also introduce hybrid models, which hinder students developing an understanding of the particle model (Justi and Gilbert 2002; Taber 2003). These hybrid models mix macroscopic descriptions of phenomena with particle and molecular ideas. For instance, they will show a diagram of water illustrating water molecules within a drawing of liquid water. This can result in students thinking of substances being made up of molecules, but they cannot identify the molecules as the substance (Johnson and Papageorgiou 2010; Liu and Lesniak 2006; Renstrom et al. 1990).

Curricula can also introduce "teaching models" that do not contribute to student understanding (Justi and Gilbert 2002; Taber 2003). "Teaching models" often are not based on scientific evidence, nor are they used for explaining scientific phenomena. Frequently, they are analogies that teachers use in an attempt to help students understand scientific content. When teachers present students with teaching models, they focus on the content of the model, not the nature of models and modeling and/or without emphasizing the role of modeling in developing what is known about the chemical behavior of matter. For example, students are introduced to the arrangement of atoms/molecules in the different states by having students behave as the molecules in the different states. This often leads students to viewing the spacing of atoms/molecules in a liquid to be closer to that of gases instead of being close together, like solids. Few efforts have been made to improve teachers' pedagogical content knowledge in this area (Justi and Gilbert 2002). Thus, in order to help students understand the particle model, teachers need to be aware of the various paths students take to a particle model.

In the field of chemistry, more than one model or representation is used to explain or illustrate different aspects of the same concept/phenomena. For instance, different models or representations highlight different aspects of data we have regarding the structure of water. Depending on the context of instruction, a water molecule can be discussed using a ball-and-stick model, a space-filling model, structural formula, or line-angle drawing. Each of these different models and representations highlight different features of water important to explaining a concept or phenomena. For example, a space-filling model shows the space that molecules take up as well as the angles at which the atoms in the molecules bond, while structural formulas show the relationship between atoms and types of atoms in a molecule. Furthermore, understanding these different models/representations is important for understanding more complex concepts such as hydrogen bonding or molecular models used to explain potassium channels in cell biology. Moreover, students have difficulty understanding how to interconvert between ball-and-stick models, structural formulas, space-filling models, and line-angle drawings (Baker and Talley 1972; Ferguson and Bodner 2006; Kozma et al. 2000). These difficulties stem from students not understanding the importance of these different representations in explaining different chemical concepts and how they are used to explain phenomena. Thus, for students to understand the significance of these different models, they need the skills to understand these different representations and how phenomena inform the creation of these models.

Others have shown or promoted using, creating, and understanding the nature of models as a means to help students understand physical phenomena (Grosslight et al. 1991; Harrison and Treagust 1998; Hestenes 1992; Justi and Gilbert 2002; MacKinnon 2003; Mikelskis-Seifert and Leisner 2005; Saari and Viiri 2003; Schwarz and White 2005; Schwarz et al. 2009; Vosniadou 1994). Unfortunately, students are often introduced to abstract topics like particle theory through the use of multiple models without understanding the nature of models. Teachers introduce different models (i.e., physical models, simulations, and 2-D models) based on the model's ability to explain different aspects of the same phenomenon. The various models utilized to represent specific phenomena confuse many students. This is especially true for the teaching of abstract concepts in which analogies and models can be confused with reality. Moreover, teachers should help students to understand shared and unshared attributes of models as well as the limitations of different models (Harrison and Treagust 1996). Thus, students not only need help in understanding models used to explain particle theory, but they also need instruction that helps them to understand the limitations of these different models.

Several studies indicate that students' development of a particle model of matter takes different paths and that, as students' content knowledge grows, students' models can change – both toward a more complete particle model and back to their initial understanding (Johnson 1998; Margel et al. 2008; Nakhleh et al. 2005). Johnson (1998) found students' models correspond with their explanation of phenomena, such that a continuous model relates to macroscopic explanations of phenomena while a complete particle model relates to submicroscopic explanations of phenomena. Margel et al. (2008) found a similar pattern of students moving from a macroscopic to molecular model as well as macroscopic to molecular explanations within a 3-year curriculum in Israel. On the other hand, Nakhleh et al. (2005) found that students were able to give submicroscopic explanations for familiar substances, but their understanding was fragmented based on particular substance or phenomena.

In sum, students' understanding of matter originates both from everyday experiences and classroom instruction. As such, students' conceptions should not be looked upon as misconceptions but as resources for developing greater knowledge. In addition, student nonnormative ideas have provided insight into how student understanding of the particle model develops over time. This development perspective provides opportunity to (1) track student understanding during instruction, (2) determine students' prior knowledge, and (3) gain an understanding of how this knowledge changes through instructional interventions. Moreover, the ability to track student progress also serves as insight into how instruction impacts these changes. The development and application of progress variables is one method that has been suggested as a means for tracking student understanding (Wilson 2005, 2009).

The sixth grade chemistry unit described in this chapter takes the approach of focusing on students' models of matter and the application of that model to explain macroscopic phenomena (Ben-Zvi et al. 1986; Kozma et al. 2000; Justi and Gilbert 2002; Harrison and Treagust 2002; Snir et al. 2003). Specifically, the development of a particle view of matter is the basis for understanding properties, states of matter, and phase changes. In addition to the development of particle model, students develop an understanding of the practice of modeling. Moreover, we conducted research to examine how students' understanding of the particle nature of matter changed as they participated in this contextualized and model-based chemistry unit. In this chapter, we examine how the curriculum supported students' development of a particle view of matter using an empirically validated particle model of matter progress variable.

## Learning Progressions and Progress Variables

As mentioned earlier, learning progressions depict students' development of more sophisticated conceptions of a specific domain over time (NRC 2007; Smith et al. 2006). Learning progressions are not developmentally inevitable as student understanding depends on instructional activities (Stevens et al. 2010). In other words, the order in which ideas are presented and built upon during instruction is a factor in how learning progresses. However, it is possible to gather evidence to show how students develop when a learning progression is either tied to key instructional tasks or curriculum. Moreover, learning progressions provide an opportunity to examine students' increasingly sophisticated ideas over the long term.

Learning progressions are also a means for helping both students and teachers to track students' knowledge over time (NRC 2007; Smith et al. 2006). Moreover, learning progressions provide a means for thinking about how to present topics to students so that they build on each other through the years. Smith and colleagues (Smith et al. 2006) progression is based on prior research related to matter and particle theory and focuses on students gaining more sophisticated understanding of matter and its properties as well as applying microscopic explanations to macroscopic phenomena. In addition, this progression identifies which topics are introduced each year and how knowledge is built in relationship to what students have previously learned. Developing a means for tracking students' long-term progress for understanding the core ideas of science is important. We also need to track students' increasingly sophisticated understanding of concepts underlying these core ideas, especially within the time frame of classroom instruction.

Progress variables represent a range of student thinking about a particular knowledge domain or construct. In other words, progress variables describe the construct or core idea that we want to track. A construct "can be part of a theoretical model of a person's cognition…their understanding of a certain set of concepts" (Wilson 2005, p. 6) and is considered a latent trait that can be measured (Wilson 2005). Like learning progressions, constructs range from low to high knowledge of a domain, with increasing complexity occurring over time. Thus, progress variables can mediate between core ideas and specific concepts and skills being learned, taking into account what research has revealed about student learning in a particular domain. For instance, one or more progress variables could be used to track student understanding of a particular construct over various time frames as short as a curriculum unit to a learning progression that covers multiple years (Wilson 2009).

Therefore, progress variables allow one to focus on student growth of a construct over time (Wilson 2005, 2009). In addition, each unit of instruction contributes to students' progress, which necessitates that assessment aligns with one or more progress variables. Consequently, both what students are learning must be clearly defined and a theoretical framework for interpreting students' progress is necessary to establish the construct validity of an assessment system (Wilson 2009). Constructs are latent traits we cannot see, so we develop measures within the context of the classroom to serve to make students' thinking visible (NRC 2001). Thus, summative and embedded assessments must be aligned with the progress variable. Alignment of assessments with instruction "allows the creation of a calibrated scale to map the growth of students so teachers and researchers can track the progress of individual students as they undergo instruction" (Wilson 2005, p. 195). As a result, assessments must reflect the variety of instructional practices of the curriculum. Thus, the variables serve as a means for relating curriculum to standards as well as to assessment that are not related to the curriculum. Once developed, progress variables can be used to track student understanding of scientific content and practices, providing information to both teachers and students about student progress during instruction (Kennedy et al. 2006; Wilson 2005, 2009).

Progress variables are visualized through construct maps, which divide the complex levels of students' increasingly sophisticated understanding into distinguishable levels. Thus, a construct map specifies how a construct develops over time. In turn, a single construct map could be designed to represent a learning progression, or several related construct maps could be developed to track a single learning progression. When a construct map is developed in relationship to innovative curriculum, the construct map also represents the goals of teaching (Wilson 2009). The development of the construct map is also important because assessments for tracking students' understanding must align with construct map.

The particle model of matter (PMM) progress variable was developed in relationship to the Investigating and Questioning our World through Science and Technology (IQWST) (Krajcik et al. 2012) [discussed later] sixth grade chemistry unit (see Table 2). The PMM progress variable was developed to determine how student understanding of the particle nature of matter changes during instruction (Merritt 2010). The curriculum focuses on student development of a particle view of matter using models of matter that they construct. We developed this construct map by an iterative process of considering the logic of the discipline, what was known about how students' ideas regarding the particle model, and empirical work based on the curricular intervention.

This map illustrates how students' understanding of the particle model builds over time. The "particle model" construct map encompasses both the varying starting points students had before the curriculum began and their varying end points, with the least sophisticated understandings at the "descriptive model" level (bottom of table) to most sophisticated at the "complete particle model" level (top of table). This map reflects students' increasingly sophisticated understanding of the particle model as it relates to properties and phase change, starting from the "descriptive model." It also takes into account the instructional sequence in order to move students from one level to the next level. For example, the unit focuses on developing a particle model to understand structure of matter before applying the model to explain properties and then phase changes. The "example student response" column shows actual student responses, which demonstrate the types of understandings students exhibit at each level. The "progressing to next step" column illustrates examples of instructional strategies that could help students reach the next level (e.g., progress from a descriptive to a mixed model).

Students at the descriptive model level have a macroscopic view of matter that can explain phenomena using qualitative descriptions. Students describe ice as water in the solid state. Mixed model level students are beginning to develop a particle model but blend the particle model with the descriptive model. At this level, students view some substances on a macroscopic level and others as particles and do not identify particles as atoms or molecules. For example, they would describe water in the liquid state as being composed of particles within the liquid. Students at the basic level students use a particle model of matter to explain phenomena. At the basic level, the particle model can include atoms or molecules but have difficulty explaining the movement or arrangements of atoms/molecules in different states. However, students at this level can explain that different substances have different properties due to the arrangements of its atoms. Though the model is more scientifically accurate, students still hold incomplete understandings about the spacing between atoms/molecules in the different state. For example, students often think molecules of a liquid are more spaced apart than those in a solid. At the

**Table 2** Particle model of matter construct map

| Category | Description | Example student response | Progressing to next step |
|---|---|---|---|
| Complete particle model | Students use particles (molecules) to explain phenomena. There is empty space between the particles. The students are able to *distinguish spacing AND motion relevant to the particular state* they are in. Different substances have different properties because they are made of different atoms OR have different arrangements of same atoms | Water vapor, liquid water, and ice are all made up of water molecules. The molecules in water vapor are far apart and move around freely. In a liquid, they are closer together but move around each other. In a solid, they are close together and vibrate<br>Sugar and water are not the same because they are made up of different molecules | |
| Basic particle model | Students use *particles* (may use atoms and/or molecules) to explain phenomena. There is an empty space between the particles. Students have difficulty in explaining the difference in spacing in different states and/or are unable to distinguish the difference in movement for all states. *Different substances have different properties because they are made of different atoms or have different arrangements of same atoms* | Water vapor is made up of water molecules that are spaced far apart and move freely everywhere. Liquid water is made up of water molecules that are moving but are closer together than in water vapor. In ice, the molecules are even closer together<br>Sugar and water are not the same because they are made up of different molecules | Students need to understand the difference in movement of a substance in different phases. For example, a simulation of the same substance as a solid, a liquid, and a gas should include the same representation for water molecules but with different spacing and movement, including how movement changes as temperature changes |

(continued)

**Table 2** (continued)

| Category | Description | Example student response | Progressing to next step |
|---|---|---|---|
| Mixed model | Students use both *particle* and *descriptive ideas* to explain and describe phenomena. Though they recognize that different substances have different properties, their explanation for why remains at a macro-level | Water is made up of water particles. The water particles exist within the liquid water. Thus, in between the particles is liquid water | The idea that water is made up of the same atoms/molecules no matter the state should help students to realize that a substance's atoms/molecules do not change. For example, a model of ice, water, and water vapor should include the same representation for water molecules but with different spacing and movement |
| Descriptive model | Students describe objects *exactly as they appear*. When an object is broken into smaller pieces, it always has the same properties | Water is a clear, colorless liquid. Ice is a "clear" solid. They have different structures and are described differently. Therefore, they are not the same substances | The ideas that objects are made up of parts could be a useful idea to help students realize that a piece of a substance that looks continuous can be broken down into smaller pieces. Student needs to realize that a substance is changeable (it can change phases) or, in other cases, may be broken into smaller pieces |

**Table 3** National standards (AAAS 1993; NRC 1996)

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|---|
| *AAAS 4D/M1*: All matter is made up of atoms, which are far too small to see directly through a microscope. The atoms of any element are alike but are different from atoms of other elements. Atoms may stick together in well-defined molecules or may be packed together in large arrays. Different arrangements of atoms into groups compose all substances |
| *AAAS 4D/M3*: Atoms and molecules are perpetually in motion. In solids, the atoms are closely locked in position and can only vibrate. In liquids, the atoms or molecules have higher energy, are more loosely connected, and can slide past one another; some molecules may get enough energy to escape into a gas. In gases, the atoms or molecules have still more energy and are free of one another except during occasional collisions. Increased temperature means greater average energy of motion, so most substances expand when heated |
| *NRC B5-8: 1A*: A substance has characteristic properties, such as density, a boiling point, and solubility, all of which are independent of the amount of the substance |

complete level, students have a particle model that can explain states of matter, phase changes, and differences in properties of substances. Students at this level describe water as being composed of water molecules and can describe the arrangement and movement of molecules in the different phases.

## *The Curriculum*

The Investigating and Questioning our World through Science and Technology (IQWST) curriculum (Krajcik et al. 2012) takes the approach of building a student's understanding of core ideas over time. In the sixth grade *How can I smell things from a distance?* unit (Merritt et al. 2012), students develop understanding of the particle nature of matter model by using and refining the model to explain phenomena, such as states of matter, phase changes, and properties. For example, the particle model can be used to explain a property like boiling point. The boiling point of a substance occurs at a fixed temperature and involves the rapid evaporation of anywhere in a bulk liquid. During heating, particles gain energy and move faster. At the boiling point, the energy of these molecules is enough to overcome the attractive forces of the other liquid molecules so that it goes from the liquid to the gas phase.

## *Identifying and Unpacking Standards*

For the development of this unit, we identified three standards (see Table 3) from the Benchmarks for Scientific Literacy (AAAS 1993) and National Science Education Standards (NRC 1996). Although IQWST was developed prior to the National Research Council's New Framework for K-12 Science Education (NRC 2012), the ideas in this unit correspond to ideas that all learners should understand by the end of eighth grade in the Structure and Properties of Matter core idea (Physical Science 1.A). The identification of a small number of standards sets the IQWST curricula apart because of our focus on depth instead of breadth.

Once the standards were identified, we underwent a process of unpacking what it means to teach them. Unpacking, in this instance, means we carefully read through the standard to identify concepts within them which are important, what knowledge students may bring to these ideas, what prior knowledge is necessary and what misconceptions students have as well as to what depth these concepts should be explored, in this case, in sixth grade (Krajcik et al. 2008).

For example, the first standard (AAAS 4D/M1) begins with the idea: All matter is made up of atoms. We determined that this idea was composed of two concepts: (1) that matter is made up of particles and (2) that these particles are atoms. Then, we determined that students need to understand what matter is – anything that has mass and takes up space. From research and our experiences, we identified that students would have difficulty in differentiating weight and mass as well as difficulty in identifying air and other gases as matter (Driver et al. 1985, 1994). Additionally, we looked at what prior knowledge students should have of matter based on the preceding national standards. In some instances, as we unpacked the standards, we also identified what concepts students would not be expected to learn at this time. For example, students are not expected to understand that a single atom has the chemical properties of that element, but it takes several atoms to give the element its physical properties.

This process of clarifying and elaborating the standards helped to ascertain what it means to teach sixth grade students the particle nature of matter and how the particle model is used to describe states of matter, as well as explain phase changes and properties. Unpacking process also helped to identify what ideas needed further support for students (Krajcik et al. 2008). For instance, helping students understand that matter is anything that has mass and volume is a fundamental concept for helping students to understand both states of matter as well as developing a particle view of matter. Students often conflate the terms mass and volume. Therefore, the decision was made to include activities for students to measure mass and volume as well as to include discussions of matter and volume on both macroscopic and microscopic levels when discussing states of matter. In the United States, students often enter the sixth grade with underdeveloped ideas of these two important concepts. From this work, we were able to develop a unit that contains three learning sets and corresponding assessment items.

The unpacked standards were then used to construct learning performances that serve as the unit learning goals (Table 4). A learning performance results from combining the content standard with an inquiry standard. These learning performances clearly specify what students are expected to be able to do with the knowledge described in the benchmark. Moreover, they "serve as the learning goals that guide development of learning activities and assessments" (Krajcik et al. 2008, p. 7). Thus, in this unit students use the particle model of matter to explain phenomena related to states of matter, phase changes, and properties (see Appendix for a complete list of learning performances).

**Table 4** Example of a learning performance

| Content standard | Inquiry standard | Learning performance |
|---|---|---|
| *AAAS 4D/M3*: Atoms and molecules are perpetually in motion. In solids, the atoms are closely locked in position and can only vibrate. In liquids, the atoms or molecules have higher energy, are more loosely connected, and can slide past one another; some molecules may get enough energy to escape into a gas | Develop…models using evidence (NRC 1996, A: 1/4, 5–8)<br>Models are often used to think about processes that happen… too quickly, or on too small a scale to observe directly… (AAAS 1993, 11B: 1, 6–8) | Using the particle model, students will explain phase change from a solid to a liquid |

We use a driving question to contextualize students' learning of the particle model of matter. The driving question (Krajcik and Blumenfeld 2006) provides a real-life context to engage students in learning about scientific ideas to explain phenomena. The driving question for the unit is "How can I smell things from a distance?" Thus, the anchoring context of the unit has students smell different odor-producing objects and create models to explain how they smell the object from a distance. Throughout the unit, students engage in phenomena, creating models to explain to explain them and use the evidence they gather to help them answer the driving question. In other words, as students experience the unit, they create models to explain phenomena and revisit and refine their models based on what they have learned from these other experiences.

Second, the unit involves the creation of student artifacts, the models that students create. Students experience various phenomena throughout this 8-week unit to help them to gain knowledge and understanding of the different aspects of the particle nature of matter. Key phenomena were placed throughout the unit to help build student understanding and take it to the next level. Peer-to-peer and whole class discussions are utilized to help students discuss and critique their models and understand scientific concepts.

Our approach also provides students with opportunities for using multiple models when students are initially developing their modeling skills. In this case, the use of multiple models refers to students creating and discussing a variety of models of matter (including their peers' models). In addition, teachers lead discussions of student models to help students understand both the particle nature of matter and the purpose of creating models.

Our curriculum work builds from the foundational 1978 Novick and Nussbaum study. Novick and Nussbaum found that students least internalized aspects of the particle nature of matter that opposed their sensory perception of matter. The aspects relevant to our study are that matter exists as tiny particles, empty space (the vacuum concept), and intrinsic motion (particle kinetics). These aspects tend to lead students to forming a continuous-particle model. In particular, students cannot conceive of empty space in ordinary matter, including gases. In designing our unit, we also made use of innovative ideas from Joseph Nussbaum's development of curriculum materials in Israel on the particle nature of matter.

Based on the findings of the 1978 Novick and Nussbaum study, the first learning set of the unit focuses on the following:

- Bulk properties of gases that may make it difficult for students to accept the idea of empty space and various properties of gases (addition, subtraction, compression, and expansion of a gas; air has mass and volume).
- Relationship between heat and speed of motion to understand the intrinsic motion of particles.
- Exposure to more phenomena that are dissonant with their sensory perception of matter would lead to greater accommodation of the particle conception of matter.

The unit contains three learning sets (see Appendix for brief descriptions of the lessons in each learning set) and takes approximately 8–10 weeks to complete. The first learning set (Lessons 1–5) aims at helping students understand what matter is (anything that has mass and volume and exists in one of three states). Students investigate the melting and freezing of menthol to understand that substances can exist in more than one state as well as that they can undergo changes in state. Students also investigate the properties of air (expansion, compression, addition, and removal) to develop a particle model of matter. They realize that gas within a fixed volume can be compressed or expanded using a syringe. And that gas can be removed from a flask of a fixed volume. Students use these four properties to develop a particle model of matter that can account for these four phenomena. By the end of the first learning set, the class develops a consensus model of matter in which matter is composed of particles, there is empty space between particles, the particles are constantly moving, and that particles have mass and occupy space.

Learning Set 2 (Lessons 6–9) helps students to identify and explain properties of substances (elements and compounds), including that properties are a result of the arrangement of atoms in a substance. Students investigate the properties of elements to understand that different substances have different properties. They use their particle models to explain that these differences result from the elements being composed of different types of particles and these particles are atoms. Later, students smell different substances, for which they only see their chemical formulas. From this experience, students develop understanding that the different arrangements of atoms in a molecule (some substances have the same formula, but different odors) result in different properties.

Learning Set 3 (Lessons 10–15) involves students using their models of matter to explain phase changes. Students investigate the effect of heating and cooling on the ability for ammonia to change the color of indicator paper. Students use their particle models to explain this phenomenon, phase change – boiling, condensation, melting, and freezing as well as evaporation. By the end of the unit, students revisit and revise their consensus model based on what they have learned throughout the unit.

The anchoring activity of the unit has students create models (student models are defined as their drawing of gases at the molecular level plus explanation) to explain why they think they can smell an object from a distance. The modeling activity of Lesson 1 is not only a way for teachers to elucidate students' initial notions of the particle nature of matter but is also an activity that is repeated during and at the middle and end of the unit to assess and monitor students' progress.

The smell unit is also designed to be educative for teacher. Educative curriculum materials are designed to promote teacher learning (Davis and Krajcik 2005). As mentioned earlier, teachers need to understand the practice of modeling, the hybrid models of matter, and student misconceptions of matter. As such, the unit includes teacher boxes to help teachers in understanding models (and the particle model in particular), common student ideas (or misconceptions) and ways to help students with these ideas, and subject matter knowledge. In addition, descriptions of the types of discussions they should use to help students in understanding the scientific content, phenomena they are experiencing, and about the models the students are creating throughout the unit. For each discussion, the purpose for having the discussion, suggested questions, and a rational for why these questions help student understanding and what ideas the students should gain from the discussion are explicated.

## *Teachers' Role in Curriculum Development*

Teachers played a vital role in the development of the unit. During the initial development phase of the unit, teachers helped to select the driving question and develop the learning goals of the unit. After a 2-h professional development session for three lessons, one teacher piloted these initial lessons of the unit to help us to determine whether having students create and critique their own models of matter would be an effective instructional strategy. These lessons were all videotaped, and the teacher provided us feedback on these initial lessons immediately following instruction.

The entire unit was piloted by teachers for 2 years prior to national field trials. The teachers received professional development prior to enactment. In the first year, one teacher piloted the unit. A researcher was in the classrooms almost daily, videotaping enactment and providing support when needed. In addition, the teacher contacted us via email with questions, comments, and/or feedback. The teacher filled out evaluation forms to provide feedback on the lessons. At the end of the enactment, we met with the teachers to go over their feedback. This feedback was one part of the information used to modify the unit.

This same process followed in the second pilot year, in which six teachers from across the United States participated in piloting the unit. Teachers received

3 days of face-to-face professional development and online support through a message board where they could post questions and discuss issues with each other as well as researchers. Researchers also videotaped three of the teachers' enactments. The other sites also received support from researchers through site visits. Teachers filled out surveys to provide feedback at the end of each learning set as well as at the completion of the entire sixth grade unit. The feedback was used to revise unit.

Our review of the literature informed us about students' conceptions of the particle nature of matter. This information was used both in the development of the curriculum as well as our construct map. The construct map that was developed both incorporates student conceptions of matter as well as reflects the goals of the curriculum. Next, we discuss how the construct map was used to track students' progress during instruction.

## Supporting Student Development of a Particle Model of Matter

This study investigated how students' understanding changed as they engaged in a contextualized model-based chemistry unit aimed to help them to develop a particle model of matter. The overarching question guiding this study was: *How does middle school students' understanding of the particle nature of matter change during enactment of a model-based unit?* This study was a part of a larger study in which the PMM progress variable was validated. Six hundred and two students and their seven teachers were involved in the study (Merritt 2010). The larger study focused on students' gains in knowledge of particle theory from pretest to posttest. These identical pre-/posttest assessments were found to be valid and reliable measures of student performance (Cronbach $\alpha$ of 0.85 for the assessments). In this study, we investigated the use of the particle model of matter progress variable to track student learning during the curriculum. In addition, we examined how the instructional strategies of the curriculum supported student development of a particle view of matter.

This study involved three teachers from three different schools in three different cities and 122 students of varying proficiencies. Each teacher had taught the unit previously. We collected identical pre-/posttests and embedded assessments from three schools in the Midwest and Southwest United States. School 1 was located in a Midwest rural town of varying socioeconomic status. Forty-three students from school 1 participated. School 2 was located in a suburb of a large Midwest city and the teacher has taught the unit for 3 years. Fifty-eight students participated from school 2. School 3 and its 21 students are located in a midsize urban city in the Southwest. The students are not a representative sample of all students that participated in the study but are students who completed all three embedded assessments (AS1.1, AS5.2, and AS15.2) that were included in the study. Students' understanding of the particle model of matter was tracked using pretests, embedded assessments, and posttests.

## *Teachers' Professional Development*

Teachers received two half-day professional development sessions for the chemistry unit in the summer. These sessions introduced teachers to the anchoring context of the unit and how creating and using models support students in developing a PMM. Prior to enactment of the chemistry unit, teachers also received 2 days of professional development. The professional development encompasses teachers experiencing the major investigations of the unit as well as creating models that help explain the phenomena that they observed. In addition, teachers were introduced to the scoring rubric that we use for assessing student work. Student work from previous pilots of the unit was used to help teachers evaluate students' knowledge as well as to help teachers in understanding how to facilitate discussions based on students' models of matter.

In addition, teachers received online support as members of an online support group by posting questions, discussing issues, and sharing ways to deal with issues that arose during enactment with each other and facilitators. Researchers made visits to a few schools, but not all schools had available local support.

## *Student Artifacts*

Data collection included identical pre- and posttests composed of 11 multiple-choice items and three written response items. The multiple-choice items covered the key learning goals of the unit: particle nature of matter, matter, phase change, and properties. Two of the written response items required students to create models to explain phenomena, and the third item focused on students explaining how two substances could be differentiated from each other based on their properties. The results of the pretest served to provide insight into students' prior knowledge. The three embedded assessments from the sixth grade chemistry were used to track student progress in developing a particle model of matter. These similar embedded assessments occur during Lesson 1, Lesson 5, and Lesson 15. The embedded assessment for Lessons 5 and 15 are slightly different in that students are asked additional questions, for example, comparing their current models with their previous models and identifying why they made their changes based on what they had learned. For the purpose of this study, only the student models (Question 3), which encompass a key (Question 4), their drawing, and explanation (Question 5) in all three activities, were analyzed (AS1.1, AS5.2, and AS15.1; see Fig. 1).

## *Scoring*

The pre-/posttest was scored using a scoring guide. Multiple-choice items were scored dichotomously; thus, correct responses received a "1" and incorrect responses received a "0." Scoring guides were developed for written response

Name ______________ Date ______________

**Activity 1.1**

## Can you Smell What I Smell?

**PURPOSE**

In class, your teacher opened a jar that had an object in it. The object in the jar had an odor to it, and the odor moved across the room. In this activity, you will record your ideas about how an odor can go from an object to your nose.

**DATA COLLECTION/OBSERVATION**

1. Write the odor you smell

______________________________

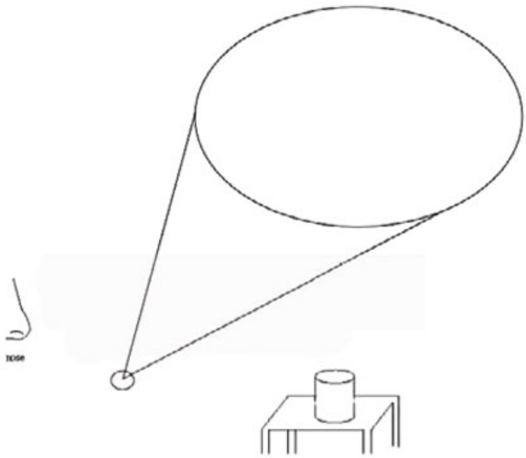
2. Describe what happens when your teacher opens the jar.

______________________________

______________________________

______________________________

3. Imagine that you have a very powerful microscope that would allow you to see the odor up really, really close. What would you see? Create a drawing that shows how the odor got from the source to your nose. The large circle in the drawing below represents the magnified part of the air between the jar and your nose. In the circle, draw a picture of what you think the odor looks like between the jar and your nose.




4. Label what the parts in your drawing represent.

GO

6th Grade Chemistry Activity 1.1 1

Fig. 1 Modeling embedded assessment for activity 1.1

**Table 5** Scoring guide for explanation portion of smell model embedded assessment items

| Code | Level description | Examples of actual student responses |
|---|---|---|
| | No response | |
| 0 | Descriptive – describes model OR describes what happened in class OR gives completely incorrect explanation OR uses prior experience to explain what is happening | It shows how odor [travel] through air. OR<br>The lines where ammonia and little circles are air [particles] and arrows were movement |
| 1 | Mixed model<br>Student tries to explain odors traveling from the source to the nose but uses the incorrect mechanism or focuses on a macrolevel | The air and scent go faster [with] more heat and slower [with] less heat. OR<br>The fan blows air into the air blowing over the tuna smell picking up the smell traveling in a straight path to the nose. OR<br>The odor molecules mix in the air and flow up the nose |
| 2 | Basic particle model<br>Student is able to explain that odor molecules travel from the source to the nose. Student may explain how air helps in this process | The [odor] is in a gaseous state. The air and odor molecules spread around the room |
| 3 | Complete particle model<br>Student is able to correctly explain on a submicroscopic level the movement: odor particles travel in air, random collisions of odor, and air molecules. Student may also describe sublimation/evaporation from the source on a submicrolevel | First, the ammonia particles gain enough energy to evaporate and turn to gaseous ammonia. Then it moves in a straight path [until] it runs into something. Eventually it travels to a nose |

and embedded assessment items. These guides take into account actual student responses to the item as a means for mapping them to the different levels of the construct map. Table 5 is the scoring guide for the written response portion of the embedded assessment item in which students are explaining to a friend how an odor can travel from its source to their noses using their drawing (see Fig. 1). For example, the "basic particle model" level of the construct map indicates that students recognize that particles travel from the source to the nose, but unlike the "complete particle model" level, they cannot describe the random motion of the particles.

The written response items were scored with one other rater, obtaining inter-rater reliability of 94.4 %, which was determined by coding nine pre-/posttests, and then dividing the number of items coded identically by the number of items coded. The embedded assessments were also scored using the scoring guide. An inter-rater reliability of 89 % was obtained, which was determined by coding nine embedded assessments, then dividing the number of items coded identically by the number of items coded.

## Data Analysis

We used a one-dimensional partial credit Rasch-based model with maximum-likelihood estimation (MLE) because the test includes multiple-choice items that cover a single level of the construct map as well as items that cover multiple levels of the construct map. By using this model, we were able to estimate student proficiency estimates and item difficulty on the same scale. This common scale allowed us to describe students' expected performance based on their estimated proficiency in comparison to estimated item difficulty. When a respondent's proficiency and the item difficulty are at the same location, there is a 50–50 chance of them getting the item correct. When the respondent's proficiency is above an item, they have a greater than 50–50 chance of answering correctly. Respondents have lower chance of getting the item correct when the item is above the respondent's proficiency. The Rasch model did not violate the assumptions of item response modeling that each subscale is unidimensional and higher scores are associated with higher proficiencies as the data fit the model sufficiently (Merritt 2010).

The Construct Map software (Kennedy et al. 2005) was used to calibrate items. All items (pretest, posttest, and embedded assessment) were calibrated together. Therefore, each student observation was treated as two different students. For example, a student's pretest is one student and their posttest is another "student." We were then able to anchor the difficulties generated for the entire set and look at each of the items separately. We then examined how students' models progressed in relationship to the instructional strategies of the unit.

## Student Progress to a Particle Model of Matter

Table 6 details the mean and sample variances of the student ability estimates for the particle model of matter (PMM) variable. Logits are the unit of measure used by Rasch and represent the probability of a correct response, and the higher the logit number, the more likely students are to respond correctly to the items. This group of students starts out with a higher average ability estimate on the pretest than those in our overall study of student performance (Merritt 2010). The wide variance in student

**Table 6** Means and variances of person ability estimates for the PMM progress variable ($N = 122$)

| Assessment | Mean (in logits) | Sample variance |
|---|---|---|
| Pretest | –0.54 | 0.80 |
| AS1.1 | 0.82 | 3.39 |
| AS5.2 | 1.03 | 2.75 |
| AS15.1 | 1.27 | 3.79 |
| Posttest | 1.08 | 0.62 |

**Table 7** Student proficiency estimate gains from each successive assessment

| | Gain | $p$ |
|---|---|---|
| Pre–AS1.1 | 1.36 | <0.001 |
| AS1.1–AS5.2 | 0.21 | 0.31 |
| AS5.2–AS15.1 | 0.24 | 0.20 |
| AS15.1–post | –0.19 | 0.26 |

results for the embedded assessments indicates the different models that students created for each assessment.

Students performed consistently better from the pretest to AS15.1. Gains in students' proficiency estimates are reported in Table 7, as well as results of paired-sample t-tests. There were significant gains from the pretest to AS1.1. There were gains from AS1.1 assessment to the AS15.1 assessment, but they were not significant. There is a slight (−0.19), but insignificant ($p = 0.26$), drop in performance from AS15.1 to the posttest. This drop may be explained because there is no scaffolding for the modeling items of the posttest.

The pretest and posttest separation reliabilities were satisfactory for the PMM progress variable ($r \geq 0.80$). However, those for the embedded assessments were less satisfactory ($r = 0.67$). These results were most likely due to the small sample size ($n = 122$). The embedded assessments also displayed a wide variance in student performance. These may be due to a number of factors, including teacher effects and fidelity to curriculum.

Another way of looking at students' progress from pretest to posttest is the Performance Map (Fig. 2). The Performance Map shows students' ability estimates over time. A Performance Map can be generated for a single student, for an entire class, or entire groups of students. Figure 2 shows the average progress for all students from pretest to posttest. Overall, this indicates that student conception of matter improved during instruction. Prior to instruction, the average student had a "mixed" model of matter, which means they represented and explained phenomena with matter as having both macroscopic and submicroscopic components. After the first lesson (AS1.1), the average student was now explaining phenomena with a "basic" model of matter which means they represented and explained phenomena with matter being composed of particles. However, students did not describe what these particles were. After Lesson 5 (AS5.2), more students are explaining phenomena with a "basic" model of matter. At this point in instruction, many students are now including motion and the concept of empty space in their model as they have learned these ideas in the lessons prior to the assessment. The final embedded assessment (AS15.1) shows that on average, students have progressed to a "complete" model of matter. At this point, students have been taught that the particles are atoms/molecules and have used their models to explain phase changes as well as that the atoms/molecules and their arrangement in different substances results in different properties. Just as the results show in Table 6, the average student had a "basic" model of matter.

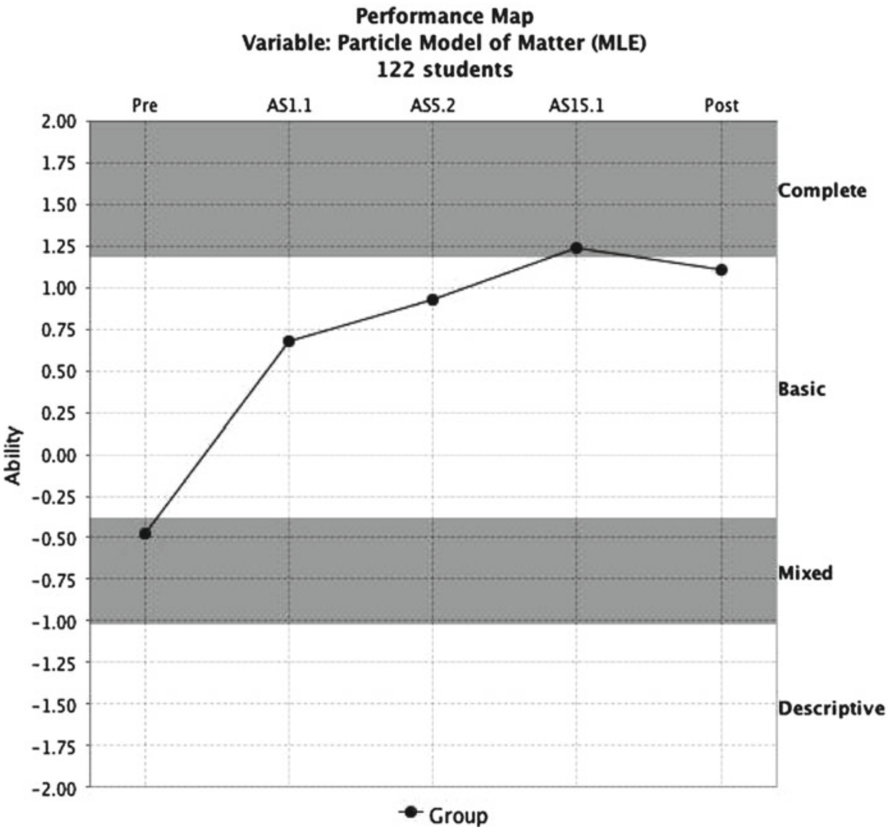



**Fig. 2** Map of average student progress on the PMM progress variable

## Student Development of a Particle Model of Matter

Through the development of the particle model of matter progress variable, we were able to track students' development of a particle model of matter during instruction. At the pretest, most students ranged from a descriptive to a basic model of mater. By the first embedded assessment (AS1.1), students displayed significant growth in performance (from pretest to AS1.1). AS1.1 occurs at the beginning of the unit, and results indicated that most students had either a mixed or basic model of matter. This growth could have occurred because of the discussions students have prior to and during creating their models. During this discussion, students had the opportunity to talk about how they thought odors are able to travel through the air. In addition, students were able to talk with peers as they created their models. Figure 3a shows Laura's initial model of smell. Laura shows odor as shaded lines, representing a descriptive model of matter.

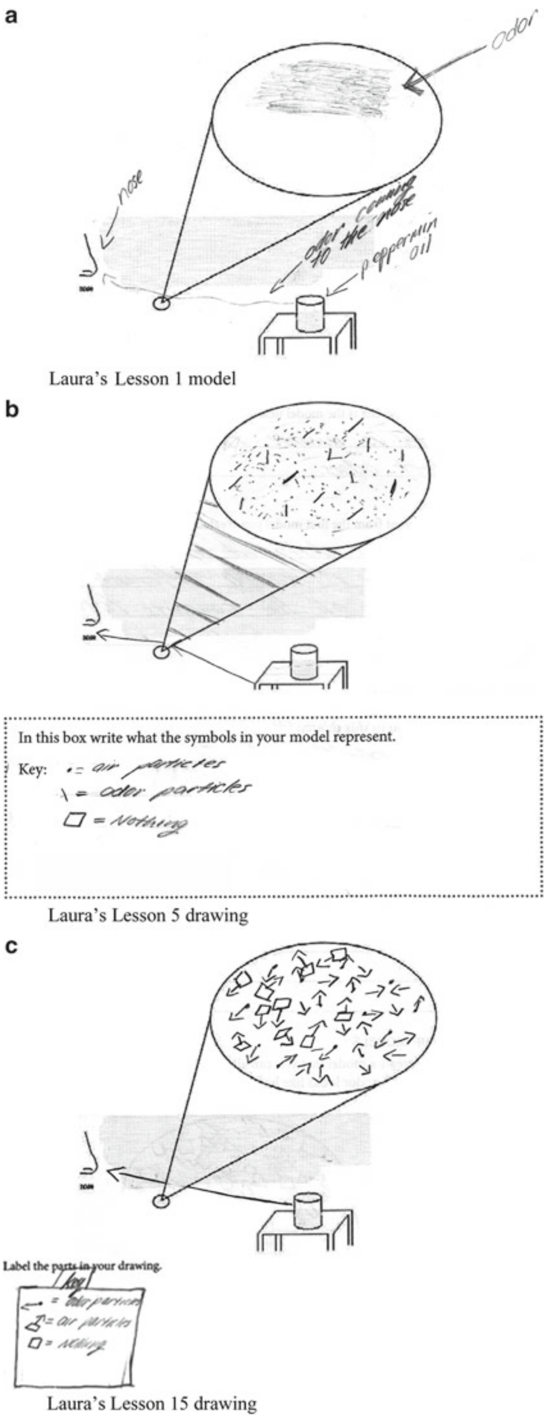



**Fig. 3** Laura's drawing for how smell travels during instruction: (**a**) Lesson 1, (**b**) Lesson 5, and (**c**) Lesson 15

In the three lessons that follow, students investigated matter, defining matter as anything that has mass and takes up space. Students then grouped different materials as solids, liquids, and gases and characterize each of the different states of matter. Students also observed the melting and freezing of menthol to understand that heating and cooling can change matter from one state to another. The next set of instructional activities was key in helping students to gather evidence that matter is made up of tiny particles. Students studied the properties of gases by observing that air can be removed and added to a flask. Moreover, they use syringes filled with air to understand that gases can be expanded or compressed because there is empty space between the particles of a gas. Students created their own models of matter to explain these phenomena. Students were challenged to show how their models could account for the evidence (i.e., explain these various phenomena). Thus, these investigations were used as evidence for a particle model of matter.

Using student models, in Lesson 5, students were introduced to the idea that everything is made up of particles. They investigated the ability of an acid and a base to change the color of indicator paper without being dipped in the liquid. Through creation of models and discussions around the phenomenon and the models, students developed an understanding of evaporation and that the particles of the liquid are the same as those of the gas. Then, students were introduced to a different model, a computer simulation to explain how smells travel across a room before constructing their own models of smell. Students' models indicate that these instructional strategies helped students to further develop a particle view of matter. For example, Laura's model (see Fig. 3b) reflects the ideas that she gained from prior lessons. In her model of smell traveling, she now indicates that there are air particles and odor particles with and nothing between those particles. This is vastly different from Laura's first model of smell (Fig. 3a), which showed only odors as continuous. This also indicates that Laura has moved from a "descriptive" model of matter to a "basic particle" model of matter (see Table 2).

In the next learning set, students experienced phenomena to help them understand properties and phase changes on a molecular level. During these lessons, students learned about atoms and molecules. By the end of the second learning set, students should understand that the properties of different substances are the result of the different atoms in the molecules in that substance.

In the third learning set, students revisited phase changes. Students created models for phase changes on a molecular level. Students modeled how the substances appear in the different states as well as how heating and cooling changes the states of matter. For example, students examined whether gases move faster at higher temperatures by investigating how long it takes ammonia vapor to change indicator paper blue when a test tube containing drops of ammonia is in a warm versus cool water bath. Although there are several instructional strategies that occur between Lesson 5 and Lesson 15, it is difficult to pinpoint which of these have contributed most to student learning gains from Lesson 5 until Lesson 15. Since the unit was written with a particular sequence of learning performances and their associated learning activities, it can be postulated that this learning sequence helped students to develop a particle model of matter. Most students developed a "complete" model of matter at the end of the unit. For example, Laura (see Fig. 3c) has an even more sophisticated model of matter, as she now represents random movement of particles in her model.

Student performance, on average, dropped between AS15.1 and the posttest. AS15.1 occurs before a class review of all the major concepts students have learned. During this review students create models of phenomena before coming to a class consensus model that can explain all the phenomena that they have reviewed. Similar to the findings of McNeill et al. (2006), where they observed a drop in student performance between the end of instruction and the posttest for writing explanations because of the lack of scaffolding and peer-to-peer sharing that occurred during the unit, may also explain student performance on the posttest modeling items for this unit.

## Conclusions and Implications

The particle nature of matter is a core idea of science (Smith et al. 2006; Stevens et al. 2009) that serves as the foundation for explaining a myriad of science phenomena including properties, phase change, and chemical reactions. Previous interview studies (Nakhleh et al. 2005; Novick and Nussbaum 1978; Stavy 1991) have outlined the difficulties students have with understanding particle theory and its related concepts. Our work shows that carefully sequenced curriculum materials that support students in using the scientific practice of modeling can help students develop an initial particle view of matter.

The scientific practice that served as the focus of the unit was modeling – an important and vital tool for helping students to understand abstract concepts such as the particle nature of matter (Harrison and Treagust 1998; Mikelskis-Seifert and Leisner 2005; Saari and Viiri 2003; Schwarz and White 2005). Research has suggested that students need to be introduced to modeling early in their school years (Grosslight et al. 1991; Harrison and Treagust 1998; Hestenes 1992; Justi and Gilbert 2002; MacKinnon 2003; Mikelskis-Seifert and Leisner 2005; Saari and Viiri 2003; Schwarz and White 2005; Vosniadou 1994). We designed the unit so that students would make observations through their investigations that would allow them to build more successive and appropriate models of the PMM over time based on evidence.

Studies have also suggested that students' understanding of the particle nature of matter would improve if a sequenced, developmental approach was taken to supporting students understanding of particle theory (Ben-Zvi et al. 1986; Harrison and Treagust 2002; Justi and Gilbert 2002; Kozma et al. 2000; Snir et al. 2003). This study showed that curriculum designed to allow students ideas to build over time with teachers who implement the unit helps students to do this. Our study found that this started with students' creation and critique of their own models to explain phenomena that account for their observations of phenomena. Results showed that as students gathered more evidence from phenomena, they were able to draw more sophisticated models, especially at the particle level. Learning progressions have been proposed as a means to address the need for curriculum and assessments that can help teachers improve their practice as well as to inform both students and teachers about students' performance. Wilson (2005) and Wilson and Sloan (2000) propose that one method for linking assessments to learning progressions is through the use of progress variables (Wilson 2009). Moreover, progress variables have been proposed as a method to tracking student performance during instruction (Wilson 2005, 2009). This study demonstrated that the PMM progress variable, developed for a curriculum unit designed to be coherent, can track student progress toward a PMM during instruction. Student performances on the embedded assessments indicated that students made gains in their proficiency as they experienced the unit, achieving higher levels of proficiency during instruction. Although average student performance dips to the "basic" level on the posttest, the results showed that students were able to develop a PMM by the end of the unit. It is important to realize that the performance on the posttest was not supported. Thus, the development of the progress variable provided the opportunity to track students' progress prior to, during, and after instruction. Furthermore, results showed that the instructional strategies helped students to develop a particle view of matter.

Scoring guides were developed for this study that aligned with the levels of the progress variable, which were delineated through the construct map. As the construct map also reflects the learning goals and instructional sequencing of the curriculum, it also points out the importance of embedded assessments tied to the learning goals of a curriculum (Kennedy et al. 2005). Therefore, the validated PMM progress variable could now be used by teacher and students to track student progress. Moreover, teachers could use the PMM progress variable to track students during instruction and provide feedback to students.

Results showed that students performed consistently better from pretest to the last lesson of the unit. Student performances on the embedded assessments indicate that students make significant gains in their proficiency as they experience the unit, achieving higher levels of proficiency. Thus, the development of this progress variable provided the opportunity to identify the range of models students created prior to and during instruction. Results show that the instructional strategies of the sixth grade IQWST chemistry unit help students develop a particle view of matter.

There were several limitations to this study. We anticipated that there would be some teacher effects as well as fidelity issues related to students' performance. During this study, we did not collect videos of instruction or interview the teachers about their experiences with the unit. This information could provide more insight into differences in student performance as they experience the unit as well as their performance on the posttest. Although this information was not collected, it does not affect the ability to track students understanding as they experience the unit. However, it does show that more work is needed in terms of both understanding fidelity to curriculum as well as documenting strategies teachers implement in supporting their students in progressing toward a particle view of matter.

Second, the embedded assessments consist of only two questions that are identical in content. Although having only two items does not limit the ability to determine estimation parameters for these items, having more items would provide better estimates of the construct. Moreover, there are several other embedded assessments that could also be utilized to better analyze students' particle view of matter in relationship to phase changes, states of matter, and properties of substances.

Finally, all the teachers that participated in the study did not return the embedded assessments as well as the pretests and posttests. Despite constant communications and reminders to send these items, many teachers did not send complete data. As a result, only three teachers returned complete materials. Although this was less than ideal, it did not inhibit our ability to track students understanding in three different locations.

In sum, a curriculum that is designed to help students to explain new phenomena through the practice of modeling with teacher who implement the curriculum using the intended practices can support students in developing a PMM. As students experienced the unit, results indicate that the particle model of matter progress variable could be used to track students' understanding during instruction. In addition, results show that students can develop a "complete" particle view of matter during instruction. Utilizing the PMM progress variable, most students moved from a "mixed" to a "basic" view of matter with a number of student reach the complete model by the posttest. This is reflected in students learning gains from pre- to posttest and in the increased sophistication of the models students created during instruction.

Now that the PMM progress variable has been validated, it provides the opportunity to return to the classroom to evaluate its use during instruction. The linking of instruction to assessment is vitally important to obtain a complete picture of how closely teachers are following the curriculum, what modifications they make to the curriculum, and how they utilize the embedded assessments to inform their practice, evaluate student progress, and provide feedback to students. Thus, teachers could be instructed to use the scoring guide to evaluate student progress to help them in understanding their students' progress as well as to provide feedback to students. The progress variable could also be used as evidence for learning progressions that span multiple grades. However, this is only one approach for supporting students in the development of a PMM. More work is needed to assess how other instructional strategies help students' progress to a PMM.

**Acknowledgments** This research was conducted as part of the Investigating and Questioning our World through Science and Technology (IQWST) project and the Developing an Empirically-Tested Learning Progression for the Transformation of Matter to Inform Curriculum supported in part by the National Science Foundation Grants ESI 0101780 and DRL-0822038, respectively. Any opinions expressed in this work are those of the authors and do not necessarily represent either those of the funding agency or the University of Michigan and Michigan State University.

## Appendix

Lesson Descriptions and Learning Performances for the *How can I smell things from a distance?* Unit

| | Lesson no. | Description | Learning performance |
|---|---|---|---|
| Learning set 1 | 1 | Students smell odors coming from two jars, recognizing that the jar must be open in order to smell an object. During this investigation, students draw pictures and write descriptions that represent their understanding. Next, the teacher facilitates a discussion to help students think about (a) how odors travel and (b) how scientific models help them to understand and explain this phenomenon | Students construct initial models to help them explain how odors travel across a room<br>Students describe one purpose of a scientific model |
| | 2 | Students measure the mass and volume of different substances, including an inflated/deflated ball to understand that odors and air have mass and occupy space (have volume) and conclude that anything with mass and volume can be called "matter" | Students describe air as occupying space (having volume) and having mass<br>Students identify the relationship between the amount of a substance and the measured mass of that substance<br>Students characterize things as matter (or not matter) based on whether they have mass and volume |
| | 3 | Students classify materials as solid, liquid, or gas. Students learn that matter can go through phase changes by observing the melting and cooling of menthol. As an optional activity, students can also observe the phase changes of water | Students identify and describe materials in three states of matter, using scientific terminology (solid, liquid, gas)<br>Students describe and compare the characteristics of solids, liquids, and gases<br>Students describe typical changes of states that occur when substances are heated or cooled<br>Students provide examples of materials changing states |

(continued)

(continued)

| | Lesson no. | Description | Learning performance |
|---|---|---|---|
| | 4 | Students investigate the ability of air to be added and removed, expanded and compressed in closed systems, using their own models to explain them. Through the critique of their models, students begin to understand that the building blocks of matter are particles. Empty space between the particles explains addition, subtraction, compression, and expansion | Students construct and revise models to explain and account for all of the following phenomena: subtraction, addition, compression, and expansion of gas in a closed container |
| | 5 | Students develop an understanding that matter, in the gaseous state, contains particles that constantly move in linear motion by observing indicator paper changing color without being dipped in two different liquids. Students also view a simulation of odor traveling in a room with air. By the end of this lesson, the class develops a consensus model for the particle model of matter | Students construct models of the particle nature of gases<br>Students use their models to explain why indicator paper changes color and how smell travels<br>Students describe evaporation as particles of liquid changing phases to particles of gas without boiling |
| Learning set 2 | 6 | Students observe and record the emission spectra of different gases. Through discussion of their data and modeling of different gases, students come to the idea that different materials have different properties; thus, we can distinguish among materials based on their properties | Students compare one substance to another, based on their properties |
| | 7 | Students are introduced to the elements of the periodic table and the physical properties of elements, by observing and investigating different elements. Students use their results to explain that the elements have different properties because they are made up of different types of atoms. Students are also introduced to fundamental concept of the atom – as a basic particle of all elements | Students compare several elements to one another, based on observable properties and uses<br>Students define what an element is using the concept of atoms (and not particles) |

(continued)

(continued)

| Lesson no. | Description | Learning performance |
|---|---|---|
| 8 | Students create molecular models of oxygen, carbon dioxide, nitrogen, and water using gumdrops, Styrofoam balls, or other molecular modeling kits to represent atoms and molecules. The molecular models are then placed in a clear bag to represent air as a mixture of gases. The teacher facilitates discussions to help students understand these models and to introduce molecules as being composed of more than one atom that "stick" together and that different molecules make up different substances | Students use physical representations to explain the relationship between molecules and atoms<br>Students identify a sample item as either a substance or a mixture on a molecular level |
| 9 | Students rotate through stations smelling different substances. Each station will include a 2-D image of the molecule. Students recognize the fact that the same atoms (C, H, O) can be in different arrangements and that these different arrangements make a new substance with new properties (in this lesson, a different odor) | Students explain that different smells are caused by different arrangements of atoms in a molecule, using molecular models |
| 10 | Students observe the time it takes ammonia vapors at different temperatures to reach indicator paper | Students predict how molecules move at different temperatures |
| | Students revisit the virtual simulation of air and odors in a room, manipulating temperature to show the difference in molecular movement at higher and lower temperatures | Students describe what happens to the molecules in a gas when it is cooled and heated<br>Students construct models to demonstrate that molecules have different speeds at different temperatures<br>Students explain why an odor moves faster at higher temperatures |

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| Lesson no. | Description | Learning performance |
|---|---|---|
| 11 | Students observe the cooling and heating of a balloon placed in and removed from a dry ice bath. Students use the particle model to explain their observations. Finally, a mechanical model is used to demonstrate the relationship between temperature and volume in the heating and cooling of gases | Students describe what happens to the molecules in a gas when it is cooled and re-heated<br>Students explain the relationship between temperature and volume of gases |
| 12 | Students observe the heating and cooling of bromine and create models of bromine in both the gas and liquid phase to help understand the process of evaporation. Then, students observe the evaporation of alcohol and water from two different surfaces to understand that different substances, which are composed of different molecules, have different evaporation rates. Third, a teacher demonstration of water boiling is used to explain the process of boiling and what happens as a liquid undergoes a phase change to gas. Students model the process of boiling to develop understanding of this process. Finally, students observe the process of condensation, through water condensing and evaporating in a bottle and the condensation of water on the outside of a plastic cup filled with ice water | Students explain phase changes from gases to liquids and liquids to gases at the molecular level |
| 13 | Students observe the expansion of water when it is heated and create physical models to explain their observations. Students then use their models to predict what happens when dye is added to hot and cold water. Students discuss whether their predictions match their observations and revise their models accordingly | Students describe the difference between liquids at different temperatures, including the fact that liquids expand upon heating<br>Students explain the difference between liquids at different temperatures using a particle model |

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| Lesson no. | Description | Learning performance |
|---|---|---|
| 14 | Students observe the phase change from a solid to a liquid by observing ice melting and through a teacher demonstration of melting an unscented, paraffin wax candle, creating models of solid and liquid water (or wax). Students observe sublimation using dry ice. Teacher reviews the menthol experiment (Lesson 3) and students create models of the molecules in the solid, liquid, and gaseous states | Students explain phase change from a solid to a liquid and from solid to a gas (sublimation), using the particle model<br>Students explain different states of same substance, including in their explanations that the particles are the same but behave differently |
| 15 | Students revisit the models they created during Lessons 1 and 5 and create models of smell. The class reviews what they learn and develop a class consensus particle model. Then, students use their consensus model to address a real-world problem | Students evaluate models (compare and critique their models of odor)<br>Students explain a related phenomenon, which is presented in a format of a short newspaper article, using the particle model<br>Students create a poster/brochure suggesting a solution to a real-world problem |

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