Development of a Learning Progression for the Particle Model of Matter

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Abstract: Prior research indicates that one of the most difficult concepts for students to understand is that of the particle nature of matter. The *How can I smell things from a distance?* chemistry unit takes the approach of building students' ideas through the construction and revision of models. The purpose of this study is to describe the changes in students' understanding of the particle nature of matter as they were engaged in an eight-week model-based curriculum. One teacher and her two 6th-grade classes in a midwestern school district were the focus of the study. Data sources include pre- and posttests, students' artifacts, and video recordings of the curriculum enactment, including students' creation of models of various phenomena. Results from this study were used to help develop a learning progression for the particle nature of matter.

Introduction

The particle nature of matter is the foundation for understanding a myriad of science phenomena including properties, phase change, and chemical reactions. As such, particle theory has been an intense area of research around the world. In Israel, Novick and Nussbaum (1978) studied students' ideas about the particle nature of matter as it relates to gases. They found that students did not internalize ideas related to the vacuum concept (empty space), the intrinsic motion of particles, or the interaction between particles during a chemical change. Philip Johnson, a British researcher, completed a longitudinal study related to students' understanding of substances and phase changes (1998). He found that students took varying paths towards a particle model. Australian researchers, Harrison and Treagust (2000) have looked at the importance of helping students to develop modeling skills when learning the particle model. In the United States, Lee et al. (1993) found that students had a difficult time explaining macroscopic phenomena on a molecular level. These studies represent only a tiny fraction of the research surrounding students understanding of the particle nature of matter and the challenge to learn particle concepts due to curriculum and instruction.

One reason students find it difficult to learn the particle model is that traditional curriculum materials just present the ideas to students without helping them to develop these ideas. Typically, the particle nature of matter is introduced in either a short paragraph, or as a chapter on the atom and the history of the atom (Harrison & Treagust, 2002). Often students don't develop appropriate ideas because they never apply and reapply these ideas to explain phenomena. One method for helping both students and teachers to track students' developing understanding of this difficult construct is learning progressions (Duschl, Schweingruber, & Shouse, 2007; Smith et al., 2006).

Learning progressions are depictions of students' increasingly sophisticated ideas about a specific domain over time. A progression ranges from the simple to complex understanding of a domain. In addition to studies regarding student understanding, several interview studies have been completed that suggest there is a learning progression for understanding the particle nature of matter (Renstrom, Andersson, & Marton, 1990; Johnson, 1998; Nakhleh, Samarapungavan & Saglam, 2005; Liu & Lesniak, 2006; Margel, Eylon & Scherz, 2007). Smith et al. (2006) have proposed a learning progression for students in K-8 for matter and atomic-molecular theory. This 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 to using microscopic explanations of macroscopic phenomena.

We attempt to further this work by starting the development of a learning progression for the particle nature of matter during an 8-week curriculum in which students use particle ideas to explain macroscopic phenomena. To begin the development of this progression, we focused on our study of how 6th grade students' understanding of the particle nature of matter changed as they participated in a contextualized and model based unit in chemistry. And much like Smith et al., we used prior research as well as logic of the science as the start to the development of our learning progression. In this paper, we discuss our initial development of a learning progression for the particle nature of matter.

Curriculum

The *Investigating and Questioning our World through Science and Technology (IQWST)* project (Krajcik, McNeill and Reiser, in press) takes the approach of building student's ideas over time. This study focuses on the 6th grade chemistry unit of the IQWST curriculum entitled "How can I smell things from a distance?" This unit emphasizes modeling as an important scientific practice for students to learn, as well as to help students understand the particle nature of matter. Modeling was chosen because the particle nature of matter is: 1) an abstract concept and 2) is used to explain a range of phenomena. In addition, models allow the visualization of explanatory frameworks. The IQWST approach to modeling involves students creating models to explain phenomena and then reflecting on how the model accounts for these phenomena. Students build towards a consensus model and then experience new phenomena to add onto this model. Moreover, students evaluate the models ability to account for new phenomena and revise them accordingly. Most important for our study, the models that students develop provide a window into both students' ideas and their prior knowledge.

We have designed a unit in which learning the particle model of matter is contextualized through the use of a driving question. The development of a driving question (Krajcik & Blumenfeld, 2006) serves to: 1) produce a context for students to learn about scientific phenomena and 2) anchor students learning within a context. In our unit, students' knowledge is the basis for instruction and discussion. Thus, students' models provide a window for teachers into their students' thinking. Students' models are revisited throughout the curriculum so that students can apply both their real-world experiences and what they have learned through experiencing phenomena to their answering of the driving question. Moreover, the anchoring context is revisited throughout the completed curriculum as students gain greater knowledge and understanding of concepts related to the phenomena studied and enable them to answer the driving question, "How can I smell things from a distance?"

The approach of this unit is for students to experience different phenomena that help them come to a consensus about the particle model of matter. The unit contains three learning sets. The first learning set (lessons 1-5) focuses on helping students understand what matter is (anything that has mass and volume and exists in one of three states) and to develop a consensus model of matter: matter is composed of particles, there is empty space between the particles and the particles are constantly moving. Learning Set 2 (lessons 6-9) helps students understand properties and that properties are a result of the arrangement of atoms in a substance. Thus, students are now able to detail what the particles are (atoms/molecules) in their consensus model. Learning Set 3 (lessons 10-15) involves students applying their model of matter to explain phase changes. Students can now incorporate the effects of energy (in this case temperature) on the movement of the particles into their consensus model.

Embedded Assessments

The initial pilot study of the unit identified the modeling activity of lesson 1 as not only a way for teachers to elucidate students' initial notions of the particle nature of matter, but also as an activity that could be repeated throughout the unit to assess students' understanding. (Student models are defined as their drawing plus explanation.) Thus, we identified points along the curriculum in which we thought students were likely to have learned enough to cause them to revise or create new models to explain how smells travel. As Kennedy et al. (2006) note, it is important to incorporate embedded assessments at "critical junctions where we wanted to make sure students were adequately prepared to learn the next segment of the curriculum" (p. 4). Thus, the same modeling activity from lesson 1 was added to lessons 5 and 15 for the purpose of monitoring students' learning.

The focus of this study was to understand how students' understanding of the particle nature of matter changes over time as they experience new phenomena and grapple with how to account for these new phenomena. In order to track students understanding over time, we looked at pre and posttest learning gains as well as student models at specific points throughout the unit. Thus, we sought to answer the following research question in this study: *How does students' understanding of the particle model of matter change over time as they construct models to explain phenomena?*

Methods

This study reports our findings from one teacher's two classes of students in a large Midwest college town who enacted the 8-week *Smell* unit. The students were from various ethnic and socioeconomic backgrounds and differing academic abilities. The teacher has had previous experience in piloting reform-based curricula. In sum, 57 students participated in the study.

Data Collection and Analysis

Student Artifacts

All students completed pre- and posttests that included 18 multiple-choice questions and 3 open-ended items (maximum score of 18 for both sections). The multiple-choice items covered the key learning goals of the unit: particle nature of matter, phase change, and properties. Rubrics were created to analyze students' pre/posttest open-ended items. There were two scorers for the open-ended items. We randomly sampled 20% of the open-ended test items, which were scored by a third independent rater. Percent agreements were used to estimate inter-rater reliability for each open-ended item. Inter-rater agreement was above 90% for each component of each question.

In addition, a rubric was created for the activity sheets which was based on those developed for the open-ended test items. Originally, students were allowed to take home their work. This resulted in the collection and analysis of only 43 students' worksheets.

Findings and Discussion

Overall Student Learning Gains

A paired samples t-test was used to examine the change in students' knowledge of key learning goals was using a paired samples t-test. Table 1 provides the overall learning gains for students. The total score is the sum of scores on open-ended items and multiple-choice items. Questions related to content items (phase change and particle nature of matter) include multiple-choice and open-ended questions. Most of the items related to phase change also included aspects of the particle nature of matter in that they ask students to explain macroscopic phase changes on a microscopic level. Students had the largest learning gains with items related to the particle nature of matter and phase changes. Overall, students achieved significant learning gains from pre- to posttest.

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Table 1: Overall Student Learning Gains (n = 57)

Items (Max Score)	Pretest Mean (SD)	Posttest Mean (SD)	Gain (SD)	Effect Size[a]
Total (36)	16.87 (4.09)	28.18 (5.17)	11.26 (4.97)	2.77***
Multiple Choice (18)	8.75 (2.98)	14.19 (2.87)	5.44 (2.98)	1.83***
Open Ended (18)	8.41 (2.14)	13.99 (3.11)	5.52 (3.27)	2.58***
Content Items				
Phase Change (13)	5.42 (1.98)	10.16 (2.36)	4.74 (2.68)	2.39***
Particle Nat. (18)	7.64 (2.43)	14.61 (2.91)	6.97 (3.24)	2.87***

*** $p < .001$

[a] Effect size: Calculated by dividing the difference between pre and posttest mean scores by the pretest standard deviation

Next, we examined students' learning gains related to the modeling open-ended test items. For each modeling question, the model was assessed for its content, type and explanation. The content refers to the relevant concepts included in the model. For example, Question 2 asks students to chose whether a smell would reach them faster from a cold room, a warm room or at the same time. The drawing portion of the model must then reflect the affect that different temperatures have on the movement of the odor molecules. The highest scored model for Question 2 includes air and odor molecules, movement, empty space and includes the effect that temperature has on the movement of the particles.

Type is a subcategory of content. It refers to whether the model is continuous, mixed or particle, with particle model receiving the highest score. This data was reported separately to indicate the types of models started out with and where students ended up. Table 2 shows that for this modeling item, students showed significant learning gains.

Question 2 deals with the aspects of smell that students have learned throughout the unit. This question provides insight into what students' initial ideas are about how smell travels as well as whether they think temperature has an affect on how fast the odor travels. Initially, many students have a continuous view of smell and incorporate the idea that warmer air rises and cooler air falls in their answers. By the end of the unit, most students' responses to this question indicate they have a particle view of matter and that temperature affects the movement of matter.

Mark's responses to open-ended item 2 (see Figure 1) represent the typical responses to this question, especially in relation to the types of models and details students included in their model. In the pretest (Figure 1a), Mark represents the air freshener as continuous, rising in the warm room and sinking in the cold room. Air is not represented in this model. In his explanation for part C of the question, Mark indicates that he believes that cold air moves faster than warm air. By the end of the unit (Figure 1b), Mark has a particle view of both air and odor. In the posttest, Mark represents air and odor molecules as moving through the use of arrows. Longer arrows indicate more movement. In the written portion of his response, Mark explains that the warm room provides more energy for the air and odor molecules to move. In addition, he describes the random motion of the particles.

Open-ended item number 4 asked students to create a model to explain what happened when a small corked jar filled with bromine gas is opened while inside a larger jar filled with air. Students' learning gains for this item were very similar for this item.

Table 2: Learning Gains for Modeling Open-Ended Question 2

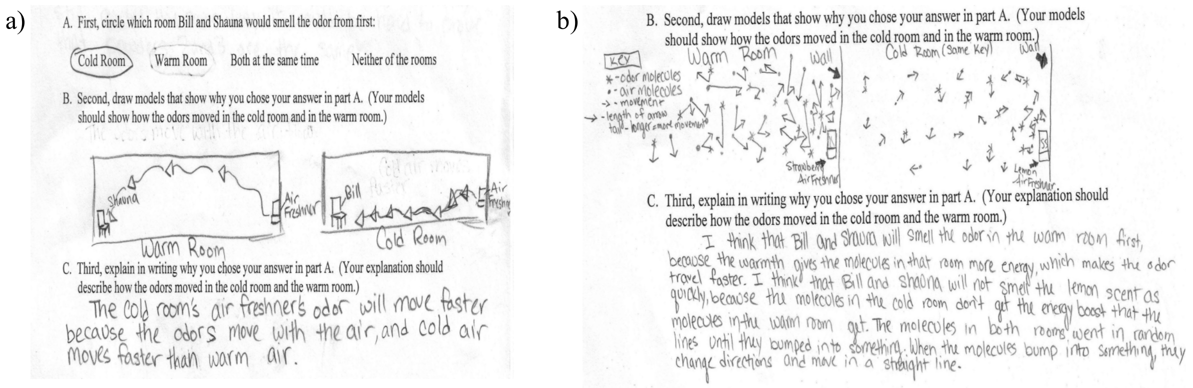
Items (Max Score)	**Pretest Mean (SD)**	**Posttest Mean (SD)**	**Gain (SD)**	**Effect Size**[a]
Question 2 (9)	4.19 (1.31)	7.01 (2.05)	2.82 (2.34)	2.15***
Room Choice (1)	0.64 (.49)	0.96 (.19)	0.33 (.51)	0.67***
Content (4)	1.40 (0.79)	3.08 (0.92)	1.68 (1.15)	2.13***
Type (0.6)	0.12 (.22)	0.50 (0.21)	.38 (0.30)	1.73***
Explanation (4)	1.27 (.655)	2.52 (1.14)	1.25 (1.28)	1.91***
Question 4 (6)	2.26 (1.28)	4.81 (1.59)	2.56 (1.87)	2.00***
Content (4)	1.37 (0.81)	2.84 (1.06)	1.47 (1.28)	1.81***
Type (0.8)	0.15 (0.30)	0.64 (0.31)	0.49 (0.39)	1.63***
Explanation (2)	0.76 (0.53)	1.34 (0.63)	0.58 (0.68)	1.09***

*** $p < .001$

[a] Effect size: Calculated by dividing the difference between pre and posttest mean scores by the pretest standard deviation

Embedded assessment: Modeling the same phenomena

The lesson 1 anchoring activity of the Smell unit involves students creating models (student models are defined as their drawing plus explanation) to explain why they think they can smell an object from a distance. This modeling activity is repeated in lessons 5 and 15 of the curriculum and serves as a means to monitor students' learning. Analysis of students' artifacts indicates that in general, students produce more accurate models (see Table 3), with more accurate explanations as they progress through the unit. For example, figure 2 shows the changes of one student's model as he progressed through the unit. The model in figure 2(a) is a continuous model, which over 45% of students created in the first lesson. Half the students included only odor in their models and 87% gave descriptions of their models such as "The odor is coming out of the source".



a)

A. First, circle which room Bill and Shauna would smell the odor from first:

[✓ Cold Room] Warm Room Both at the same time Neither of the rooms

B. Second, draw models that show why you chose your answer in part A. (Your models should show how the odors moved in the cold room and in the warm room.)

C. Third, explain in writing why you chose your answer in part A. (Your explanation should describe how the odors moved in the cold room and the warm room.)

The cold room's air freshner's odor will move faster because the odors move with the air, and cold air moves faster than warm air.

b)

B. Second, draw models that show why you chose your answer in part A. (Your models should show how the odors moved in the cold room and in the warm room.)

C. Third, explain in writing why you chose your answer in part A. (Your explanation should describe how the odors moved in the cold room and the warm room.)

I think that Bill and Shauna will smell the odor in the warm room first, because the warmth gives the molecules in that room more energy, which makes the odor travel faster. I think that Bill and Shaona will not smell the lemon scent as quickly, because the molecules in the cold room don't get the energy boost that the molecules in the warm room get. The molecules in both rooms went in random lines until they bumped into something. When the molecules bump into something, they change directions and move in a straight line.

Figure 1. Example of Mark's pretest (a) and posttest (b) models, open-ended item 2.

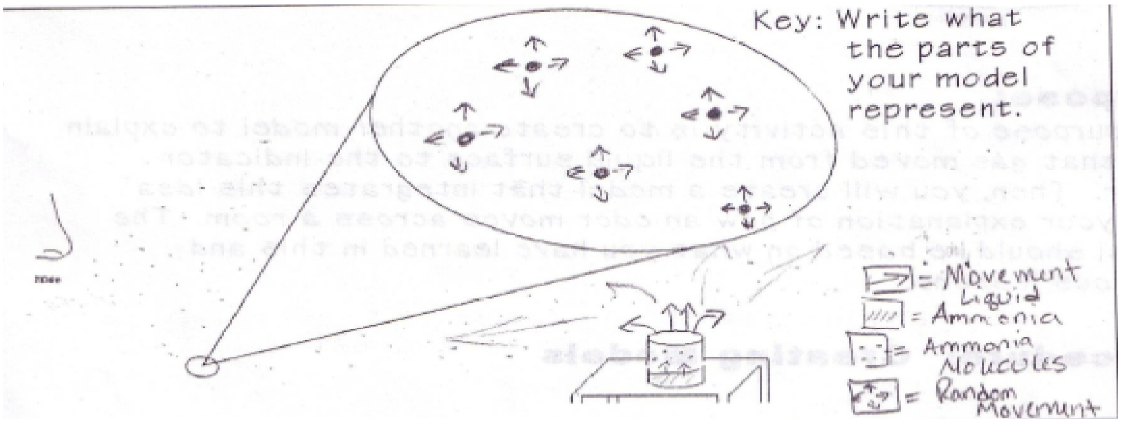
Table 3. Types of models students created

Model Type	**Lesson 1 (%)**	**Lesson 5 (%)**	**Lesson 15 (%)**
Continuous	45.5	2.3	0
Mixed	34.1	45.5	25
Particle	20.5	52.3	75

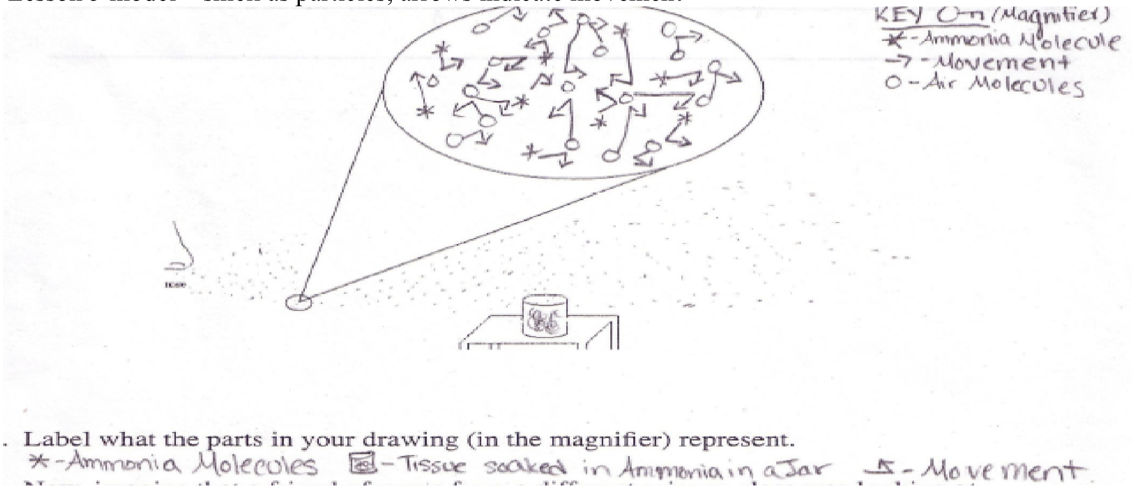
The lesson 5 model (see Figure 2(b)) now represents odors as particles and that the particles are moving in all directions. In fact, 52.3% of students created a particle model at this stage of the curriculum. Other students created a mixed model (45.5%). A key feature of student models at this point is that 70.5% now include particles with some indication of movement. In addition, students' written descriptions of their models now are trying to explain the phenomena, albeit with the incorrect mechanism. Mark describes what is happening as follows: " Molecules in the liquid come off the surface of the liquid and become a gas. They move around and change direction when they come in contact with another object."

The lesson 15 model (see Figure 2(c)) represents odor and air molecules that are moving in straight lines until they collide with another air or odor molecule. At this last lesson in the unit, 75% of students created a particle model of matter, while 25% created a mixed model of matter. Moreover, 68% of students included odor particles that are moving in straight lines until they collide with each other. The remaining 32% of students included both odor and air in their models. Finally, most students have moved from a written description of their model, to writing about how their models explain how an odor moves across a distance.

(a) Lesson 1 model – smell as waves



(b) Lesson 5 model – smell as particles, arrows indicate movement



(c) Lesson 15 model: air and ammonia molecules, movement includes molecules bouncing off one another.

Figure 2. Changes in Mark's models of the same phenomena

Overall, a majority of students move to a particle model of matter throughout the curriculum. Students' models also indicate that they also include the motion of particles. The motion of particles included in students' models becomes more sophisticated as they add notions of particles in the gaseous state moving in straight lines until they bump into each other. In addition, there are students who include empty space as a labeled concept in their model. We used these findings towards the development of a learning progression for the particle model of matter.

A Learning Progression for the Particle Model of Matter

Based on these findings and previous research, we began the development of an initial learning progression for the particle model of matter. This progression shows how students' understanding of the particle model develops over time. Figure 3 encompasses the various starting points students had during the curriculum, as well as their varying endpoints. As we have defined students' models as both their drawing and their explanation, our initial learning progression reflects students' increasingly sophisticated understanding of the particle model as it relates to both their drawings and their explanations. We developed this progression 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 a curricular intervention. The simplest understanding is represented as level 0, with the most complex understanding represented by level 6.

Increasing complexity

Level	Category	Particle Model
6	Complete Particle	All relevant substances are made up of particles. Particles are identified as atoms/molecules. The particles are in motion relevant to a particular state, for example, in the gaseous state, there is empty space between the particles and the particles move randomly.
5	Basic Particle	All relevant substances are made up of particles. There is empty space between the particles. The particles are in motion.
4	Incomplete Particle	A substance is made up of particles. There is empty space between the particles.
3	Mixed	Combines both particle and continuous ideas. The substance is made up of particles within a continuous medium.
2	Continuous	No notion of particles,
1	Descriptive	Describes what is happening in words and/or draws an exact replica of phenomena
0	No response	No response or nonsense response.

Figure 3. Learning Progression for the Particle Model of Matter

We use one student's assessments to illustrate how the learning progression works. Both Mark's pretest (see Figure 1a) and Lesson 1 model (see Figure 2a) represent level 2 models. Mark's models are typical of students in the two classes at this stage of development. Between lessons 1 and 5, students experience phenomena and complete instructional tasks that support them in developing an understanding that matter is made up of particles and that there are empty spaces between these particles. By the end of the unit, most students in this study had either a level 5 or 6 model. Mark exhibited a level 6 model in both the last model he created for the unit (see Figure 2c) and in his posttest (see Figure 2a).

Conclusion

The particle nature of matter is a fundamental science concept for understanding a myriad of phenomena. Research also indicates students have had a difficult time learning this key idea (Novick & Nussbaum, 1978). Learning progressions have been proposed as a means for tracking student learning. We developed a learning progression that shows how students' ideas of the particle model develop across time. We developed this progression through an iterative approach of considering the logic of the subject matter, what was known about student understanding of the particle model and what we learned through our own empirical work. This work extends the work proposed by Smith and colleagues (Smith, et al., 2006) by showing the development of students' understanding of the particle model through a curricular intervention.

We have found that a model-based curriculum helps students to gain understanding of the particle nature of matter. In addition, we found that most students can move from a continuous to a molecular view of matter, which is reflected in: 1) students learning gains from pre- to posttest and 2) the increased sophistication of the models students created during instruction. Analysis of student models also indicates that students take different paths towards developing a particle model of matter. This progression is important because it shows us where students' understanding begins and how their understanding develops. Moreover, it gives us the ability to track students understanding during the enactment of the unit. This study is the beginning of a progression, which can influence future studies in science, particularly chemistry.

During our development of the progression, we have been able to identify lesson 4 (which includes students investigating expansion and compression of air) as important to students understanding the concept of empty space between the particles. Although this progression has been developed partially based on findings from our study on 57 studies, it will be further refined through later studies. In these studies, we plan to further refine the development of our learning progression. This will involve examining student pre/posttests and artifacts from more than 3,000 students across the United States. In addition, we hope to expand our progression to follow students from 6th grade (phase changes) to 7th grade (chemical changes). Through these studies we hope to identify which lessons are critical for helping students to reach a new level, the range of starting (and ending) points for students and what effect students' starting points have on how they transition to new levels of understanding.

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