Developing Kindergarten Students' Conceptions of Microscopic Properties of Matter Through Modeling-Based, Technology-Enriched instructions

Ala Samarapungavan, Purdue University

Bima Kumari Sapkota, Purdue University

Lynn A. Bryan, Purdue University

Carolyn Staudt, The Concord Consortium

Alaina Glidden, Purdue University

Jamie Broadhead, The Concord Consortium

Hector Emilio Will Pinto, Purdue University

Krista Hook, Purdue University

Corresponding Author:

Ala Samarapungavan, Purdue University

Dept. of Educational Studies, BRNG

Email: ala@purdue.edu

Abstract

This mixed-methods longitudinal study investigated kindergarten students' developing models of matter through participation in technology-mediated, inquiry-based modeling instruction implemented by their regular public-school teachers. One hundred and thirty-nine students from seven classrooms investigated the properties of matter in solid, liquid, and gas states and during phase changes, constructing model inscriptions in their science notebooks to represent these properties. Individual interviews were conducted to assess changes in students' models of matter before and after instruction. Analysis of science notebook inscriptions during learning and interview data showed that kindergartners moved from initial macroscopic descriptions to particle-based representations of matter as they progressed through the curriculum. The findings suggest that young learners can fruitfully construct and use simple particle-based models of matter.

Objectives

This study is part of the Sensing Science through Modeling (S2M2) project (Staudt, Bryan, Samarapungavan, & Foreman, 2016). It aims to field-test a technology-integrated, inquiry-based modeling curriculum (Bryan & Samarapungavan, 2017) designed to teach kindergarten students about the properties and behavior of matter in different physical states (solid, liquid, and gas) and during phase transitions (melting, freezing, evaporation, and condensation). Data from a pilot implementation showed that kindergarteners learned particle models to explain the properties of matter in solid, liquid and gas states but explaining phase changes was challenging for them (Samarapungavan, Bryan, & Staudt, 2019). The pilot data guided S2M2 curriculum revisions around three digital tools, the Thermoscope, Particle Modeler (Kimball, Forman, & Staudt, 2019), and Thermonator (Staudt et al., 2015) to support children's modeling of particle behavior. In this study, seven public school teachers implemented the revised S2M2 curriculum. Our analysis of learning was guided by two research questions: (1) Do children's particle models of matter differ across pre- and post-instructional interview assessments? and (2) How do kindergarten students' model inscriptions change as they progress through S2M2 investigations?

Theoretical Framework

Historically, science educators have assumed that scientific concepts derived from kinetic-molecular theories of matter are too abstract and far removed from children's everyday experiences to be taught in the early grades (Snir et al., 2003; Stevens, 2010). In the United States, students do not receive formal instruction about the particulate nature of matter until upper elementary/middle school. However, research shows that adolescents and adults often struggle to learn kinetic-molecular models, suggesting that the delayed introduction of particle models is not necessarily beneficial (Talanquer, 2009, 2018).

In the last three decades, developmental research has shown that young children can learn abstract causal principles and reason mechanistically (e.g., Gopnik et al., 2017; Keleman, 2019). This work has inspired educators to rethink the possibilities for introducing key disciplinary concepts to young children. For example, research suggests that preschoolers posit the existence of tiny unseen particles in certain contexts. Children from 3 to 7 years of age believe that when sugar is dissolved in aqueous solutions, tiny invisible particles of sugar continue to exist, affecting the solution's taste (Au, Sidle, & Rollin, 1993; Rosen & Rozin, 1993). Liu & Lesniak (2006) found that early elementary students ascribe materiality to invisible particles in the context of mixing and dissolving. Based on this research, we conjecture that one can fruitfully introduce simple particle models in early science instruction.

Drawing from social-cultural perspectives, we posit that kindergarteners can learn simple particle models by engaging in discourse-scaffolded practices of sensemaking around familiar phenomena, aided by digital tools that connect particle behavior to macroscopic observations of matter (Gordin, Polman, and Pea, 1994; Odden & Russ, 2019; Rogoff et al., 2018). Researchers have found that model-based inquiry can support second graders' learning of particle models to explain material phenomena (Samarapungavan, Bryan, & Wills, 2017). Scaffolded discourse around technology-mediated dynamic visualizations of particles supports young children's conceptualizations of microscopic properties of matter (Jakab, 2013; Staudt et al., 2015). Building on recent research, this study examines kindergarteners' learning of simple particle models through their engagement with a technology-mediated, model-based curriculum.

Methods

This is a mixed-methods longitudinal study. Table 1 summarizes the design. In School 1 (a public school in a small Midwestern city), three kindergarten teachers and their students (n=56) implemented S2M2-Technology 1 lessons which employed the Thermoscope and the Particle Modeler digital tools. In Schools 2 and 3 (metropolitan public schools in the Northeast), participants included four kindergarten teachers and their students (n=83). Two of these teachers also implemented S2M2-Technology 1 lessons. The other two teachers implemented S2M2-Technology 2 lessons, which employed the Thermoscope and Thermonator digital tools.

The curriculum comprised of three multi-day lessons (see Table 2) implemented over 12 class periods, twice a week: Lesson 1 introduced students to the nature and use of models in science. Lesson 2 helped children identify macroscopic properties of substances in solid, liquid and gas states (for example, liquids take the shape of their container) and to explain these properties in terms of the behavior of constituent particles. Lesson 3 extended the use of particle models to explain phase transitions (melting, freezing, evaporation, and condensation) as substances gained or lost heat.

The lessons were structured as model-based inquiry cycles. The first lesson introduced children to the scientific practice of modeling. In the culminating activity of the modeling lesson, students explored particle models of hot and cold water with the Thermoscope (Figure 1). Digital probes measuring the temperature of the observed materials connected to a Thermoscope screen displaying dynamic simulations of their particle behavior. In the second lesson, students first engaged in whole class discussions to identify macroscopic properties of exemplar liquids (vegetable oil and dish soap) and solids (wood and rock). Next, they constructed model predictions for the oil in their science notebooks, using strategies of drawing, invented spelling, and telling an adult helper what to write. Students then used the Thermoscope to investigate particle models of oil. Technology 1 students followed Thermoscope investigations by using the Particle Modeler to construct a model for liquids. The Particle Modeler (Figure 1) presented a beaker-shaped container into which students could drag and arrange particles to model matter. Students could use *Heat* and *Cool* buttons to speed up or slow down the particles in their model and open or shut the “lid” of the container to explore how these changes affected particle arrangement and behavior. Technology 2 students followed Thermoscope investigations with Thermonator explorations (Figure 1), creating particle models by manipulating combinations of four properties: speed, attraction, elasticity, and gravity. The students then repeated the investigation with dish soap. The activity cycle concluded with a whole class discussion of students' models of liquids in which the teacher and students co-generated an explanation of macroscopic properties/behavior of liquids in terms of the arrangement and movement of constituent microscopic particles. This inquiry cycle was repeated with the exemplar of solids (wood and rock), and finally with gas (air). Figure 2 presents an example of whole class discourse to scaffold children's sensemaking with the Thermoscope.

---Insert Figure 1---

---Insert Figure 2---

Data Sources Coding and Analysis

1. Models of Matter-Kindergarten (MMK), a semi-structured interview, was administered to students individually before and after S2M2 instruction. The interview comprised of two sets of questions: *States of Matter (SOM)* questions assessed students' models using exemplars of matter for solid (Q1 cube of green clay), liquid (Q2 vial of maple syrup), and gas (Q3 air in Ziploc bag). *Phase changes (PC) questions* examined students' models for evaporation (Q4), melting (Q5), freezing (Q6), and condensation (Q7). Examples of SOM and PC questions are provided in Figures 3a-b.

---Insert Figures 3a-b---

MMK responses were coded using cognitive science bootstrapping techniques for analyzing verbal protocol data (Chi, 1997; Samarapungavan et al., 2017). Initial *item level* coding focused on responses to individual question sequences (see Table 3 for item coding rubric). For item level coding, the response unit was a student's complete set of answers to each question sequence. *MMK-SOM* scores were obtained by aggregating scores for Q1-Q3, *MMK-PC* scores were aggregated for Q4-Q7, and *MMK-Total* scores were the sum of scores on all items (Q1-Q7). A repeated MANOVA was conducted to examine if there were statistically significant differences in pre and post *MMK-Total*, *MMK-SOM*, and *MMK-PC* scores.

---Insert Table 3---

A coherence analysis of item level codes was conducted to examine the consistency and accuracy of particle models for SOM and PC question sets. See Table 4 for definitions of SOM and PC coherence codes. A heat map (Chambers, 2008) was generated to provide descriptive data on patterns of change in particle model coherence from pre to post MMK.

---Insert Table 4---

2. Emerging Models of Matter (EMM): Students' science notebook model inscriptions were analyzed using qualitative interpretive methods (Lincoln, 2002; Ryan & Bernard, 2000). Video-recordings of relevant science lessons were used to clarify science notebook entries. Results are presented below with reference to the two key research questions that this study was designed to address.

Results

Research Question 1. Do children's particle models of matter differ across pre and post instructional interview assessments? To answer this question, MANOVA were conducted on the students' pre and post MMK scores. See Table 5 for descriptive data.

---Insert Table 5---

Initial equivalence of groups. There were statistically significant differences in students' pre-MMK-*Total* scores by Teacher [$F(6,138) = 4.92$, $p < .01$, $\eta p^2 = .183$]. However, there were no statistically significant differences on Pre-*MMK-Total* scores by Technology type (1 = Thermoscope + Particle Modeler; 2 = Thermoscope + Thermonator) indicating that the children in each technology condition had similar knowledge of matter prior to instruction.

Pre-post comparison of MMK scores. Kindergarten students showed statistically significant pre-post differences on *MMK-Total* [$F(1,32) = 196.75$, $p<.01$, $\eta p^2 = .60$], *MMK-SOM* [$F(1,32) = 196.75$, $p<.01$, $\eta p^2 = .60$], and *MMK-PC* [$F(1,32) = 103.35$, $p<.01$, $\eta p^2 = .44$] scores. All subgroups (by Teacher and by Technology) showed gains in mean scores on every MMK component (see Table 5). The only statistically significant interaction effect on Pre-Post MMK scores was by Teacher $F(1,32) = 4.24$, $p<.01$, $\eta p^2 = .14$]. Some of the largest pre-post MMK score gains were for teachers whose students scored lower on the Pre-MMK (see Table 5).

---Insert Figure 4---

---Insert Figure 5---

Particle model coherence. The heatmap (Figure 4) of pre and post SOM and PC coherence scores illustrates the overall shift from undetermined/macroscopic models before instruction to microscopic models after instruction. Figure 5 illustrates how a student's responses change from Pre-MMK macroscopic to Post-MMK microscopic models. For Pre-SOM, 115 students (82.7%) had undetermined or macroscopic (continuous or pieces) models and only 3 students and (2.2%) had particle models, while 21 students (15.1%) had mixed microscopic and macroscopic models. For Pre-PC, 128 students (92.1%) used undetermined or macroscopic (continuous or pieces) models to explain phase changes and 11 students (7.9%) used mixed models. In contrast, for Post-SOM, 57 students (41%) used particle models and 56 students (40.3%) used mixed particle and macroscopic models while only 26 students (18.7%) had macroscopic or undetermined models. For Post-PC, 56 students (40.3%) used particle models and 44 students (31.7%) used mixed particle and macroscopic models. Only 39 students (28.1%) had macroscopic or undetermined models.

Research Question 2. How do kindergarten students' model inscriptions change as they progress through S2M2 investigations? To answer this question, we conducted a qualitative interpretive analysis of children's science notebook model inscriptions. We present two cases to illustrate trajectories of model development.

Case 1: Henry. After participating in the Thermoscope investigation of hot and cold water, Henry predicted a *Macroscopic Pieces* model for oil, comprised of bubbles that bump slowly (Figure 6a). Following a Thermoscope investigation, Henry recorded an observed particle model of oil. He then predicted that dish soap was composed of particles (instead of bubbles) bumping into each other. Henry extended his liquid models to a predicted particle model for wood (Figure 6b) and said that wood comprised of "lots of circles and they are bumping into each other." However, on the following solid, Henry reverted to a *Macroscopic Pieces* model of rock while generalizing the vibrating motion to rock pieces (see Figures 6a and 6b).

---Insert Figures 6a and 6b---

Case 2: Steven's SOM predicted models. After participating in the Thermoscope investigation of hot and cold water, Steven's predicted models for liquids (oil and dish soap) represented particle composition but motion was not represented (Figure 7a). His observational models for liquids from Thermoscope investigations included particle composition and motion. However, Steven's first predicted solid model (wood) was a Macroscopic Pieces model (Figure 7b), suggesting that initially, transfer of particle models was harder across states than within a state. Eventually, Steven spontaneously generalized a particle model to gas, describing air as made of "particles of gas" that were "moving fast and slow."

---Insert Figures 7a and 7b---

Our qualitative analysis found that students were more likely to construct particle models as they progressed through lessons. However, the trajectories of learning were not linear. Many students were more likely to spontaneously generalize particle models to new liquids but not to solids or gases. Students who understood that all matter comprised of particles, sometimes overgeneralized specific particle motions across all states of matter and phase changes.

Discussion and Implications for Education

Overall, our findings demonstrate that kindergarteners can learn to use simple particle models through explorations with a discourse-scaffolded and technology-mediated modeling curriculum. Our results suggest that kindergarten students' trajectories of learning are at least partially similar to the learning progressions of much older students, including those in middle and high school (Smith, Wiser, Anderson, & Krajcik, 2004; Smith, Wiser, Anderson, Krajcik, & Coppola, 2006; Talanquer, 2009). Our findings also build on recent research by Jakab (2013) and Staudt et al. (2015) showing that young children can learn simple particle models in interactive technology-mediated contexts. The results of the current study demonstrate that scaffolded, model-based inquiry instruction can support the coherent learning of simple particle models in the early elementary years.

However, developing particle models across states of matter and during phase changes is a non-linear process that requires engagement in systematic and extensive practices of sensemaking for varied material phenomena (Passmore, Gouvea, & Giere, 2014). We found that kindergarten students in this study were less consistent in their use of particle models than second grade students we had studied in the context of the MPG (Modeling in Primary Grades) project, using a similar curriculum (Samarapungavan, Bryan, and Wills, 2017). Further, in both studies, we found that students constructed intermediate non-normative particle models. Some children drew particles of different sizes to depict a substance such as water in different states. Typically, children drew particles of smaller size for solid than for liquid or gas states. Another non-normative idea that emerged among some students was that that gases contained fewer particles than solids or liquids.

Research on learning progressions conducted with much older students suggests that there is no linear path of progress at any age from the macroscopic to the (sub)microscopic particle world (Johnson, 2013; Liu & Lesniak, 2006; Merritt & Krajcik, 2013; Smith, et al., 2006; Wiser, Frazier, & Fox, 2013). Our findings support the case for introducing simple particle models to students early in instruction to equip them with tools for thinking about matter across multifold phenomena over the course of their science learning. With time and across grade bands, these early models can be extended and integrated into many areas of science curriculum (e.g., the water cycle or electron flow in circuits). From our perspective, the explanatory potential of these models mitigates the costs of the constructive errors that children make as they begin their journey from the macroscopic to the microscopic world.

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Table 1. Design Summary

School	*Teacher*	*Students (N=139)*	*Assessment 1*	*S2M2 Implementation*	*Assessment 2*	*Assessment 3*
			Site 1: Midwest-Suburban			
1	1. Ms. Parker	20	Pre-MMK	Technology 1	Science notebook	Post-MMK
	2. Ms. Money	15	Pre-MMK	Technology 1	Science notebook	Post-MMK
	3. Ms. Lacey	21	Pre-MMK	Technology 1	Science notebook	Post-MMK
			Site 2: Northeast-Metropolitan			
2	4. Ms. Brooks	18	Pre-MMK	Technology 1	Science notebook	Post-MMK
	5. Ms. Marsen	23	Pre-MMK	Technology 2	Science notebook	Post-MMK
3	6. Ms. Reed	21	Pre-MMK	Technology 2	Science notebook	Post-MMK
	7. Ms. Valliere	21	Pre-MMK	Technology 1	Science notebook	Post--MMK

Note. Technology 1 teachers used the Thermoscope followed by the Particle Modeler. Technology 2 teachers used the Thermoscope followed by the Thermonator.

Table 2. Summary of S2M2 Instruction

Learning Goals	Instructional Activities
Lesson I: Models and Modeling	
• Conceptualize models and modeling process • Identify examples of models from everyday real-world materials • Construct models to represent properties and behavior of real objects	• Exploration and whole-class discussions of models of real objects (e.g., earth) • Introduce the Thermoscope as a modeling tool to explore constituents of matter ("particles") that are too small to see directly • Thermoscope investigation of particle models of hot and cold water • Use the Particle Modeler / Thermonator to (re)construct previously observed models of hot and cold water
Lesson II: State of Matter (SOM)	
• Identify and distinguish exemplars of three states of matter: solid, liquid, and gas • Describe differences in macroscopic properties/behavior of matter in solid, liquid, and gas states • Explain differences in macroscopic properties/behavior of matter in each state in terms of differences in the arrangement and movement of constituent microscopic particles	• Inquiry cycles to investigate exemplars of liquid (oil and dish soap), solid (wood and rock) and gas (air). For each exemplar, the sequence of activities was: a) individual model predictions in science notebooks followed by whole class discussion, b) Thermoscope investigation connecting models of particle behavior to macroscopic properties/behavior of the exemplar (e.g., oil) c) use of the Particle Modeler / Thermonator to reconstruct the Thermoscope models of the exemplar, d) whole class discussion supports student sensemaking following each component activity. • Human models: Groups of students model the arrangement and motion of particles in each state (each student behaves like a single particle), while classmates observe and provide feedback on models.
Lesson III: Phase Changes (PC)	
• Identify and describe macroscopic changes in properties and behavior of matter as it undergoes phase transitions • Model how changes in the temperature of matter are related to changes in the behavior of its constituent particles • Explain macroscopic changes in the matter during phase transitions in terms of the changes in motion and arrangement of constituent particles caused by changes in temperature	• Inquiry cycles to investigate phase changes when heat was added to or lost from a substance. Students investigated melting, freezing, evaporation, and condensation using varied exemplars for each phase change (e.g., ice cubes, wax and chocolate chips for melting). The overall sequence of activities was the same as described for States of Matter above.

Table 3. Coding Rubric for Pre-and Post MMK Interview Data

States of Matter (SOM Q1 Solid, Q2, Liquid, Q3, Gas)		
Dimensions	*Codes*	*Response Examples*
Composition	1. Don't know / No response / Unclear response	
	2. Non-material (made of nothing)	*The air has nothing in it.*
	3. Macro continuous	*It's a huge blob of stuff. One big thing.*
	4. Macroscopic pieces/ Macroscopic continuous + pieces	*A bunch of little, tiny pieces.*
	5. Mixed: Macroscopic & microscopic pieces	*"Made of sand and color dye. Tiny little particles.*
	6. Microscopic particles: partially correct	*It is made of tiny little pieces, [we can see them because] they are made out of pencil. [We cannot see them] because they are tiny.*
	7. Microscopic particles correct	*It is made of tiny little particles. You can't see them. Cause they are so small that you cannot feel them.*
Distance	0. NA - Continuous	*It's a huge blob of stuff. One big thing.*
	1. Don't know/unspecified	
	2. Incorrect	E.g., [Particles of air] *They are close together.*
	3. Mixed	E.g., [Particles of clay] *Close together, sometimes they are farther and sometimes they are closer together.*
	4. Correct	E.g., [Particles of air] *Far.*
Spatial Arrangement	0. NA - Continuous (Said one big thing - macro continuous for composition)	*It's a huge blob of stuff. One big thing*
	1. Don't know / unspecified	
	2. Incorrect	E.g., Draws particles embedded in one part of the substance only or shows particles of solid spread far apart randomly
	3. Mixed	E.g., Draws some particles of gas close together and arranged regularly like a solid while others are spread far apart.
	4. Correct	E.g., Draws particles of a solid arranged close together in square, cube, or lattice like pattern
Types of Motion	0. NA - Do not move (Macro continuous on composition) / stay still etc.)	*They stay in place.*
	1. Don't Know / No response/ Unclear	
	2. Some move and some don't / move sometimes but not at other times	*Sometimes they move, sometimes they still.*
	3. Move-Unspecified	*They are moving. Not sure how they are moving.*
	4. Move-vibrate in place (jiggle/wiggle) for liquid/gas	*They are wiggling. That is all they are doing.*
	5. Move-bump	*Particles bump into each other.*
	6. Move across space: linear or other incorrect motion	*They move back and forth (draws linear motion)*
	7. Correct	E.g., *Bump and vibrate in place* or *move slowly* for solid /*slide over each other fast and bump* for liquid.

Table 3 Cont.

Dimensions	Codes	Response Examples
Phase Changes (PC Q4 Evaporation)		
Cause of Motion	1. Undetermined /No Response	*I forget. I ran out of ideas.*
	2. Macroscopic continuous	*The walls are really foggy, and they soaked it.*
	3. Macroscopic Pieces / Macroscopic continuous + Pieces	*It is both of these, this is what it looks like when they get dropped in there and this one shows it shrinking, and these are all the little, tiny pieces and it starts to shrink. Can see them, can feel.*
	4. Mixed macroscopic (continuous or pieces) & microscopic	*We cannot see the particles and feel them.*
	5. Microscopic 1: Incorrect arrangement or motion	*Because the little particles are shrinking the water.*
	6. Microscopic 2: Correct arrangement and motion	*These are small particles. Cannot see them. Can't feel them.*
Phase Changes (PC Q5 Melting, Q6 Freezing, Q7 Condensation)		
Cause of Motion	1. Don't know/unclear	
	2. Circular – macroscopic restatement	*It melted because someone kept it in the room.*
	3. Human action / external agent (e.g., rain, sun)	*The liquid is orange, and it came from the sun. It came from the sky. The liquid is there because somebody didn't eat it.*
	4. Heat changes not mentioned / incorrect	*Particles vibrate and stay in place when it gets hot.*
	5. Heat change-correct	*It comes from the popsicle. It is inside the popsicle but when it gets hot it starts coming out.*
Type of Motion	1. Don't know / unclear	
	2. None – macroscopic continuous description only	*It melted because it was hot.*
	3. Macroscopic + Pieces / drops etc. break off and form new state	*On the left is the clean window, on the right, water drops falling. The trail is where the water is moving.*
	4. Mixed – includes macroscopic and microscopic elements moving	*These are particles and going to get stuck. Liquid is moving.*
	5. Microscopic with incorrect motion	*Particles do not move in the popsicle because they are frozen.*
	6. Microscopic with correct motion	*Popsicle particles are moving a little bit and vibrating. They move fast. The lines show that they are moving all around (juice).*

Table 4. Coherence Coding Definitions

SOM Coherence Codes	*Definitions*
1. Undetermined / no response	The child did not respond, or the response was unclear / irrelevant
2. Macroscopic	*A. Continuous:* Matter is a continuous whole described only at macroscopic level. Arrangement/motion questions not applicable
	B: Pieces: Matter is comprised of smaller macroscopic pieces that have the same observable properties (e.g., color, texture) as the whole. The macroscopic pieces are stationary or move only if an external force such as "squishing" by humans is applied.
3. Mixed Microscopic and Macroscopic	Matter is comprised of some macroscopic pieces that one can directly see/feel and some microscopic particles that are too small to see or touch. Descriptions of motion are often mixed. For example, a child might correctly describe the type of motion (e.g., "jiggle in place") for a solid but incorrectly attribute the source of motion to human action such as "shaking."
4. Microscopic	*A. Partially Correct:* Matter is comprised of microscopic particles that are too small to see or touch. The descriptions of arrangement/motion contain non-normative elements. For example, the child models particles of clay as moving very fast through space or particles of gas as staying close together and not moving.
	B. Correct: Matter is comprised of microscopic particles that are too small to see or touch and the description of particle arrangement and movement are reasonable approximations of a normative model. For example, the child shows particles of clay as close together and jiggling or vibrating in place or bumping into each other slowly at close range.
PC Coherence Codes	*Definitions*
1. Undetermined / no response	The child did not respond, or the response was unclear / irrelevant.
2. Macroscopic Continuous	*A. Continuous.* The child either describes macroscopic changes in the shape of the whole substance (e.g., the melting popsicle "spreads out" and is "like water") or does not recognize that the materials at the start and end of the phase transition are the same substance (e.g., the condensation of air from one's breath on a cold windowpane is attributed to "rain").
	B. Pieces. The child describes macroscopic changes by saying that macroscopic pieces get rearranged during phase changes. For example, the child says that when a liquid melts, droplets break off and fall down to form a puddle.
3. Mixed	The child combines elements of macroscopic models (see above) with microscopic models (see below) to explain phase changes.
4. Microscopic incorrect	*A. Incorrect motion.* The child models phase changes in terms of the movement of microscopic particles but the description of motion is unclear or incorrect. For example, the child models freezing by showing that individual particles move sequentially in straight line from the liquid to form a solid.
	B. Correct motion. The child models phase changes in terms of the movement of microscopic particles and provides a reasonable approximation of changes in the arrangement and movement of particles as heat is added or lost.

Table 5. MMK Per and Post Interview Total and Component Scores by Technology and by Teacher

	Pre-Total		Pre SOM		Pre PC		Post Total		Post SOM		Post PC		
	Mean	*Sd*	*Mean*	*Sd*	*Mean*	*Sd*	*Mean*	*Sd*	*Mean*	*Sd*	*Mean*	*Sd*	*N*
Technology 1	43.05	12.79	20.27	9.95	18.48	5.33	66.85	25.69	43.04	20.50	23.81	8.56	95
Parker	31.20	8.12	17.65	6.77	13.55	5.82	58.25	26.16	38.40	21.19	19.85	7.33	20
Money	40.27	11.01	21.87	9.09	18.40	4.44	57.20	23.79	38.33	17.65	18.87	7.77	15
Lacey	44.33	15.90	23.71	12.56	20.62	5.71	60.00	21.61	35.33	17.84	24.67	7.53	21
Brooks	43.50	11.60	22.78	11.77	20.72	3.79	85.72	21.46	55.00	19.69	30.72	5.58	19
Valliere	35.24	7.73	16.05	6.53	19.19	2.91	72.62	25.47	48.29	20.61	24.33	9.48	21
Technology 2	43.05	12.79	20.99	10.15	20.52	4.02	79.39	20.39	49.93	18.00	29.45	5.13	44
Marsen	47.35	13.63	26.09	11.15	21.26	4.66	77.48	20.47	48.13	17.48	29.35	5.95	23
Reed	38.33	10.12	18.62	8.40	19.71	3.08	81.48	20.60	51.90	18.78	29.57	4.19	21

Note. The maximum possible MMK scores were: Total = 147; SOM = 39; Phase changes 108

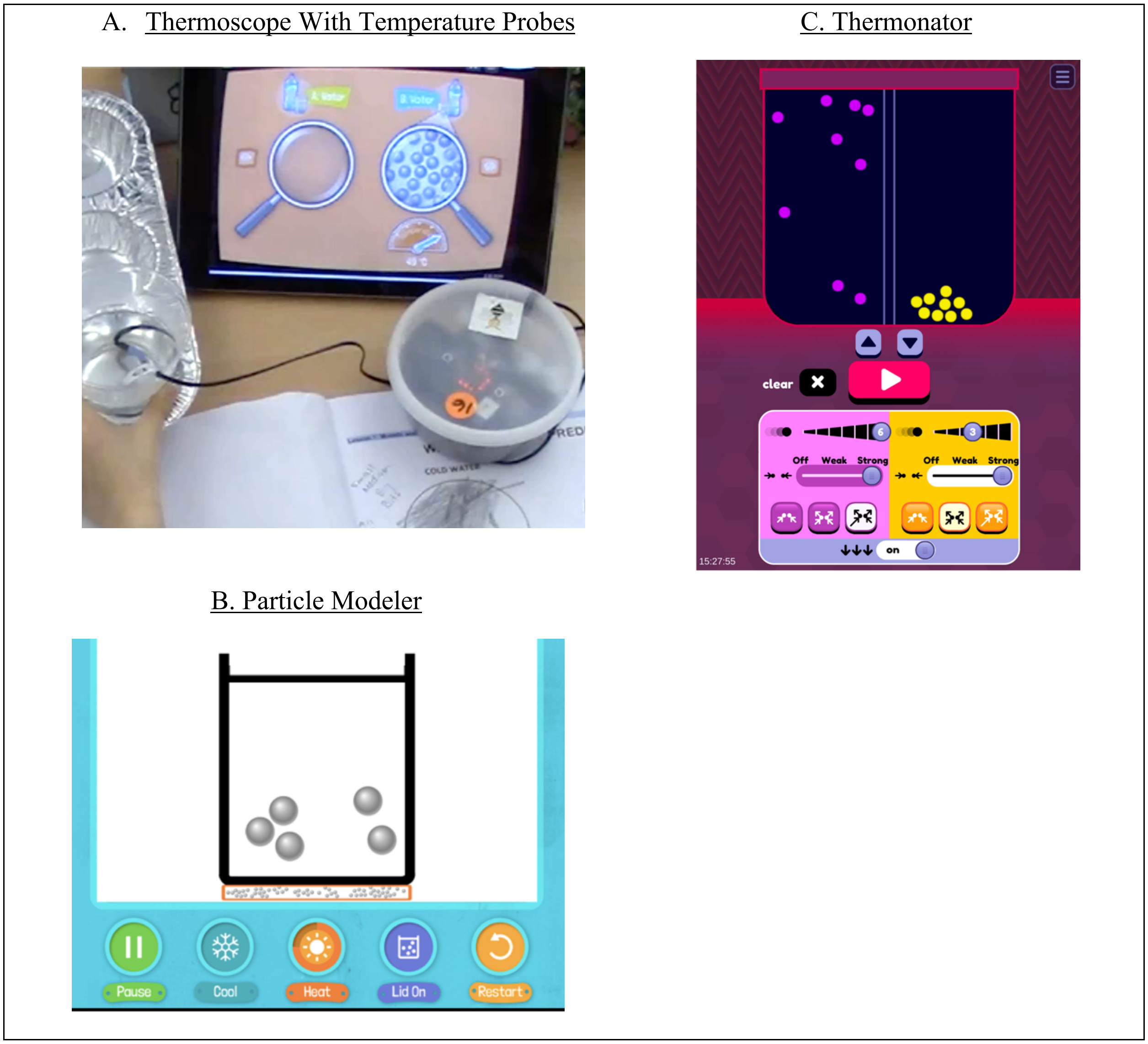


Figure 1. Examples of Thermoscope, Particle Modeler and Thermonator screens.

Teacher: So, if I cranked up the temperature and changed it and the air was even hotter, do you think anything would happen to the particles? Please draw in the first circle what you think would happen if I changed the temperature and made it hotter.
01:01
Child: It will be bouncing around super-fast.
Teacher: Don’t tell me, show me [points to science notebook page]
…
Teacher: All right my friends so we’ve made our predictions. We were thinking about -What do we think will happen to the particles in the air if we made it even warmer in the room. So, the way that we are going to look at that is we have a bottle that’s being warmed up … this warming pad is warming up the air and we are going to see what the particles look like when the air is even warmer. So, think about the prediction that you made. Would anyone like to share what they think is going to happen? Erin, what do you think will happen if we warm up the air?
Erin: It’s gonna be moving faster.
…
Teacher: You think they’ll be even faster than when we just did the plain air? Laila, what do you think?
Laila: I think they’re gonna be moving like a little bit slow kind of like the oil.
Teacher: Oh, interesting. Nolan did you hear what Laila said? What did she say?
Nolan: I think they’re gonna move a little bit slow um a little bit slower.
Teacher: Good. Thank you. Yes, Patterson?
Patterson: I think they’re gonna [inaudible]
Teacher: You think they’re gonna be what?
Patterson: Huge because when the air gets hotter sometimes it can cause particles to get big.
Teacher: Oh, so you think the particles will grow in size. Interesting. I hadn’t thought about that. All right so let’s see what happens when we warm up the air. So again, we’re to look just at the B circle (on Thermoscope). I’m going to put the B sensor into the warm air. Remember it’s in a bottle just like our other air but this time the warming pad is heating up the air.
Teacher: So … what are you noticing about the particles? Jason?
Jason: Going faster.
Patterson: They didn’t change size.
Teacher: They didn’t change size, so Patterson made a really interesting prediction, but the particles actually didn’t change size, they just started moving a little bit faster.

Figure 2. Excerpt from whole class discussion of particle behavior when air is heated.

Q1. SOM-Solid

[If child only describes macroscopic properties such as color or shape, ask] What is this clay made of? Is it one big thing or is it made of little pieces? [If the child says it is made of pieces or particles, ask]

Are the little pieces close together or are they far apart?

Can you draw the smallest pieces that clay is made of? What do they look like? [If needed ask]

Tell me about your drawing. What did you draw here [point to any parts of the picture that are unclear]?

Do these pieces sit still, or do they move around? [If child says they move but does not describe the motion ask}

Can you show me how they move?

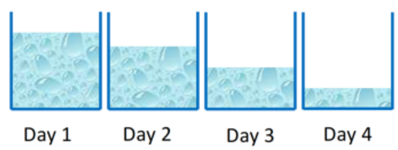
Do they take up space?

Can you see the smallest pieces that clay is made of with your eyes?

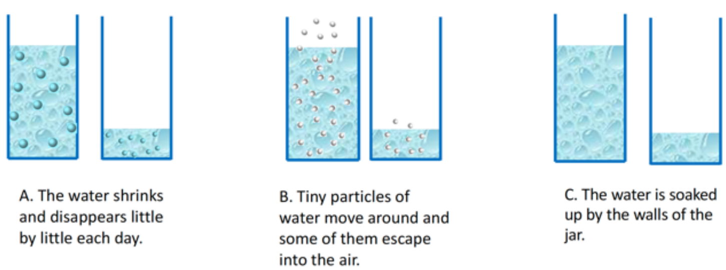
Do they have a color?

Can you feel them?

Q4. PC-Evaporation



Toby leaves a jar of full of water on the kitchen counter. Each morning he notices that the jar seems to have a little less water and he wonders what happens to the water. His sister Kaya tells him that the water evaporates. Which picture below shows what Kaya means when she says the water evaporates. Circle the best answer.



After the child makes a choice ask: Why did you choose this one? What does it show?

Q5. PC-Melting

[Show child picture of a melting popsicle and say] This is a popsicle that has been left out in a warm room for a while. Can you see the liquid over here [point to melting liquid]? Where does this come from? [If child says popsicle is melting or provides another macroscopic description ask]

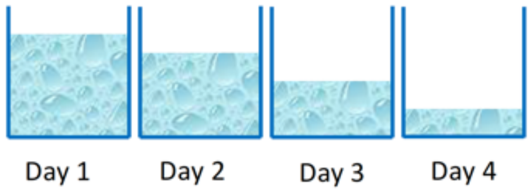
Imagine the smallest particles that this popsicle is made of. What would those particles look like as it melts into this liquid? Can you draw them for me? [If needed ask]

Tell me about your drawing. What did you draw here [point to any parts of the picture that are unclear]?

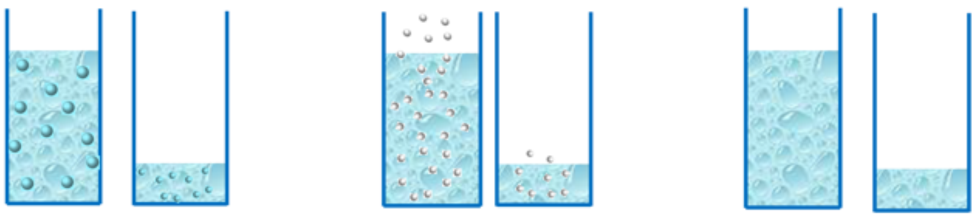
Were the particles in the popsicle moving? Were they moving before they melted? [If yes] Are they moving now? [If yes] Do the particles move faster or slower as the popsicle melts and becomes a liquid?

Figure 3a. Examples of SOM and PC questions.

Q4. PC-Evaporation



Toby leaves a jar of full of water on the kitchen counter. Each morning he notices that the jar seems to have a little less water and he wonders what happens to the water. His sister Kaya tells him that the water evaporates. Which picture below shows what Kaya means when she says the water evaporates. Circle the best answer.



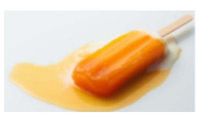
A. The water shrinks and disappears little by little each day.

B. Tiny particles of water move around and some of them escape into the air.

C. The water is soaked up by the walls of the jar.

After the child makes a choice ask: Why did you choose this one? What does it show?

Q5. PC- Melting



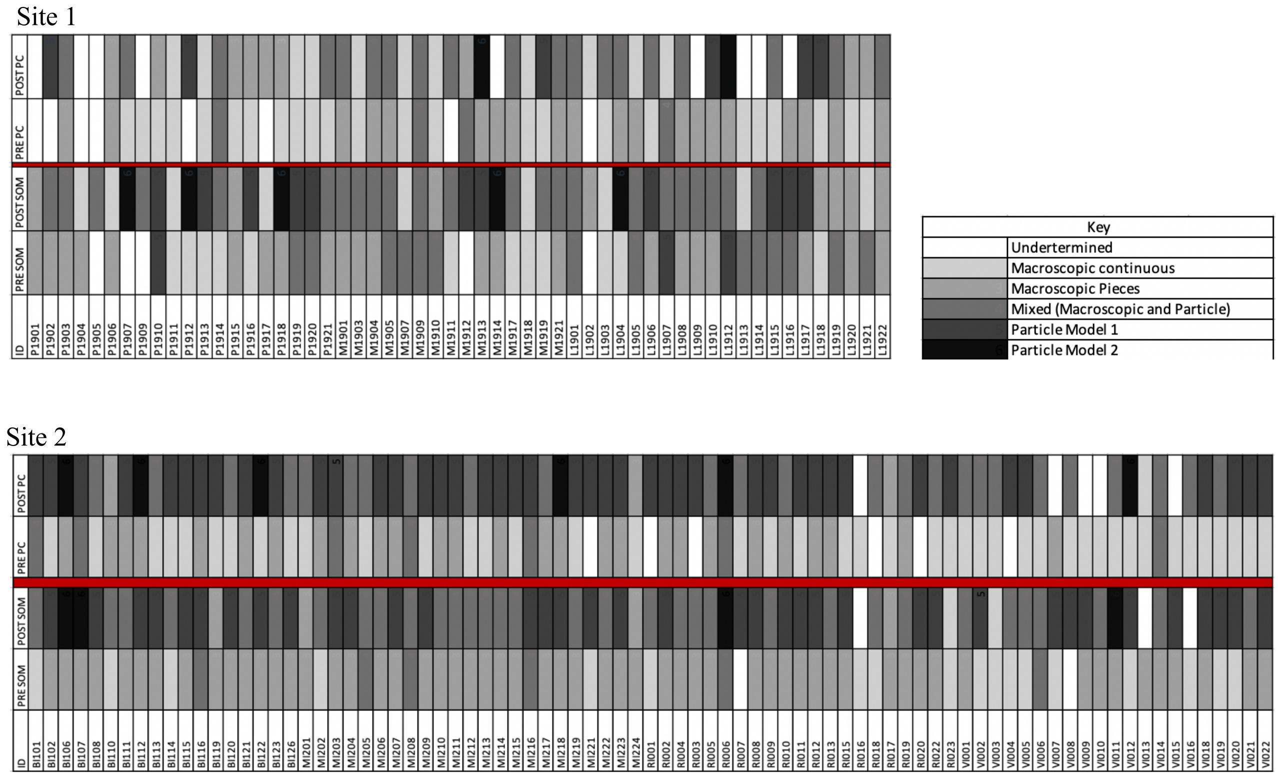
[Show child picture of a melting popsicle and say] This is a popsicle that has been left out in a warm room for a while. Can you see the liquid over here [point to melting liquid]? Where does this come from? [If child says popsicle is melting or provides another macroscopic description ask]

Imagine the smallest particles that this popsicle is made of. What would those particles look like as it melts into this liquid? Can you draw them for me? [If needed ask]

Tell me about your drawing. What did you draw here [point to any parts of the picture that are unclear]?

Were the particles in the popsicle moving? Were they moving before they melted? [If yes] Are they moving now? [If yes] Do the particles move faster or slower as the popsicle melts and becomes a liquid?

Figure 3b. Examples of Phase Change (PC) questions.



For both sites, the cells in the lowest row (ID) represent individual students. The cells in the two rows immediately above show each child's pre-SOM and post SOM coherence scores. The cells in two rows above the red dividing line show each child's pre and post PC coherence scores. Dark grey cells indicate particle models while light grey cells indicate macroscopic models and white cells indicate undetermined models.

Figure 4. Heat Map of Pre -Post MMK Coherence Scores for students by Site.

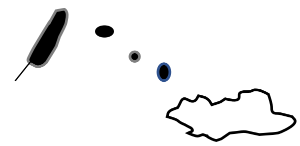
Jenna's models	Examples of SOM responses	Examples of PC Responses
Pre-MMK: Macroscopic - pieces	Q1. Clay: *Made of playdoh that never gets solid. You can see them, [they are] green, can feel them. The pieces sit still. You have to use your hands to make them move.*  Q2. Syrup: *When you drop them [droplets] in the bottle they come close together.*	Q5. Melting: *The frozen melts into water and it drops into, the drops make the water.* 
Microscopic - Correct	Q1. Clay: [is made of] *Particle*. [see/feel] *No they are very tiny. They are jiggly.* [take up space] *Not much, they are tiny.* 	Q5. Melting: *The particles were moving in the solid and they move more, faster, when they melt. The heat makes them whizz all around and bump each other.* 

Figure 5. Jenna: Examples of change from macroscopic Pre-MMK models to microscopic Post-MMK models.

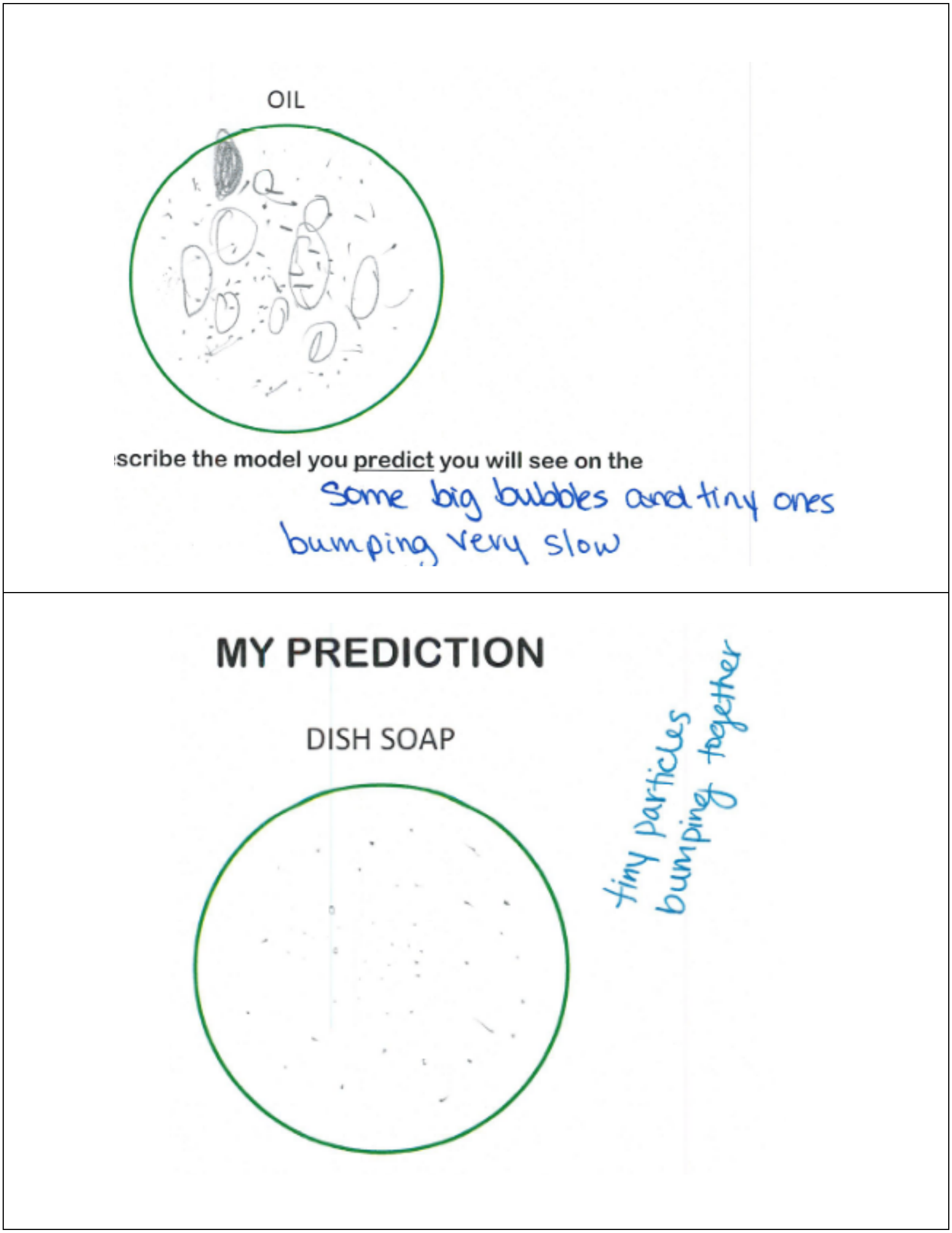


Figure 6a. Henry's science notebook inscriptions showing his SOM model predictions for liquids (oil and dish soap).

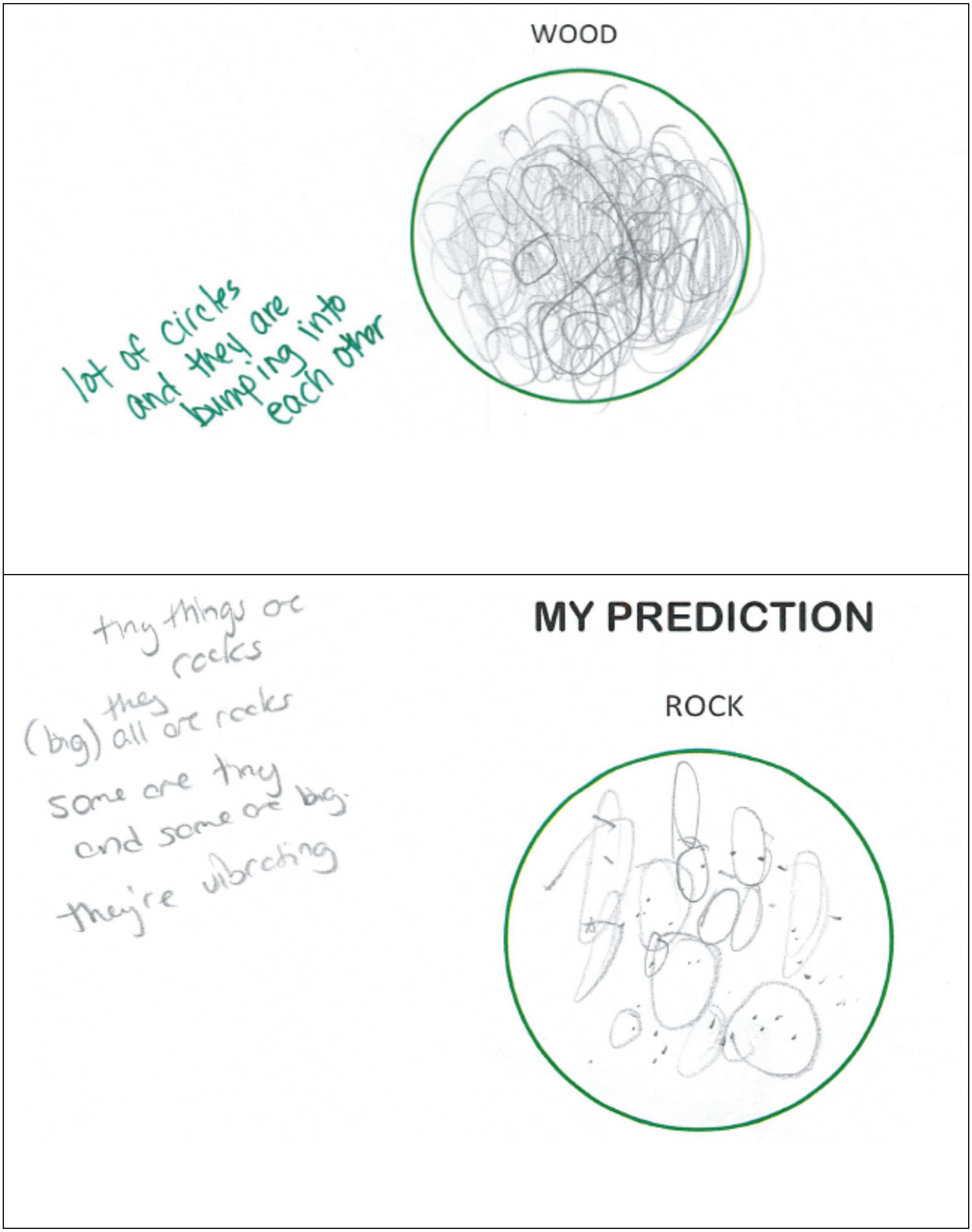


Figure 6b. Henry's science notebook inscriptions showing his SOM model predictions for solids (wood and rock).

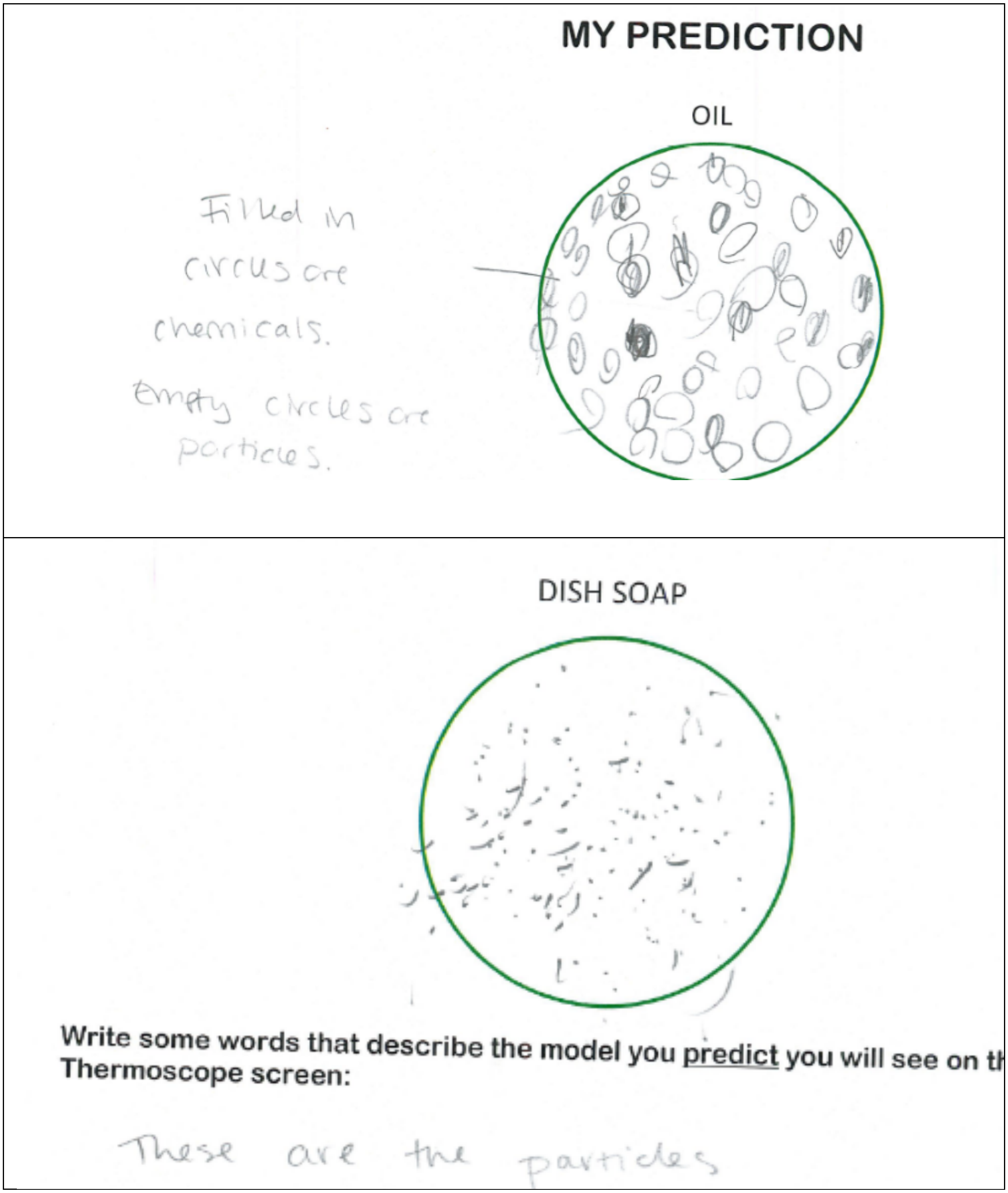


Figure 7a. Steven's science notebook inscriptions showing SOM model predictions for oil and dish soap.

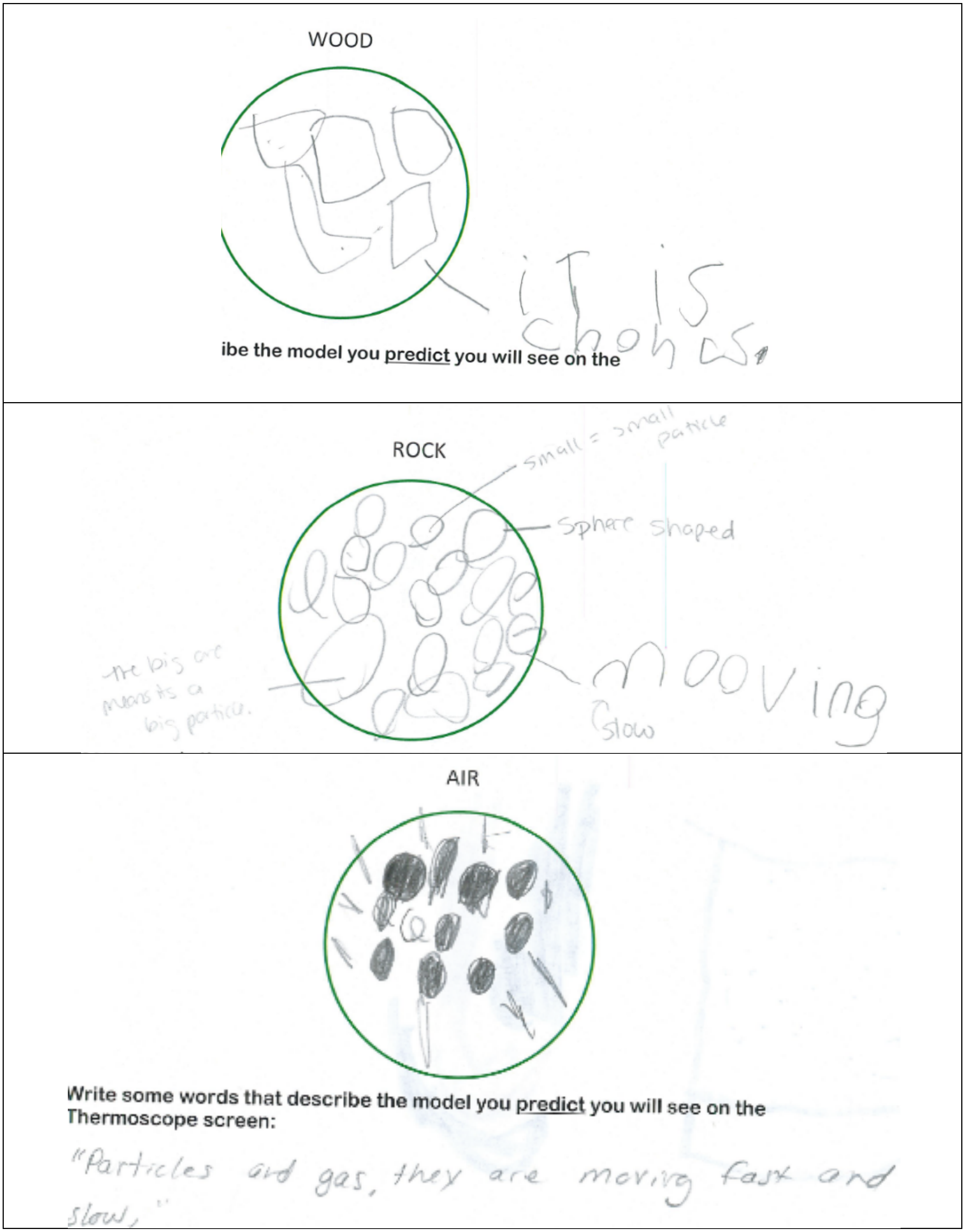


Figure 7b. Steven's science notebook inscriptions showing SOM model predictions for wood, rock and air.