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UNIVERSITY OF CALIFORNIA
SANTA CRUZ

**DIFFERENTIATING MASS FROM DENSITY:
THE EFFECT OF MODELING AND STUDENT DIALOGUE
IN A SIXTH-GRADE CLASSROOM**

A dissertation submitted in partial satisfaction
of the requirements for the degree of

DOCTOR OF EDUCATION

in

COLLABORATIVE LEADERSHIP

by

Martha L. Deich

December 2015

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2015

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ABSTRACT

DIFFERENTIATING MASS FROM DENSITY: THE EFFECT OF MODELING AND STUDENT DIALOGUE IN A SIXTH-GRADE CLASSROOM

by

Martha L. Deich

The concept of density can be difficult to learn. In the middle grades, students characteristically conflate mass and density, and even after instruction many students do not distinguish them consistently (Smith, Maclin, Grosslight, & Davis, 1997). Few develop a conceptualization of density that accounts for the implications of changing mass, volume, temperature, and/or state. My work looks specifically at how students make sense of the relationship between mass and volume as they refine their understanding of density.

The concept of density is challenging to teach. Traditional methods of teaching density in middle-school classrooms typically involve either the measurement of an object's mass and volume and the subsequent calculation of the ratio of the two quantities, or the observation of different materials in water to learn about their buoyancy. Unfortunately, as Carol Smith and her colleagues have documented (1985, 1992, 1997), these approaches leave many students stuck in their "commonsense frameworks" that merge mass and density into one concept. Teachers need better ways to teach density.

Hence I designed an intervention to study the effects of some possibly more effective ways to teach density. I developed and taught a complex intervention

(Brown, 1992) featuring student modeling, extensive student dialogue on data and data analyses, formative assessments, the substitution of hands-on inquiry for mathematical problem sets, and multiple thought experiments. The hallmarks of the intervention were modeling and student dialogue, and the research question I posed was: Does classroom practice that encourages modeling with open-ended discourse help students differentiate between the concepts of mass and density?

I patterned my research on a Smith study of density instruction in eighth grade (Smith, Maclin, Grosslight, & Davis, 1997), which had a quasiexperimental research design that compared the results of teaching density differently in two classrooms. I selected an intervention class and a comparison class from those I was teaching. The core of the density curriculum was similar in both classes. Instead of the intervention, though, the comparison class closely followed the lesson sequences provided by the classroom textbook, which tended to focus on formal and formulaic density instruction. I modified Smith's assessments for sixth graders. After teaching one class the intervention curriculum and the other the textbook-based curriculum, I evaluated and compared the progress of research participants in both classrooms by means of a pre- and post-instruction clinical interview, a pre- and post-instruction written test, and the end-of-chapter test from the textbook used in the comparison classroom.

The results of my study were consistent: the intervention students outperformed and showed greater improvement on all assessments compared to the comparison students. In this study, modeling and student discourse were more

effective ways to teach density than a standard textbook-based lesson sequence. The intervention helped students start to disrupt the conflation of mass and density, fostering both the comprehension of volume as a variable property of matter, and a nuanced understanding of density beyond formulaic reasoning.

This dissertation is a report of my study for two audiences—academics and science educators. For the latter, I include recommendations for improving density instruction that are informed by my research.

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CHAPTER 1

INTRODUCTION

I begin this dissertation with a scene from my own classroom to explain my interest in the problem that I studied. I then describe the problem in greater detail in the second section of the chapter, and I provide an overview of my research to address the problem in the last section.

A Scene from My Classroom

I started class by holding up a stack of green plastic 10-gram pieces. “I know that I am holding a mass of 50 grams. How do I know this?” Hands shot up in my sixth-grade science class. The students had been measuring the mass of various objects over the past few days using a simple two-pan balance, and they were quite familiar with the different sizes and colors of the assorted plastic and brass gram pieces that we used for the measurements.

One student answered, “You have five 10-gram pieces.”

“That’s absolutely right,” I responded. I then held up a small brass 50-gram piece. “Again, I know that I am holding a mass of 50 grams. How do I know this?”

Hands went up again, and one student responded, “It says ‘50g’ on the top!”

“Exactly right,” I answered. “Now, if I put the brass piece on one side of the pan balance and the five plastic pieces on the other side, what will happen?”

One child answered, “The side with the brass will be lower.”

“Why would that be, if both masses are 50 grams?” I asked.

“Because metal is heavier than plastic,” responded the student.

Another student said, “It doesn’t matter if the material is brass or plastic; 50 grams is 50 grams. The balance will be straight across.”

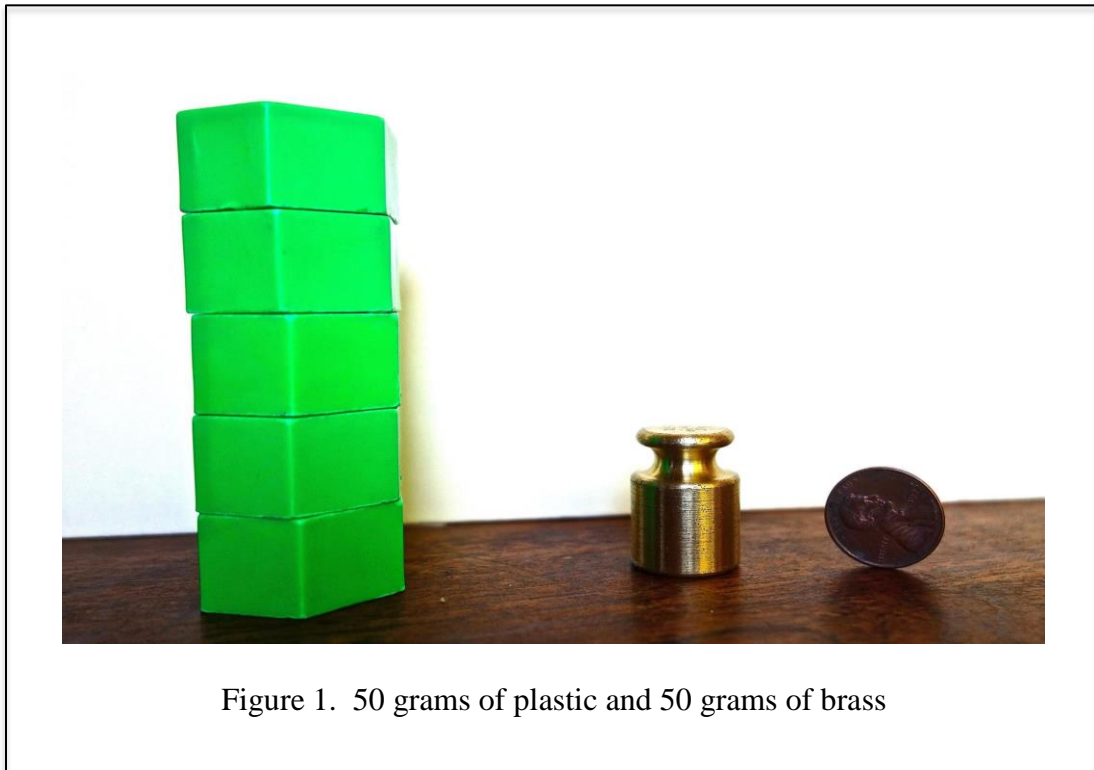


Figure 1. 50 grams of plastic and 50 grams of brass

So I took a poll of the class. “Who thinks the pans will be balanced when the brass piece is on one pan and the stack of plastic pieces is on the other?” Twenty hands went up. “Who thinks that the side with the brass piece will be lower than the side with the five plastic pieces?” Ten hands went up.

The Problem

Why did the students have different opinions regarding this question? Is their reasoning related to their understanding of matter? Does the density of a material such as a metal influence their understanding of the metal’s mass? The study reported on in this dissertation is concerned with two interconnected aspects of mass

and density in a middle-school science classroom. The first is how students in the middle grades think about density and how they change their ideas about it, and the second is the question of how best to teach them about the concepts of mass and density.

Density is not an easy concept to master. It is a ratio of two extensive quantities—mass and volume. The term “extensive” refers to an additive property that changes in relation to the amount of material present. Density itself is “intensive,” a property that is constant regardless of the amount of material present. Intensive and extensive properties can be phase-dependent. For example, the density constant of gold is a value calculated at standard temperature and pressure. Gold’s density (as a solid) will change when it is heated sufficiently to liquefy and will continue to change as it is heated to the gas phase. The mass of the sample of gold remains constant, but the volume and temperature increase as the gold is heated. As mass is held constant (the number of gold particles is not changing), the volume increases with increasing temperature, leading to a decrease in the gold’s density. Even some adults lack full understanding of the density concept.

Piaget observed children trying to make sense of equal volumes of liquids in containers of various shapes. He concluded that children do not reach the developmental stage necessary to understand conservation of volume at room temperature until around age 11, which corresponds to sixth grade (Ginsburg & Opper, 1969). In science classrooms, mass and volume may be introduced before sixth grade, but density is rarely taught before then.

Carol Smith and her colleagues have studied how students learn density (Smith, Carey, & Wiser, 1985; Smith, Snir, & Grosslight, 1992; Smith, Maclin, Grosslight, & Davis, 1997). They have repeatedly found that, like the ten sixth graders in my class who considered 50 grams of metal to be “heavier” than 50 grams of plastic because metal is denser than plastic, many students in the middle grades conflate the concepts of mass and density in various ways. Therefore, the problem I decided to study was how a middle-school science teacher could help students separate these concepts. What type of instruction would help students differentiate mass from density and understand each one?

Overview of the Study

My normal teaching practice combines teacher-directed pedagogy (*e.g.*, demonstrations, lecture, whole-class discussion, direct vocabulary instruction, open-ended questioning, and diagram construction and analysis) with lab work and activities in which students develop their own questions to test. I was not satisfied with this approach to density, however, because too many of my students were “stuck” with a conflated mass-density concept. Practice with reasoning using the density formula helped all of my students answer the density word problems typically found in textbooks and on standardized tests, but few students had sufficient understanding of density to explain why a log floats in water but a penny sinks, or why a golf ball might hover motionless in the middle of a salt-water column, or why 50 grams of brass is not “heavier” than 50 grams of plastic.

I sought greater opportunities for students to test out their ideas about matter with each other and to develop models to explain their thinking. Therefore, I developed a complex intervention (Brown, 1992) featuring modeling (Schwarz, *et al.*, 2009; Windschitl, Thompson, & Braaten, 2008), extensive student dialogue about data and data analyses (Hakuta, Santos, & Fang, 2013; Quinn, Lee, & Valdes, 2012; Wells, 1991), formative assessments as reflective lessons (Ayala *et al.*, 2008; Shavelson, 2006), the substitution of hands-on inquiry for mathematical problem sets, and thought experiments (Smith, Maclin, Grosslight, & Davis, 1997).

My study is patterned on a Smith study of density instruction in eighth grade (Smith, Maclin, Grosslight, & Davis, 1997) which had a quasiexperimental research design that compared the results of teaching density differently in two classrooms. I selected an intervention class and a comparison class from those I was teaching. The core of the density curriculum was similar in both classes. Instead of experiencing the intervention, though, the comparison class closely followed the lesson sequences provided by the classroom textbook, which tended to focus on formal and formulaic density instruction with a few additional enrichment activities to expand themes in the chapter. Smith used her data collection instruments as assessments. I shortened those instruments and modified them to reflect sixth-grade math knowledge. After teaching my density intervention in the intervention class and a standard density unit in the comparison class, I evaluated the performance and improvement of research participants in both classrooms by means of a pre- and post-instruction clinical interview, a pre- and post-instruction written test, and the end-of-chapter test from the

textbook used in the comparison classroom. I wrote about the learning trajectory of each class, drawing on data from “case-study” students chosen as typical representatives, and I reported the aggregate assessment results.

What I did not anticipate at the start of my study was that my research questions would change as my study progressed. My initial research questions were modeled after Smith’s (1997) central questions about two types of students’ general understandings of matter. Smith and her colleagues defined commonsense matter theory 1 to describe conceptions that conflated mass and density, and that required matter to be readily observable by touch, feel, or sight to exist. Students who conceived of matter as having both mass and volume, as infinitely divisible, and as not necessarily being directly observable were described as having commonsense matter theory 2. Theory 2 students understood that air is matter, for example, but theory 1 students contended that air is not matter because it is invisible. My original research questions were patterned closely on Smith’s central questions: To what extent do sixth graders transition to commonsense matter theory 2 from commonsense matter theory 1; and for those who do, what is the nature of that transition, and what factors promote or inhibit that transition?

The preinstructional data that I collected revealed that, unlike Smith’s classes, most of my students were already quite comfortable with the idea of nonobservable, infinitely divisible matter. Further, most understood the particulate nature of matter and told me in the preinstructional interview that adding more clay to a clay ball, for instance, did not increase the density of the clay, but did increase the weight of the

ball. Hence the initial data collection for my study informed me that my first research questions were not applicable to my student population.

I modified my study to focus on students' specific pathways to differentiating mass from density within their varied locations within commonsense matter theory 2. As I began to carry out the intervention, I reflected on the complex parts of the intervention that I was teaching, and I recognized that some elements were more significant than I had previously expected. I decided that the hallmarks of the intervention were modeling and opportunities for student discussion and engagement, and so the final iteration of my research question became: Does classroom practice that encourages modeling with open-ended discourse help students differentiate between the concepts of mass and density?

I have written this dissertation for both academic and practitioner audiences. Academics may be interested in the nature of the intervention, my findings and the strength of the evidence for them, and the insights I record from the perspective of a teacher-researcher trying to tease apart her students' thinking about mass and density. Practitioners, especially middle-school science teachers, may appreciate the details of the intervention, the students' learning trajectories with samples of their work, my findings, and the teaching recommendations that I have drawn from the study. Ideally I would like my dissertation research findings to reach all those who contemplate how best to teach density to eager and curious sixth graders who are ready to examine their own thinking about matter.

In this chapter I opened the dissertation by discussing and illustrating the problem it addresses and the need for better teaching practices to help students distinguish and understand mass and density, and by presenting an overview of my study, which may contribute towards a solution to the problem. Chapter 2 lays out the literature review and theoretical background for the study. Chapter 3 is a record of the methodological decisions about the study, including research design, study and participant characteristics, and methods for data collection and analysis. In chapter 4 I present the results, both the narrative learning trajectories and the aggregate assessment outcomes. Chapter 5 includes discussion and interpretation of the results, my insights about student understanding of density with teaching recommendations, and other aspects about the study and next steps.

CHAPTER 2

THEORY AND LITERATURE REVIEW

This chapter, consisting of four major sections, lays the theoretical foundation for my study of the teaching of density. The first section presents the theoretical framework on teaching and learning that undergirded my study, and it also introduces the studies on modeling and on discourse, language, and science literacy that shaped my inquiry. The second section applies a theoretical lens to the teaching of density and to factors—textbooks, tests, and standards—that condition the teaching of density. The third section reviews the relatively few studies of teaching density in the middle grades, and the last section discusses the theoretical perspectives that have shaped my own practice and the conduct of my study.

Theories of Teaching and Learning

To review the literature on teaching and learning, Greeno, Collins, and Resnick (1997) developed a framework that is still widely cited today. It organizes the approaches to pedagogy advocated by scholars of the past century according to behaviorist, cognitive/constructivist, and situative/sociocultural theories. This section of the chapter begins with a summary of their framework that emphasizes its classroom implications. The section then discusses the growing importance of the sociocultural perspective and the focus that it places on science language and literacy. The section concludes by introducing modeling as a recent pedagogical innovation in science education and discusses how modeling fits into the framework.

A Theoretical Framework for Teaching and Learning

Greeno, Collins, and Resnick (1997) sort both the research on cognition and learning and the literature on instructional practice into three categories. They give the first set of studies, with empiricist roots in Locke and Thorndike, the label “behavioralist.” For behaviorists, knowledge is an organized collection of associations and skill components, and learning is acquiring and applying this knowledge (Greeno, Collins, & Resnick, 1997, p.16). Descartes and Piaget lay the rationalist foundation for their second category, the “cognitive” or “constructivist” perspective. Under this approach, researchers consider knowledge to be an understanding of concepts and theories; it also encompasses cognitive abilities like reasoning and problem solving. Adherents tend to regard learning as a constructive process of conceptual and cognitive growth (Greeno, Collins, & Resnick, 1997, p.16). The third group, the “situative” or “sociocultural” perspective, traces its origins to the pragmatist and sociohistoric positions developed by Dewey, Mead, and Vygotsky. Those with a situative/sociocultural perspective hold that knowledge is constructed by individuals and distributed across an informed community. Whereas Piaget and constructivists hold that development precedes learning, Vygotsky argued that social learning precedes development:

Every function in the child's cultural development appears twice: first, on the social level, and later on the individual level; first, between people (interpsychological), and then inside the child (intrapsychological). This applies equally to voluntary attention, to logical memory, and to the formation of concepts. All the higher functions originate as actual relations between human individuals (Vygotsky, 1978, p. 57).

Thus individuals learn through the participatory process of becoming "...attuned to constraints and affordances of material and social systems with which they interact" (Greeno, Collins, & Resnick, 1997, p. 17).

Greeno and his colleagues also classify studies and reports on teacher practice with their tripartite theoretical framework. They argue that the learning environment of a behaviorist classroom is well organized and controlled by the teacher, with clear goals and established routines. In an effort to help students avoid errors, teachers simplify or eliminate the everyday contexts for the subject being taught and deliver didactic instruction followed by repetitive rehearsal and practice. The curriculum is carefully sequenced from simpler to more complex, and teachers expect students to gain expertise by memorizing or being able to reproduce the knowledge of experts in terms of definitions, formulae, and calculations. Practice problems, homework, and assessments tend to reward correct answers rather than demonstrations of understanding (Greeno, Collins, & Resnick, 1997, pp. 28-29, 33-34, 37-38).

Under the cognitive or constructivist perspective, the classroom learning environment, curricula, and assessments look quite different from those described above. To facilitate conceptual understanding and enhance cognitive abilities, teachers prefer exploratory environments where students can examine hands-on materials and reason about them. They help students construct knowledge through problem solving based on interactive activities that engage student interest. Students cooperate with their classmates, rather than competing with them, to carry out

concrete problems or simulations. The curricula reflect what specialists deem to be meaningful learning in specific disciplines—from issues that are judged to be within the students’ reach to more challenging topics—augmented by the study of general reasoning and metacognitive skills. Assessment is often based on student performance on projects extended over time or on portfolios that capture demonstrations of student understanding and growth (Greeno, Collins, & Resnick, 1997, pp. 29-31, 34-36, 38-39).

The situative or sociocultural approach shares elements with the constructivist perspective, such as the use of hands-on materials and the importance of exploration and interactive problem solving, but its point of departure is the centrality of developing positive inquiry skills and the student’s identity as a capable learner. Teachers support students’ abilities to formulate questions and arguments as much as they help them evaluate evidence to draw conclusions. Learning the concepts of a subject means “...learning to participate in the discourse of a community in which those concepts are used” (Greeno, Collins, & Resnick, 1997, p. 31), so students discuss their understanding and their reasoning with others. In their curricula, teachers sequence both the social practices they expect students to master and the discipline-specific subjects they introduce through realistic problems and meaningful activities. Teachers help students learn to show agency in their work; teachers encourage discussion of alternative understandings and individual representations; and they provide space and support for students to defend their own positions. Some forms of assessment are similar to those used under the constructivist perspective

(projects and portfolios), but students are active evaluation participants, and the assessment goal is to evaluate the quality of student participation in inquiry and in the social practices of learning (Greeno, Collins, & Resnick, 1997, pp. 31-33, 36-37, 39).

A Turn towards the Sociocultural Perspective and Science Literacy

The number of classroom teachers who embrace the sociocultural perspective has been on the rise over the past decades. Wells (1999) made several interrelated recommendations about the construction of knowledge through schooling for these educators. The first was that teachers need to recognize that the primary goal of education is the development of understanding. Students develop understanding as they engage in activities with others that encourage collaborative knowledge building about questions and problems that interest them. His second recommendation was that teachers give students the opportunity to formulate and test their own theories and to submit them to critical evaluation by peers. This ties together individual and collective knowledge construction in the classroom. Third, he cautioned teachers to dissuade students from relying solely on “what is known” (behaviorist knowledge transmission). Finally he advocated “dialogic inquiry;” that is, instruction that encourages discourse as dialogue rather than behaviorist school discourse that privileges writing and text (Wells, 1999). “If, as I have argued, it is knowing with and for others that is to be given pride of place in classroom activities, then it is the dialogic potential of discourse that needs to be emphasized...” (Wells, 1999, p. 92). Dialogic inquiry brings together the individual and the classroom community in their common pursuit of acquiring knowledge through communication:

Knowledge construction and theory development most frequently occur in the context of a problem of some significance and take the form of a dialogue in which solutions are proposed and responded to with additions and extensions or objections and counter-proposals from others (Wells, 1999, p 51).

Classrooms prioritizing dialogue over silence can be stimulating and energizing for students, especially in inquiry-based science classrooms. Classroom discourse shifts the focus of schooling from knowledge transmission (typical of behaviorist classrooms) to social constructivism, in which knowledge is coconstructed through activity and discourse in a collaborative community (Ash & Wells, 2006; Brown & Campione, 1994; Halliday, 1993; Lave & Wenger, 1991; Vygotsky, 1934/1986; Wells, 1999). Language is at the center of this collaborative community in two important and dynamic ways. First, conversational interaction influences language development (Halliday) and second, language is a tool for improving and deepening understanding (Vygotsky). Learning by doing, and learning by drawing on experience, with teachers evaluating and guiding students' emerging sense-making, are means of constructing solutions for problems or questions which students deem important (Dewey, 1938; Vygotsky, 1934/1986). With the teacher as guide, all participants in a dialogue-centered science classroom learn with and from each other as individuals' and the community's science literacy grows.

The sociocultural emphasis on dialogue in the classroom has helped science researchers pay greater attention to student mastery of science language and literacy. Scientific language includes some "common-sense" language (Warren & Rosebery, 1995), gestures, diagrams, representations that make sense to the student, as well as

technical vocabulary used in communication among students and between students and their teacher (Lemke, 1990). The ability to code-switch from everyday language to scientific language, *e.g.*, “force,” “volume,” or “energy,” is essential for science vocabulary development, as well as for precision in scientific discourse with regard to meaning, evidence, and claims (Quinn, Lee, & Valdes, 2012). Hakuta, Santos, and Fang (2013) urge teachers to facilitate their students’ fluency in science language and literacy by: 1) immersing students in science content through observation, investigation, and discourse; 2) using models and other representations to explain content; and 3) reflecting on the unique language demands of science texts in order to support the language development of all students. Student use of scientific language in its various forms is a tool for learning and understanding.

Modeling in Science Education

Perkins and Grotzer note that, in the years since the review by Greeno, Collins, and Resnick, the movement away from behaviorist practice in the classroom and “(t)he development of constructivist pedagogy in science education has done much to foster students’ sophistication about inquiry, encouraging them to formulate theories, test hypotheses, seek consistency, and so on” (2005, p.119). They point to the introduction of modeling as a particularly significant aspect of this shift:

In the past decade, science education has come to recognize the important role of modelling in how scientists develop and test explanations (*e.g.*, Penner, Giles, Lehrer, & Schauble, 1997; Ost, 1987; Stewart, Hafner, Johnson, & Finkle, 1992). Increasingly students are encouraged to create and test models of concepts and to engage in the systematic revision of models as they trade up for models with the most explanatory power towards the scientifically accepted explanations (Perkins & Grotzer, 2005, p.119).

A scientific model simplifies a phenomenon or a system into a representation that identifies and highlights its key features; the model is used to generate explanations and predictions about the phenomenon or system (Harrison & Treagust, 2000). Models can take many forms, such as diagrams, material models, simulations, and mental models. Further, they can represent nonvisible and nonaccessible processes and features (Gilbert, 2004). Modeling is an instructional approach that goes beyond the introduction of explanatory models in the classroom. It entails inquiry that leads to the construction, application, evaluation, and revision of scientific models in response to data about the phenomenon or system (Gobert & Buckley, 2000; Harrison & Treagust, 2000; Lesh & Doerr, 2003; Schwarz, *et al.*, 2009). Hence it is of interest to teachers with either a constructivist or a sociocultural perspective.

Schwartz and her colleagues (2009) operationalize the practice of modeling as four elements:

- Students *construct* models consistent with prior evidence and theories to illustrate, explain, or predict phenomena.
- Students *use* models to illustrate, explain, and predict phenomena.
- Students compare and *evaluate* the ability of different models to accurately represent and account for patterns in phenomena, and to predict new phenomena.
- Students *revise* models to increase their explanatory and predictive power, taking into account evidence or aspects of a phenomenon (Schwarz, *et al.*, 2009, p.635).

They posit that greater student engagement with these modeling elements accompanies, or should accompany, growing “metaknowledge” that models change as understanding improves (Schwarz, *et al.*, 2009).

Windschitl, Thompson, and Braaten (2008) advocate for “model-based inquiry,” a type of modeling that relies on student discourse to create testable explanations for the way the world works. They identify four interconnected “conversations” that support students’ understanding of the essential work of science: 1) organizing what we know into tentative models and listing what we’d like to know; 2) generating hypotheses about variables within the model or about competing models; 3) seeking evidence to test hypotheses; and 4) constructing an argument that explains the data and suggests possible model revisions (2008, p. 15). The authors suggest a set of guiding questions for each conversation, and they note that the four conversations rarely take place in sequence because new data or insights at any point lead students to revisit earlier conversations. They argue that as students’ experience with “model-based inquiry” grows, they become better inquirers, learning to ask themselves the conversational questions without prompting from the teacher (Windschitl, Thompson, & Braaten, 2008).

While classroom inquiry and investigative activity provide context and space for knowledge building, modeling helps to advance students’ scientific reasoning along the five tenets of scientific knowledge: that ideas represented as models are testable, revisable, explanatory, conjectural, and generative (Windschitl, Thompson, & Braaten, 2007; Windschitl, Thompson, & Braaten, 2008). Modeling can facilitate the generation of new knowledge for the student (Gilbert, 2004).

Some adherents of modeling argue that modeling is more than just another way for students to gain access to the subject matter; they maintain that the process of

modeling (model revision in particular) constitutes a type of scientific thinking (Gobert & Buckley, 2000; Harrison & Treagust, 2000; Schwarz, *et al.*, 2009; Smith, Snir, & Grosslight, 1992; Windschitl, Thompson, & Braaten, 2008). “Engaging learners in modeling practice enables them to revise their own conceptual models and to use those revised models in reasoning” (Schwarz, *et al.*, 2009, p. 634). Students enter the science classroom with some “commonsense theories” (Smith, Macklin, Grosslight, & Davis, 1997) or mental/conceptual models (Gobert & Buckley, 2000; Norbert, 1983) about their natural world. In order for conceptual change to occur, Strike and Posner hold that four conditions must be met: (1) students must be dissatisfied with their current conceptions; (2) a new conception must be understood at some minimal level; (3) students must find the new conception plausible; and (4) the new conception must hold the promise of opening up new areas of inquiry and have explanatory power (1985, p. 216). In addition, Schwarz and her colleagues contend that revising a conceptual model requires “metamodeling knowledge” about what scientific models are, why they are used, and how they are used (Schwarz & White, 2005; Schwarz, *et al.*, 2009). A student who has, or is developing, metamodeling knowledge and encounters compelling data, possibly in new contexts, that demonstrate limitations or problems with his current conceptual model, is ready to reason through a revision of his model. Thus modeling can be a form of scientific thinking tied to improved understanding (Gobert & Buckley, 2000; Schwarz, *et al.*, 2009; Smith, Snir, & Grosslight, 1992).

A Theoretical Look at Teaching Density

This section of the chapter examines the teaching of density through a theoretical lens. As density is a complex concept that students are often unprepared to study, the traditional approach to teaching density in the middle grades best fits the characterization of behaviorist classroom practice (Smith, Maclin, Grosslight, & Davis, 1997). This section discusses the challenges that teachers encounter when teaching density, including the influences of the California Content Standards, assessments, and textbooks on maintaining the status quo. The section closes with an introduction to the National Science Education Standards (NSES) and the recently released Next Generation Science Standards (NGSS), which encourage teachers to tackle density from constructivist and sociocultural perspectives.

Behavioralist Response to the Difficulties of Teaching Density

Students have a hard time understanding the “nonobvious” nature of density because it is relational, and so is inferred rather than seen (Grotzer & Bell, 1999; Ritscher, Lincoln, & Grotzer, 2003). Minimally, students must have a grasp of both volume and mass before understanding density, but schoolchildren often conflate the concepts of matter, mass, and volume in various ways (Driver, et al., 1994; Smith, Carey, & Wiser, 1985; Smith, Maclin, Grosslight, & Davis 1997). Volume is treated as an abstract, empty space (length times width times height) in math. An 11-year-old who is confronted with a wooden block in science class can calculate its volume with a ruler, just as she would in math class. However, does she relate this calculation to the mass the wooden block contains? She can heft the block, feeling

the mass. She can heft a larger block and notice that whereas it feels more massive, it also multiplies out to a larger volume mathematically. Yet at what point can this student's science teacher discern that she is talking knowingly about the volume of the solid rather than its mass (Driver, et al., 1994; Smith, Maclin, Grosslight, & Davis 1997)? Students can begin to understand the effect of volume on the density of matter only when they see volume as a measurement separate from mass.

In middle-school science textbooks, density is defined as a property of matter that is either a "ratio" quantity of an object's mass compared to its volume, or as a "per" quantity: mass per unit volume as a characteristic property of a substance (Smith, Macklin, Grosslight, & Davis, 1997, p. 319). In order to teach density, all teachers review the components (matter, mass, weight, and volume), but few take the constructivist or sociocultural step of organizing the instructional opportunities around students' initial understandings of these concepts (Grotzer, Powell, Carr, & Cooke, 2011; Smith, Maclin, Grosslight, & Davis 1997). Smith and her colleagues have repeatedly shown that students often confound the concepts of weight and density (Smith, Carey, & Wiser, 1985; Smith, Macklin, Grosslight, & Davis, 1997; Smith, Snir, & Grosslight, 1992). Moreover they found that many middle-school students have a commonsense theory of matter in which weight and density are conflated (*i.e.*, "heavy" and "heavy-for-size" are combined into an undifferentiated weight-density concept), and matter exists only as a readily observable solid, ceasing to exist when it cannot be seen or touched. Students who hold this commonsense theory of matter will not know what to make of density problems that involve

calculating the density of a gas, or analyzing why carbon dioxide gas (which is 1.5 times denser than air) sinks in a classroom demonstration. They can memorize the formula *density equals mass divided by volume* to calculate the density of an object, but what does the answer represent if they think that mass and density might be different ways to measure the same property? Can a student explain his understanding that the heavier an object is, the denser it must be? The concept of density requires a grasp of ratio and proportion, as well as a well formed understanding of matter, mass, weight, and volume, yet even by ninth grade these ideas are not fully developed in many middle-school children (Smith, Maclin, Grosslight, & Davis 1997).

Another factor making density hard to teach is the complexities in measuring volume and density. Whereas students tend to encounter few difficulties estimating mass, they often find it challenging to measure volume because it is three-dimensional. Volume is also phase-dependent: it varies according to thermodynamic properties such as pressure and temperature, *e.g.*, the volume of a copper penny as a solid at room temperature is vastly different from the volume of that same penny in the gaseous state. Further, volume is measured in both liters and in cubic units such as cubic centimeters, and the measurement labels do not necessarily match the nature of the material being measured (as in, for example, five cubic centimeters—or cc's—of saline solution). These factors can complicate a student's efforts to measure volume. As the ratio of mass to volume, density is difficult to teach both for the impossibility of measuring it directly and for the complexities in measuring volume.

In response to the difficulty of teaching density and to students' uncertain prerequisites for understanding the concept, teachers have traditionally taken a behaviorist approach to the subject. When Smith and colleagues (1997) studied density instruction, they saw well organized, didactic presentations that stripped the concept down to its formal essentials that did not investigate or address students' initial knowledge or commonsense theories about ratios, mass, volume, and matter. New conceptions were taught by means of mathematical formulas and technical language that were unlikely to support conceptual understanding. Students' learning was assessed by asking students to calculate densities rather than to explain results. In sum, the concept of density is difficult to teach and learn, and researchers studying science classrooms have found that the commonly used behaviorist methods have had little success in promoting scientifically accepted understandings (Hitt, 2005; Smith, Maclin, Grosslight, & Davis 1997).

Behavioralist Standards and Textbooks

Density and mass first appear in the California science standards in eighth grade. Volume appears in the second-grade standards, "*students will measure length, weight, temperature, and liquid volume with appropriate tools and express those measurements in standard metric system units*" (California Science Content Standards, 1998, p.6), in the fourth-grade standards, "*students will measure and estimate the weight, length, or volume of objects*" (p.13), and again in the eighth-grade standards (p. 31). California eighth graders are expected to "*know that density is mass per unit volume*" (California Science Content Standards, 1998, p 31). This

standard represents the complicated concept of density as a transmittable fact, and teachers tend to respond by using numbers and definitions to teach it. The design and content of the California science standard for density fosters behaviorist pedagogical frameworks that are reproduced faithfully in teacher-centered classrooms where students learn to give the correct answers using formulas and calculation.

Teachers are also aware that the California standards on density will be assessed by the state in terms of students' computational knowledge and mathematical understanding of the concept. Eighth graders take the California Standards Test (CST) in science, and density is a tested concept. The California Department of Education (2009, p.10) released the following density items as typical questions from earlier years' CST science tests:

5 Red-clay bricks have a density of approximately $2000 \frac{\text{kg}}{\text{m}^3}$. Air has a density of $1 \frac{\text{kg}}{\text{m}^3}$.

Which of the following has the lowest mass?

- A 2 m^3 of bricks
- B 4 m^3 of bricks
- C 6000 m^3 of air
- D $10,000 \text{ m}^3$ of air

17 What is the density of a 64-g iron cube that displaces 8 mL of water?

- A $512 \frac{\text{g}}{\text{mL}}$
- B $32 \frac{\text{g}}{\text{mL}}$
- C $8 \frac{\text{g}}{\text{mL}}$
- D $4 \frac{\text{g}}{\text{mL}}$

Figure 2. Two density items from previous California Standards Tests in science

These multiple-choice items reflect the individual student's mathematical knowledge of density in a relatively context-free state. Students calculate and manipulate measurements and the formula rather than demonstrate an understanding of what

density means. The state of California evaluates the eighth-grade density standard with questions that require behaviorist knowledge of density rather than a demonstrated understanding of the concept.

Textbooks build on standards, and so the science textbooks adopted in California lay out a science curriculum based on the California content standards. They carry implicit behaviorist ideas and expectations from the standards into that curriculum. For example, an eighth-grade science textbook adopted by California, *Focus on Physical Science* (2001), introduces the concept of density as: "[d]ifferent substances may have the same mass, but they don't necessarily fill the same volume...density is the measurement of how much mass is contained in a given volume" (p. 450). The book gives the formula for density and offers several practice problems, such as "[t]he density of aluminum is 2.7 g/cm^3 . A metal sample has a mass of 52.0 grams and a volume of 17.1 cubic centimeters. Could the sample be aluminum? Explain your answer" (p 451). The textbook opens the eighth grader's world to the study of density with a definition, a formula, calculations, measurements, rote practice though problems set up in simplified contexts, and the goal of mathematically understanding the density formula rather than the concept itself. California teachers who want to develop density instruction from the constructivist or sociocultural perspective find little to assist them in their science standards or textbooks.

Other Theoretical Perspectives—National Standards

In 1996 the National Research Council published the first national standards, the National Science Education Standards (NSES), as guidelines for K-12 science education (see <http://www.csun.edu/science/ref/curriculum/reforms/nses/>). In 2011, the Council released *A Framework for K-12 Science Education*, an updated education document grounded in recent research on science and on how students learn science effectively. Relying on the 2011 *Framework*, 26 states, including California, took the lead in the development of a second set of national standards, the Next Generation Science Standards (NGSS), which were completed in 2013. The NGSS are designed to provide K-12 students an internationally benchmarked science education that prepares them for college or career (see <http://www.nextgenscience.org>).

In contrast to the California content standards for science, both sets of national science standards allow teachers to move away from behaviorist goals and practice. The NSES recommends teaching density through observation and inquiry in grades 5-8, and the content standard is simply stated as "... [a] substance has characteristic properties, such as density, a boiling point, and solubility..." (NSES, 1996, p.154). A sample lesson for teaching density accompanies the standard. It asks teachers to take several days to allow students to explore the relative densities of metals, wood, and various liquids. What follows is an excerpt from the sample lesson taught by Mr. B.:

For the first day, he prepared two density columns: using two 1-foot-high, clear plastic cylinders, he poured in layers of corn syrup, liquid detergent, colored water, vegetable oil, baby oil, and methanol. As the students arrived, they were directed into two groups to examine the columns and discuss what they saw. After 10 minutes of conversation, Mr. B. asked the students to take out their notebooks and jot down observations and thoughts about why the

different liquids separated. When the writing ceased, Mr. B. asked, "What did you observe? Do you have any explanations for what you see? What do you think is happening?" He took care to explain, "There are no right answers [*sic*], and silence is OK. You need to think." Silence was followed by a few comments, and finally, a lively discussion ensued" (NSES, 1996, p.150).

The subsequent parts of this lesson are student-driven, with full periods devoted to observing, predicting, and describing the behavior of different liquids and solids relative to each other. On the final day, the teacher sums up the classwork by giving a homework assignment in which students write down their ideas explaining the substances' different behaviors and identify examples of densities that they see in their daily lives. For grades 5-8, the NSES emphasizes the concept of density as a property of matter; matter can be described based on its behavior, and students observe how substances of different densities behave relative to each other.

Unlike the behaviorist expectations embedded in the California standards and textbooks, the NSES standard for density and the sample lesson do not rely on definitions, formulas, or measurements. Students observe and compare the floating/sinking behaviors of different substances. Instead of receiving didactic instruction and practice problems set in simplified contexts, they participate in an interactive environment that allows them to construct an understanding of density through reasoning activities and the discussion of examples and problems. Students are steered towards an atomistic understanding of how matter might be "compressed" or "decompressed" (Smith, Maclin, Grosslight, & Davis 1997). Their own developing expert knowledge does not consist of the isolated facts or propositions that appear as items on multiple-choice tests, but the ability to understand density in a

range of applications (Bransford, et al. 1999). The NSES approach to teaching density is informed by a constructivist perspective.

The newly released Next Generation Science Standards also represent a departure from behaviorist pedagogy. The NGSS advocate inquiry approaches to teaching science, and they define “inquiry” as a set of eight science and engineering practices:

1. Asking questions (for science) and defining problems (for engineering)
2. Developing and using models
3. Planning and carrying out investigations
4. Analyzing and interpreting data
5. Using mathematics and computational thinking
6. Constructing explanations (for science) and developing designs (for engineering)
7. Engaging in argument from evidence
8. Obtaining, evaluating, and communicating information (Appendix F, NGSS, 2013, p.1)

Few of these practices are compatible with behaviorism. Number 2 calls for modeling explicitly, yet the inquiry-driven modeling discussed earlier in this chapter (Schwarz, *et al.*, 2009; Windschitl, Thompson, & Braaten, 2008) draws on all eight practices. Numbers 2, 6, 7, and 8 emphasize student initiative, dialogue, and the acquisition of fluency in scientific literacy and communication. To adopt these NGSS practice standards, teachers will need to have an understanding of constructivist and sociocultural perspectives.

The NGSS set performance expectations, statements of what students should be able to do after instruction (NGSS, 2013). Whereas previous standards defined student expectations in terms of skills and learned facts, such as “Students know density is mass per unit volume” from the California Content Standards for Science

(1998, p 29), the NGSS use the term “practice” to emphasize that science activity requires knowledge that is specific to scientific inquiry, skills, and understanding. Key attributes of NGSS performance expectations include the recognition of patterns and variance in patterns, a grounding in scientific principles leading to the development of models for understanding, and a demonstration of science literacy in the clarity of arguments and the strength of claims and evidence.

Each NGSS standard is built on three “dimensions” as follows:

1. Investigative and engineering practices, theory development, modeling; inquiry as the formulation of a question that can be answered via investigation; engineering design that solves a problem; the collection of cognitive, social, and physical practices that solving problems require
2. Crosscutting concepts to link the different domains of science: structure and function, cause and effect, patterns and diversity, energy and matter; students will now interrelate knowledge from various scientific fields into a coherent whole
3. Disciplinary core ideas: core ideas will focus K-12 science on the most important ideas and include two or more of the following: have broad importance; provide a key tool for understanding; be relatable to life experience of students or be related to societal or personal concerns; and be teachable and learnable over multiple grades in increasing depth (*Next Generation Science Standards*, 2013).

Density is a disciplinary core idea, and the global pattern of ocean currents is a crosscutting concept that contextualizes the study of density in the middle grades.

The NGSS standard that introduces density (MS-ESS2-6 Earth’s Systems) is:

“Develop and use a model to describe how unequal heating and rotation of the Earth cause patterns of atmospheric and oceanic circulation that determine regional climates” (NGSS, 2013). Three core ideas are represented in this standard:

- 1) variations in density are due to variations in ocean temperature and salinity, which drive a pattern of interconnected ocean currents;

- 2) weather and climate are influenced by interactions involving sunlight, the ocean, the atmosphere, ice, landforms, and living things; and
- 3) the ocean exerts a major influence on weather and climate by absorbing energy from the sun, releasing it over time, and globally redistributing it through ocean currents (NGSS, 2013).

Unlike the California Content Standards that regard density as a fact that students must know, this NGSS standard embeds the study of density in practice. Students will be expected to demonstrate their understanding of density through modeling and argumentation. The NGSS set density instruction, and science instruction in general, on a path away from behaviorist patterns of knowledge transmission and towards constructive and social activity.

Classroom Studies of Teaching Density

Carol Smith and her colleagues figure prominently in the research on teaching density. Publishing in the 1980s and 1990s, Smith studied children's understandings of the subject and proposed an alternative eighth-grade density curriculum. Two other scholars have also reported on the teaching of density because density instruction offered a platform for their own innovations. First, Tina Grotzer's publications on teaching density span the past 15 years; as part of the Understandings of Consequence research, her studies examine how understandings of causality (such as students' ability to comprehend relative density through a causal model) impact ability to deal with complexity in the world. Second, Richard Shavelson and his research team turned their attention to the teaching of density in the early 2000s when they developed, pilot-tested, and revised a suite of formative assessments for a

curriculum on floating and sinking (buoyancy and density) taught in the middle grades.

Carol Smith and coauthors Macklin, Grosslight, and Davis (1997) challenged the behavioralist goals and practices commonly guiding density instruction in eighth grade. They argued that good science education should recognize both formal and qualitative or conceptual sources of understanding and that students should be encouraged to develop their own intuitions to support learning. They criticized density instruction that ignored visual models and failed to rely on student discussion and reasoning. They noted:

[i]t is important to shift the focus of instruction from an exclusively text-centered and quantitative approach to one that incorporates students' starting conceptions as essential material and that helps students to build quantitative conceptions from more qualitative notions (1997, p. 385).

Smith and colleagues tested their constructivist approach against a behavioralist approach through a quasiexperiment in which two classes of eighth-graders received ten weeks of different lessons on density. The teacher of the comparison group taught, with traditional methods, a textbook-driven unit focusing on definitions, measurement, calculations, and quantitative reasoning, and the intervention teacher taught a curriculum modified by the researchers to include content and interactive activities designed to help students become aware of their own theories and evolving understandings. In the intervention instruction, analogies, diagrams, and pictures served as avenues for students to connect new ideas to their initial conceptions. Before they had had instruction on density as a ratio of mass to volume, students compared the densities of objects using their own nonformal

reasoning, such as describing lead as “heavy for its size,” or a one-inch cube of aluminum as “more densely packed” than a one-inch cube of wood. The researcher-modified lessons asked students to conduct thought experiments and engage in group discussion about both their results and their understandings (Smith, Maclin, Grosslight, & Davis 1997). The researcher-modified curriculum and methods introduced a constructivist perspective to the teaching of density.

Based on preinstruction and postinstruction interviews and tests, the researchers found that although both approaches resulted in a quantitative understanding of mass, volume, and density, the constructivist approach was more effective at promoting systematic improved understanding. All of the students who received the modified, constructivist lessons on density became cognizant of their commonsense intuitions and restructured them to accommodate new ideas and the understandings necessary for comprehending density formally. They used their new conceptions to explain a wide range of phenomena, such as why the density of a substance is not constant under different conditions. At the end of the density unit in the comparison classroom, some students still held onto their initial notions that matter must be visible to exist and that weight and density are the same. Smith and colleagues found that the behaviorist curriculum and instruction (referred to in her work as the “standard curriculum”) were less effective at helping students change their conceptualizations and overall understanding of density (Smith, Maclin, Grosslight, & Davis 1997).

Grotzer and the Understandings of Consequence research team at Harvard conducted later studies of density instruction in middle school. Grotzer's line of research builds on Smith's work and accepts that best practices in science are aligned with the constructivist perspective and the importance of student modeling.

Perkins and Grotzer (2005) distinguish their interest in studying learners' repertoires of models, especially causal models, from modeling research that deals with either the elucidation of student models or their process of model building (p. 119). [Causal models help students investigate questions about causal relations and explain nonobvious phenomena, such as why two items with different volumes can have the same mass. Modeling was central in the study I conducted, but not causal modeling. I was concerned with the development and use of models to deepen students' understanding and differentiation of mass and density, rather than to explore questions such as "why is wood less dense than aluminum?"] Perkins and Grotzer argue that students need to learn causal models to fully understand complex science topics such as density and that learning such a causal model lays a foundation for developing models to master other complex concepts later. They tested their hypotheses with quasiexperimental classroom intervention studies that showed that students who were introduced to complex causal models for density and electrical circuits were more likely to hold accurate and complex understandings of the subjects postinstruction (Perkins & Grotzer, 2005).

Grotzer and her colleagues made constructivist practices a foundation of their research, even in comparison or control classrooms:

Great effort was invested in “honest” control conditions that supported learning with understanding, without foregrounding complex causality. The control group instruction included Socratic discussion, computer simulations, grappling with discrepant events, and so forth. All of the students engaged in constructing models (on white boards, in journals, etc.), sharing and discussing those models, and critiquing the models in terms of which had the most explanatory power given the evidence that students were discovering. The teachers and researchers scaffolded these discussions to help students focus on bringing evidence and counter-evidence to bear on the process of critiquing the models.... The instructional design assumed that students’ models would evolve and change over the course of repeated explorations” (Perkins & Grotzer, 2005, p. 137).

They also asked science teachers to employ constructivist practices such as giving students multiple opportunities to explore, observe, and discuss the interaction of mass and volume, in activities such as relating formulas to visual models whenever they instruct students to reason about density as a causal system. Grotzer promoted a constructivist approach through the online publication of a teacher’s manual of density lessons (President & Fellows of Harvard College, 2005), in professional development designed to augment teachers’ pedagogical content knowledge about density, that is, their capacity to blend knowledge of density and knowledge of pedagogy into good density instruction (Grotzer, Powell, Carr, & Cooke, 2011; Shulman, 1987), and through her research.

In the early 2000s, a research team at the Stanford Education Assessment Lab, directed by Richard Shavelson, developed a suite of formative assessments that they embedded into a 10-week curriculum to teach density and buoyancy in the middle grades. The goal of the embedded assessments was to provide teachers with frequent, timely information about what students were and were not learning in the lessons so that the teachers could adjust their instruction quickly in response. Through the pilot

test of the assessment tasks and a subsequent study of the videotaped lessons, the research team discovered that teachers found the assessments unwieldy and that they did not use the assessments formatively (Shavelson, 2006). The team then adapted the embedded assessments into “reflective lessons,” which serve to improve teaching and learning for both teacher and student, allowing them to reflect on progress while instruction is still taking place. Their reflective lessons recast the assessment suite as “...teaching tools to elicit teachable moments in the pursuit of an answer to the question, why do things sink and float?” (Shavelson, 2006, p.13). The reflective lessons were designed to help teachers meet the following classroom goals for teaching density:

...to elicit and make public student sinking-and-floating conceptions, encourage communication and argumentation based on evidence from the investigations or assessment tasks, challenge students’ why-things-sink-and-float conceptions, help students track their sinking and floating conceptions and help students reflect on these concepts (Ayala *et al.*, 2008, p.322).

Through professional development, teachers were encouraged to think of the embedded formative assessments not as summative tools, but as scripts for lesson feedback for the use of both teachers and students. The focus on student discourse, reasoning, and reflection in these formative reflective lessons was consistent with constructivist and sociocultural practices for the teaching of density.

Theoretical Perspective for My Study

My sense-making of the research literature reviewed in this chapter laid the foundation for the density study that I carried out in my classroom. This section

summarizes my understanding and use of that literature for my own practice and for the study.

I have been a science teacher for 13 years. The behavioralist perspective framed my experiences as a K-16 student and my formal teacher preparation in the 1980s. I learned that good classroom management and maintaining quiet students who listened to the teacher's talk were top priorities, and my first two years of teaching science reflected those priorities. In my third year of teaching science, I switched to sixth grade, and my pedagogical practice gradually shifted towards constructivism. The lab work lent itself to reasoning activities, and sixth graders have a proclivity to ask questions. Little by little I came to see that didactic methods were not very effective ways to increase student understanding in science, and so I strove to engage my students interactively in problem solving, reasoning, and reflection. I made time to investigate what students actually knew as a baseline for my curriculum, and I recognized the value of having them explain their own thinking explicitly. I adopted constructivist goals and practices for my classroom.

Four years ago I became a teacher-researcher, studying student inquiry during science labs and learning about sociocultural theory in my coursework at the university. Once again my practice started to shift—this time informed by the sociocultural perspective. I began to make this shift because I came to see the value of dialogue, that is, students talking and listening to each other in essential ways. I wanted my classroom to become a community of learners in which group sense-making is encouraged. Sociocultural theory offered ways to scaffold my own

pedagogical change, and I discovered that a socially organized classroom rich in dialogue and community problem solving is an excellent learning space. Whereas a constructivist classroom can appear to be a lively and dynamic learning environment, the teacher tends to be the questioner and the students tend to be the respondents. When I began teaching my goal was to always ask excellent questions. Now I am much more interested in encouraging my students to ask each other excellent questions, and I give them time to learn from each other as they formulate questions, argue their positions, and explain increasingly complex material to each other. This “distribution of responsibility for proposing questions and explanations” (Greeno, p. 20) creates different patterns of discourse in my socially complex classroom than those in my earlier, teacher-driven classes.

At the time of my study, my teaching was at the intersection of the constructivist and the sociocultural perspectives. Against this backdrop, woven from both constructivist and sociocultural threads, I posed questions about how a complex modeling intervention (Schwarz, *et al.*, 2009; Windschitl, Thompson, & Braaten, 2008) with an emphasis on science dialogue (Hakuta, Santos, & Fang, 2013; Quinn, Lee, & Valdes, 2012; Wells, 1991) would affect student understanding of mass, volume, and density. I was particularly interested in learning more about the students’ roles in their own learning of complex subject matter, and how their thinking changed as they experienced and discussed novel situations together. My early experience as an instructor had almost always been top-down in the way I guided learning, discussion, and observation, and I generally had one right answer in

mind when posing a question to the class. Shifting my practice to include open-ended questions, generated by both the students and me, and emphasizing the use of my students' models for understanding and prediction, encouraged my students to become coconstructors of the community learning environment in our classroom.

This chapter presented the theoretical perspectives and research that have informed my study. In the first section I introduced a framework for teaching and learning by Greeno, Collins, and Resnick (1997) and discussed how research on student discourse and dialogue, science language and literacy, and modeling has expanded that framework. The second section applied a theoretical lens to the teaching of density and to factors influencing it. The third section reviewed studies of density instruction, and the last section laid out my own response to this literature in terms of my classroom practice and my study.

CHAPTER 3

RESEARCH DESIGN AND METHODS

In this chapter I document the major methodological decisions made during my study. Perhaps the most difficult of those decisions dealt with the research question, which varied in its focus as I progressed in the research. The early data collection for my study informed me that my first research questions were not applicable to my student population. Then the complexity of the intervention, which relied on modeling, extensive student dialogue, formative assessments, the substitution of hands-on inquiry for mathematical problem sets, and thought experiments, offered various avenues of study. In the end, I realized that modeling and student discourse were not only central to the intervention I conducted, but were also the practices most likely to influence student learning. Hence my final research question was: does classroom practice that encourages modeling with open-ended discourse help students differentiate between the concepts of mass and density?

This chapter lays out the research design and methods used in my study of density instruction. The first section introduces the research design, the study setting, and the sixth graders who participated. The second section contrasts the intervention and comparison conditions in the study. In the third section I describe the data collection instruments and methods, and I present the data analysis methods in the final section. I include the formative assessments or “reflective lessons” (Ayala *et al.*, 2008; Shavelson, 2006) from the intervention in both the data collection and data analysis sections. They provided me with data indicating that my teaching of the

intervention was on track but not with data that helped answer my final research question, so I describe them here but omit them from the results chapter.

Research Design, Setting, and Participants

The research reported on in this dissertation, as already noted, was inspired by an earlier study comparing two approaches to teaching density in eighth grade (Smith, Macklin, Grosslight, & Davis, 1997). Smith's study took place at one school where the researchers matched two science teachers on their teaching experience, knowledge of subject, and reflective practice, and they assigned the intervention role to the teacher who was more curious about student conceptual change. The comparison classroom followed a textbook-driven unit, supplemented with lab work, that focused on augmenting students' formal or mathematical knowledge of density, whereas the intervention classroom was taught a curriculum modified by the researchers to include content and activities designed to help students become aware of, and enhance, their own theories of density. Using data collected from a subset of 15 students in each of the two classrooms both pre- and post-instruction, the researchers scored students' written responses to test and interview questions and examined them qualitatively for indications of conceptual growth. They found that both approaches resulted in a mathematical understanding of mass, volume, and density in terms of estimations and calculations, but the intervention students developed a deeper conceptual understanding of density than the comparison students (Smith, Macklin, Grosslight, & Davis, 1997).

Like Smith's work, my study also employed a quasiexperimental research design (Shadish & Luellen, 2006) to compare the effects of teaching density differently in two classrooms, but there are also important differences. In my study I was the sole science teacher, a fact that established a common pedagogical baseline from which the intervention was introduced into one classroom. It was not possible to assign students to classrooms for study purposes. Data were collected on a subset of 15 students from the intervention classroom and 15 from the comparison classroom both prior to and after the instructional period in order to address student performance and improvement. Like the findings that Smith and colleagues (1997) report, the results of this study reflect the limited number of student participants and so are intended to be suggestive rather than statistically significant.

The study was set in the only middle school of a small California elementary district with total enrollment of 2005 students in the 2013-2014 school year. That year approximately 55 percent of the district's students were "White, not Hispanic" and 34 percent were "Hispanic or Latino of any race." Roughly 12 percent of district students were classified as English learners (California Department of Education, 2014). At the middle school where the study was conducted, about seven percent of the students were English learners, and 37 percent of the students qualified for free or reduced-price lunch in 2013-2014. The school has a history of solid academic performance, ranging from five to 15 percentage points above annual statewide averages on the California Standards Tests in English, math, social science, and

science in recent years (School Accountability Report Card Reported for School Year 2013-2014, 2015). The school is designated a California Distinguished School.

At the time of the study, the state of California did not test sixth graders in science; therefore I was free to restructure the density unit in the sixth-grade curriculum into a dialogue-intensive modeling intervention for one of my classes. From my five classes of sixth-grade science, I selected my third-period class as the comparison classroom and my sixth-period class as the intervention classroom. Because sixth graders who are English learners are not offered science at my school, neither class had designated English learners. Both classes had a balance of regular-math and honors-math students and similar gender ratios. The sixth-period class became the intervention classroom because of logistics. Intervention labs required extra time to set up and break down, and as the sixth-period class was situated between my lunch period and the end of the day, it was the simpler choice for the intervention classroom.

Although assigning students to the intervention or comparison classroom was not possible, the students in the two classrooms were similar in terms of ethnicity, gender, and academic performance. In order to have comparable groups of participants and to be economical with my time—I was a full-time teacher and graduate student during this research—I narrowed my data collection to a subset of 15 students in the intervention classroom and 15 similar students in the comparison classroom. Using the students' science grade immediately before the study began (either A, B, or C), I formed three graded groups and randomly selected five

intervention and five comparison participants from each graded group for data collection and analysis. Table 1 summarizes the demographic characteristics—as identified by the state of California—and the prior achievement of the 15 study participants in each group.

Table 1
Participant Characteristics and Prior Achievement
by Intervention and Comparison Status

	Intervention group	Comparison group
Number of participants (sixth graders)	15	15
6 th -grade science grade before the study began	A: 5 students B: 5 students C: 5 students	A: 5 students B: 5 students C: 5 students
English learners	0	0
Gender	Female: 9 Male: 6	Female: 8 Male: 7
Race/ethnicity	White, not Hispanic: 8 Hispanic/Latino any race: 5 Other: 2	White, not Hispanic: 8 Hispanic/Latino any race: 5 Other: 2
California Standards Test 5 th -grade math	Proficient or Advanced: 13 Basic: 1 Below Basic: 1	Proficient or Advanced: 12 Basic: 1 Below Basic: 2
California Standards Test 5 th -grade English	Proficient or Advanced: 14 Basic: 1 Below Basic: 0	Proficient or Advanced: 14 Basic: 1 Below Basic: 0

Description of the Intervention

My study investigates the outcomes from encouraging modeling and open-ended student discourse in the teaching of density. To keep the focus of the intervention on instructional practice, I tried to maximize continuity in the curricular elements of the density unit across the comparison and intervention classrooms.

Table 2 presents these elements. Both classes reviewed/learned about measuring mass, volume, and density, and both spent the bulk of the unit doing activities to develop greater understanding of density as a characteristic property of matter. Both classrooms investigated how temperature affects the density of matter. The comparison classroom spent more time on buoyancy, but I introduced the concept in terms of neutral buoyancy to the intervention group. The curricular dissimilarities dealt with the importance of doing calculations and problems applying the density formula in the comparison classroom and learning about the particulate nature of matter and relative densities in the intervention classroom.

Table 2
Curricular Elements of the Density Unit
in the Intervention and Comparison Classrooms

Intervention	Comparison
Measurement of mass, volume, and density	Measurement of mass, volume, and density
Density as a characteristic property of matter	Density as a characteristic property of matter
Density varies by temperature	Density varies by temperature and by state
Neutral buoyancy	Buoyancy
	Density problems and calculations (density formula)
Particulate nature of matter	
Comparison of relative densities	

At the time of the study, my teaching practice was influenced by both the constructivist and the sociocultural perspectives. In my classes I nurtured a community of learners and encouraged open-ended questions and class discussion. The format of my classrooms almost exactly mirrored the “intentional learning environment” described by Brown (1992), except that I also used a structured literacy curriculum including direct vocabulary instruction (Marzano, 1996) that increased in breadth as the students’ understanding gained greater depth. Like Brown’s ideal learning environment for a science classroom, my classrooms had the following features: 1) students are researchers and are themselves teachers; 2) teachers guide discovery and model active inquiry; 3) the act of thinking serves as a valid form of inquiry; 4) curricular content is deep with recurring themes that provide explanatory coherence and increasingly finer detail; and 5) assessment measures knowledge discovery and application through performance, portfolios, and projects (Brown, 1992). These elements of practice were present in both the intervention and comparison classrooms throughout the study.

To help students better understand the concepts of mass and density, I taught a complex intervention featuring modeling and open-ended discourse to one class. The work of Carol Smith on density instruction (Smith, Maclin, Grosslight, & Davis, 1997; Weight and Density Research Group, 1994), recent research on modeling in science (Schwarz, *et al.*, 2009; Windschitl, Thompson, & Braaten, 2008), and the literature on student discourse (Hakuta, Santos, & Fang, 2013; Quinn, Lee, & Valdes, 2012; Wells, 1991) are the main sources influencing the design of the intervention. I

also incorporated three “reflective lessons” or embedded formative assessments (Ayala *et al.*, 2008; Shavelson, 2006) into the intervention to provide me with feedback on students’ progress.

Interviewer: If I move this thermometer from a cold-water bath to a warm-water bath, ... does the density of the alcohol [in the glass tube] change? Please explain your answer.

Student 1: No, the density doesn’t change. Alcohol is getting pulled up from the puddle at the bottom of the tube, and the density is the same because the alcohol doesn’t change.

Interviewer: If I move this thermometer from a cold-water bath to a warm-water bath, does the density of the alcohol in the glass tube change? Please explain your answer.

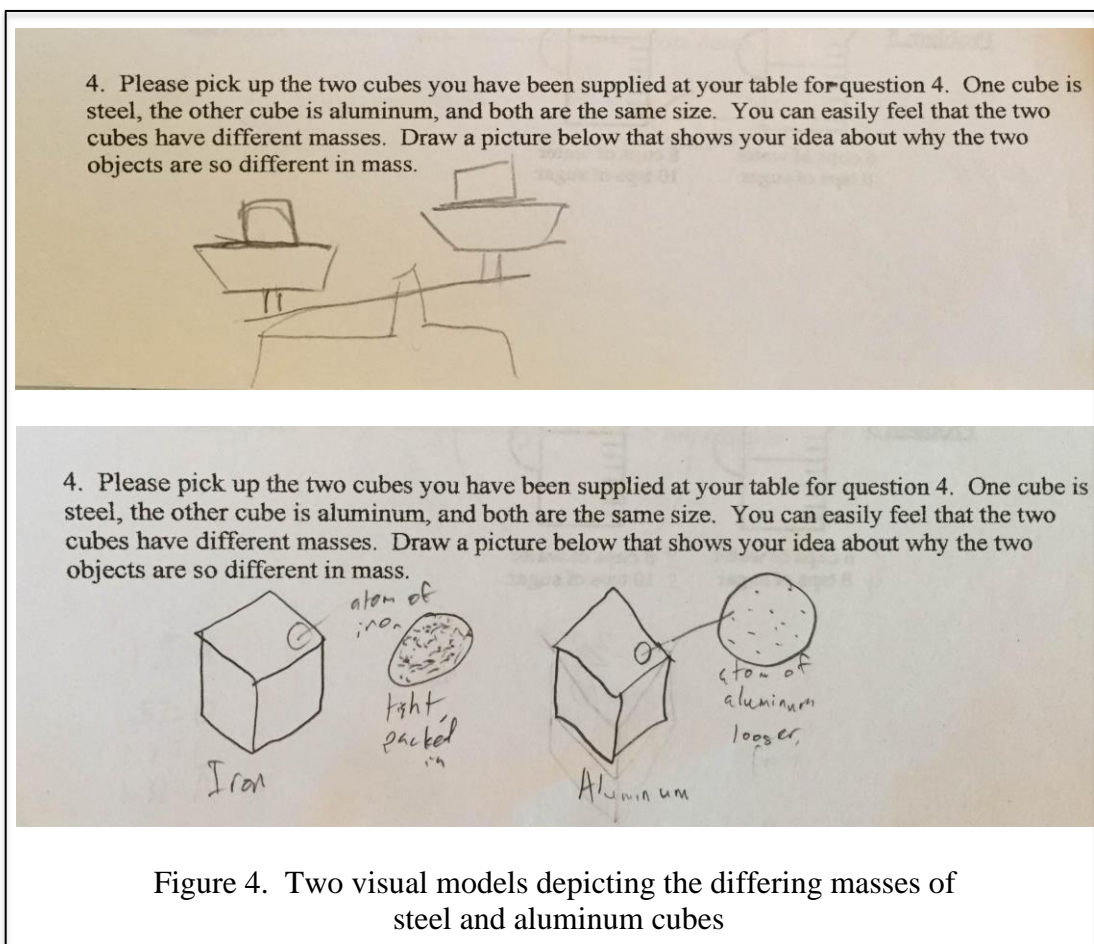
Student 2: Yes, the density does change. The atoms are moving further apart, [making] more volume and less mass.

Figure 3. Two verbal models to explain the variable nature of density

The models in this study can be characterized as verbal, visual, and symbolic, three modes of modeling commonly found in science classrooms (Gilbert, 2004). Only the intervention group did symbolic modeling, and examples are presented in the results chapter. All students were asked to model aspects of mass and/or density in their verbal responses to the data collection instruments, and intervention students spent a considerable amount of time verbally modeling the phenomena they studied and discussing how best to visually depict the models they articulated. Figure 3

presents examples of verbal models (in this case, descriptions) recorded during the preinstruction interview data collection.

The visual models in this study were predominantly student-developed graphs and diagrams. As with the verbal models, all students were asked to draw visual models as part of the data collection. In addition, intervention students regularly modeled the phenomena they studied visually, and they used their visual models to solve problems. Figure 4 consists of examples of the visual models drawn by students from the preinstruction data collection on the written test.



The intervention in this study was a complex set of instructional activities involving modeling, student dialogue, and reflective lessons. Appendix A details the instruction and instructional goals of the intervention in chronological order.

Appendix B lays out the density instruction in the comparison classroom, and it traces the linkages in curriculum and, to a lesser extent, in instruction, between the intervention and comparison classrooms. For the comparison classroom's instruction, I followed the curricular sequence recommended by our classroom textbook *CPO Focus on Earth Science* (2007) and its accompanying lab manual. I included two enrichment activities of my own design (Lessons 5 and 11, Appendix B) that reinforced the concepts introduced in the chapter and provided both additional practice and additional results to observe.

Methods of Data Collection

I collected the bulk of the data for this study, but I also trained my eighth-grade teacher's aide to help me conduct the pre- and post-instruction interviews. She watched me interview several students at the start of my research, learned when prompting questions were appropriate (for example, in a question that asks for the student to explain his answer), and studied how to fill out the interview form with student responses. Our role as data collectors was similar to that of a test proctor—assuming an impartial, nonparticipatory stance towards recording data from students.

Data were collected from both intervention and comparison students before and after the density unit. My aide and I conducted a clinical interview with all participants both pre- and post-instruction, and I administered a written test to all

participants both pre- and post-instruction. All participants also took the textbook's end-of-chapter test after instruction. In addition, I collected feedback from the intervention students on the three reflective lessons and used it to inform my instruction during the intervention.

Preinstruction Data Collection

Preinstruction interview. My interview protocol (Appendix C) was a modified version of a clinical interview on density developed by Smith, Snir, and Grosslight (1992). The instrument by Smith's group was used to administer a 45-minute oral assessment individually to eighth graders before and after the density unit. I had to adapt the instrument for sixth graders, who may or may not have mastered proportional relationships and calculations for example, and to abbreviate its administration length to 20 minutes due to my full-time teaching schedule and my students' limited availability for an interview. The interviews were administered to all 30 participants prior to the start of the density unit either before school, after school, or during class when necessary. Interviews conducted during class were administered outside of the classroom by my aide. We made digital audio recordings of the interviews and wrote notes about each student's responses on the interview protocol sheet.

I wanted to focus on mass-density differentiation and therefore designed an interview that would shine light on how students talked about 1) density as a variable property of matter and 2) masses of objects of varying densities. Smith and her group had a similar goal, but they were also looking at students' sense-making regarding

proportionality and properties of matter. To ascertain the students' underlying core beliefs about matter, I began the clinical interview with a series of questions regarding the mass and divisibility of two pieces of low-density Styrofoam. One piece was less than one square inch in area, and a smaller piece was a tiny sliver. This material was chosen because, while tactile and visible, its mass was not measureable on our classroom balance. Students were asked if either piece had any mass; if the pieces could be divided into infinitely small pieces; and if the pieces, subdivided into bits too small to see, would still exist (see Appendix C). Smith and her colleagues began their clinical interview with this series of questions to determine students' understanding regarding the particulate nature of matter.

The second and third sets of questions in my interview were also taken directly from the Smith instrument (see Appendix C). In question 2, I gave students pairs of objects to hold and compare, and I asked them to tell me which of each pair had more mass and then which was denser. Students had access to a pan balance to test the comparative masses of the pairs of objects. In the third set of activities, I asked students to put four objects in order from least to greatest mass and then to rank them again from lowest to greatest density. In Smith's interview, students were given a 1-cubic-inch cube of steel, a 1-cubic-inch cube of aluminum, a much larger and heavier aluminum cylinder, and an even larger cylinder covered in paper and made of a mystery material. I selected different materials to avoid shapes that were similar in volume because my students' ability to rank order equal-volume cubes by weight, and therefore density, was already well established by their previous classroom work. I

wanted clear tests of the students' ability to make mass comparisons and density comparisons. The materials my students ordered were a small aluminum cylinder, a larger one-cubic-inch aluminum cube, a larger "mystery" cylinder of stacked-up plastic gram masses covered in paper, and a wooden block that was larger still. Again, students had access to a pan balance for this activity.

The fourth, fifth and sixth items on my clinical interview came directly from Smith's instrument. For question four, participants watched me add a small piece of clay to a clay ball of roughly three inches in diameter. The students were then asked if any of the following changed as a result of my addition: 1) the amount of clay in the ball; 2) the mass of clay in the ball; and 3) the density of the clay. The fifth task asked students to observe the alcohol in a thermometer rise when moved from a cold-water bath to a hot-water bath. I then asked participants the following questions: 1) did the amount of alcohol in the tube change; 2) did the mass of the alcohol change; and 3) did the density of the alcohol change? I encouraged students to explain their answers. For the final question, I asked participants to define the word "density" (see Appendix C).

Preinstruction written test. I gave a written test (Appendix D) to all participants during their science classes just before the start of the density unit. The test was originally developed by Carol Smith and colleagues to assess eighth graders' knowledge of matter, mass, proportionality, and density (Smith, Maclin, Grosslight, & Davis, 1997). As with the clinical interview, I modified the range of four objects to order by density ranking to avoid objects of similar volumes. Otherwise, I replicated

their test without modification. The data I collected was a copy of each participant's preinstruction completed test.

The first three questions on the test dealt with students' understanding of matter. Question 1 presented students with a list of items and asked them to indicate whether or not each item is matter. In question two, students justified their matter decisions in the first question by describing the characteristics of matter, and in question three, they explained how they knew if something is made of matter.

The remaining questions assessed knowledge of density. Question 4 asked students to pick up two equal-volume cubes of aluminum and steel and draw a picture explaining why the cubes differ in mass. Question 5 was a set of five problems about the sweetness of different concentrations of sugar dissolved in water. Question 6 presented students with a diagram of a pan balance that was balancing nine one-gram masses with a cube that had sides three centimeters long. It asked students for the volume, mass, and density of the cube. Question 7 was a density ordering task. Students handled four different objects, each labeled with its volume and mass. They then were asked to rank the objects from least dense to most dense. Question 8, the final question, consisted of five problems. Each problem gave the mass and volume of a pair of objects, and students were asked to determine if the pair could be made of the same material. The full text of the test is in Appendix D.

Postinstruction Data Collection

Postinstruction interview. The postinstruction interview used the same protocol as the preinstruction interview (Appendix C). Interviews were administered

individually to all participants within two weeks of the end of the density unit. My aide and I held the interviews before school, after school, or during class. We made digital audio recordings of the interviews and wrote notes about each student's responses on the interview protocol sheet.

Postinstruction written test. I administered the same written test (Appendix D) given before the density instruction to all participants shortly after we finished the density unit. I kept a copy of each participant's postinstruction completed test for my data.

End-of-chapter test. The end-of-chapter test (Appendix E) was the test for the chapter on density from the textbook that I used in the comparison classroom, *CPO Focus on Earth Science* (2007). The test consisted of 25 multiple-choice questions mostly on density (rather than mass or volume). I administered the test in class to all my students on the last day of the density unit, and I retained a copy of each participant's completed test as data.

Data Collection during the Intervention

The intervention included three embedded formative assessments or "reflective lessons" (Ayala *et al.*, 2008; Shavelson, 2006). Unlike the instruments described above, which were administered to collect data to answer the research question, the purpose of the reflective lessons was to produce data to inform me about the understandings of intervention students so that I could adjust my teaching in timely ways during the intervention. The reflective lessons were chosen from the instructional activities in *Archimedes and Beyond: Helping Middle-School Students to*

Construct an Understanding of Density and Matter (1994), a collection of lessons developed by the Weight and Density Research Group led by Carol Smith at Harvard University.

Reflective lesson 1. The first reflective lesson was “The Kool-Aid Mystery;” see Appendix C to situate this lesson relative to other intervention instruction. I told students that, in a room where four people had been mixing and drinking Kool-Aid, one person had been poisoned. Our police informants told us that the sweetest of the four cups of Kool-Aid contained the poison, and so our job was to find out which cup had the sweetest Kool-Aid. In addition to being a formative assessment for me as teacher, this activity was designed to give the intervention students experience with intensive and extensive quantities and to help them relate the concentration of a solution to their conceptual model of density.

Students carried out the activity in groups of four. They worked with three variables that they had to recognize explicitly as intensive or extensive quantities: 1) the number of cups of water (an extensive quantity); 2) the total number of teaspoons of Kool-Aid (an extensive quantity); and 3) the number of teaspoons of Kool-Aid per cup of water (an intensive quantity). I gave them the following recipes as clues to solve the mystery: suspect A used 20 cups of water and 140 teaspoons of Kool-Aid; suspect B used 12 cups of water and 48 teaspoons of Kool-Aid; suspect C used 12 cups of water and 132 teaspoons of Kool-Aid; and suspect D used 24 cups of water and 132 teaspoons of Kool-Aid. Rather than expect students to know how to recognize and utilize numeric proportions, I suggested that students draw a box to

represent each cup of water and insert a dot in a box for each teaspoon of Kool-Aid, which was the strategy that grew from the students' experiences with modeling their own crowdedness in Lesson 1 (see Appendix A). Then the groups discussed their work and decided which cup was sweetest and therefore contained the poison. To test their results, the groups made one cup of Kool-Aid at each level of sweetness. I collected their paperwork after the activity.

Reflective lesson 2. The second reflective lesson was a check on students' understanding of mass-to-volume relationships in terms of the "heaviness" of objects. Students worked in groups of four. I gave each group two sets of different objects and asked them to develop models with which to compare the density of the different objects in each set. The timing of this assessment lesson relative to other intervention instruction is shown in Appendix A.

For the first set of objects, I did not provide measurements and did not make available pan balances, rulers, or other measuring devices. I wanted the students to use their hands to compare the "felt-weight" (Smith, Macklin, Grosslight, & Davis, 1997) of the objects. The set comprised three equal-volume cubes of different masses—one of acrylic, another of aluminum, and the third of wood—plus a larger volume "mystery" cylinder consisting of plastic 25-gram masses stacked together and covered with paper. All the groups approached this comparative modeling task by varying the shaded darkness or the dot compactness of their object representations.

Precise measurements of mass and volume were given for each of the second set of objects, but this time the objects were imaginary. I asked the students to

imagine a small block of clay with a volume of 2 cubic centimeters and a mass of three grams, and a block of balsa wood with a volume of 10 cubic centimeters and a mass of 4 grams. In addition to requesting students' representations of the different densities of the two blocks, I asked students to use their density models to predict the volumes of other clay and wood objects with different masses. At the end of class, I collected the models and predictions from each group.

Reflective lesson 3. The third reflective lesson provided me with data about my students' capacities to develop a model of relative densities from the sinking or floating of objects in water and to use their models to predict new sinking/floating outcomes. Students worked in groups of four, but I assessed their work individually. This was the last reflective lesson in the intervention, and its placement in the instructional timetable of the intervention appears in Appendix A.

For this task, I gave each group a large basin of water and a collection of materials: an apple, an orange with its peel, an orange without its peel, and a carrot. Further, the students saw a large, transparent basin filled with water at the front of the room that held a sunken can of soda and a floating can of diet soda which they were welcome to test for themselves for sinking and floating. I asked students not to measure the volume or mass of the objects, but they could estimate densities by "felt-weight" or other methods. The groups predicted whether an item would sink or float in their basin of water. They then tested their predictions, observing each object's behavior in terms of buoyancy and speed of sinking. From their observations, the students created a set of rules and an accompanying dot-and-box model that predicted

whether other objects would sink or float in water. Finally, students tested their predictions with a small glazed ceramic heart and wrote an explanation for the outcome. I collected students' paperwork when they completed the lesson.

Methods of Data Analysis

I chose my methods of data analysis to identify differences in student performance and gains between the two classrooms in my study. I selected a subset of the items from the interview and test data as appropriate indicators of students' understanding of mass and density. The selection criteria were instrument-specific and are discussed in the following analysis section for each instrument. I then scored the items and compiled the results. In this section, I discuss my methods of analysis for each instrument used in data collection and for the reflective lessons.

Analysis of the Interview Data

The interview questions I gave were modified versions of those in the Smith interview, which is discussed in the data collection section. I included only a subset of the questions in the analysis, though, because the responses to some questions showed little variation and because others were so difficult that almost no student got them correct. I did not want to compare 28 students to two outliers, for example.

I analyzed items from interview questions 3, 5, and 6 only; see Appendix C for the complete interview. Prior to the start of the density unit, almost all of the 30 study participants already knew about the particulate nature of solids (question 1), could determine which of a pair of objects held in their hands had more mass or greater density (question 2), and distinguished the mass of a clay ball from its density

(question 4). I eliminated these questions from the analysis because students could not really show improvement on them after instruction. In addition, one item in question 4 and in question 5 used the word “amount,” which was not clear to students. Many asked me if, by “amount,” I meant weight, size, or volume. This was another reason for dropping question 4 from the analysis, and I also discounted the “amount” item in question 5 for that reason. So my analysis of the interview was based on two items from question 3 (rank ordering objects by mass [3a] and by density [3b]), two items from question 5 (does the mass change [5a]; does the density change [5b]), and question 6 (the definition of density).

I developed a scaled scoring from 0 to 4 for question 6 to cover the full range of the students’ understanding of the definition of density. Students received a 0 for no answer or a totally incorrect answer. They received 1 point for saying that objects with the same weight, mass, or volume have the same density because they recognized that mass [weight] and/or volume are involved in determining density. Students received 2 points for defining density as heavy-for-size, and 3 points for saying equal densities mean the objects are made of equal material. They received 4 points for defining density in terms of degree of compaction or mass in a volume.

I evaluated all the other items as either correct or incorrect. I wanted each item, including question 6, to be equally weighted in the analysis, so I assigned a value of 4 (the highest value for question 6) for each correct answer on items 3a, 3b, 5a, and 5b, and a value of 0 (the lowest value for question 6) for each incorrect

answer. This method of scoring gave equal value to each item with a maximum interview score of 20.

The interview was given to all participants both before and after the density unit. I compared scores on the pre- and post-instruction interviews to gauge both the performance and improvement of the intervention and the comparison groups. I also examined knowledge of mass and of density for the two groups by doing a breakout analysis of those interview items.

Analysis of the Written Test Data

My analysis of the written test excluded three of the questions—question 3, question 5, and question 8. (The complete test appears in Appendix D.) I did not analyze the responses to question 3 (How can you tell if something is made of matter?) because they were redundant with the answers to question 2 (Please describe the properties of matter). Questions 5 and 8 were eliminated from my analysis because they proved to be too difficult for my students to answer, however. The problems in question 5 and in question 8 relied on knowledge of proportions. Smith and colleagues studied proportional reasoning in their eighth-grade sample, but I did not because my sixth graders had not yet formally studied proportions in math. Hence the analysis of the written test included responses to question 1, question 2, question 4, the three items in question 6, and question 7.

With the exception of question 1, the scoring of the test reflects equal weight for every item, with scores ranging from 0 to 4. The three items in question 6—finding the mass, volume, and density of a cube in a diagram—and the single item in

question 7—rank ordering objects by density—were each evaluated separately as correct or incorrect. Students who did not respond to the item or whose answer was incorrect received a score of 0, and those with correct answers to the item received a 4.

Question 2 asked students to describe or list the properties of matter. Students received 0 for no response or a totally incorrect answer, and 1 point for saying that matter can be seen, felt, or somehow sensed. They received 2 points for writing that matter can be sensed and has weight, and 3 points for also adding something about mass or volume. Four points were reserved for answers noting that matter can exist in different states as well as covering the items listed in lower value replies.

The responses to question 4 were drawings representing cubes of different densities (see Figure 4), and they were assessed based on the student's depiction of mass, volume, or an integration of the two. If students left the answer blank they received a score of 0. A drawing showing only weight differences received one point. A drawing showing shading variations (light shading for aluminum; heavy shading for steel) received 2 points. A drawing that showed varying crowdedness of particles between the aluminum and the steel received 3 points, and a drawing that showed volume in three dimensions and particle crowdedness received 4 points.

Question 1 was scored differently, with a range from 0 to 12. Students were asked to indicate whether each of 12 things (a dog, a tree, heat, a wish, etc.) is matter. Students received one point for each correct answer. Added to the scores for the rest of the test questions, the maximum score on the written test is 36.

As in the interview, I gave the written test to all study participants both before and after teaching about density. I compared scores on the pre- and post-instruction written tests to learn about the performance and the improvement of the intervention and the comparison groups. I also broke out the mass items and the density items for a separate analysis.

Analysis of the End-of-Chapter Test Data

The end-of-chapter test (Appendix E) consisted of 25 multiple-choice questions. I selected six of the questions—2, 13, 16, 17, 21, and 22—for the analysis of the end-of-chapter test because they concisely addressed the common themes found in the comparison and intervention curricula.

Each question was weighted equally with a possible score of 6. Questions 13, 16, 17, and 22 have one correct answer, and so students received a score of 0 for no response or an incorrect response and 6 for the correct answer on those questions. Question 2 has three correct responses, but the response that comprises both of the other correct responses is best. I gave students with no response or the incorrect response 0, and gave those with the best response a 6. Students received 3 for the responses that were correct but not the best. Question 21 has four correct responses, but the answer “all of the above” is best. I gave students who did not answer the question a score of 0, those who answered “all of the above” a score of 6, and the others a score of 2. The maximum score on the end-of-chapter test was 36.

The end-of-chapter test was administered to all study participants after their density instruction, so the performance, but not the improvement, of the two student

groups can be compared. The questions in this analysis all pertain to density, so no breakouts regarding mass versus density are possible.

Analysis (and Results) of Data from the Reflective Lessons

The purpose of the reflective lessons was to provide me with timely feedback to improve my teaching, rather than to answer my research question. I collected student work as data during the lessons, but I used techniques other than scoring to analyze it.

Reflective lesson 1. I assessed the Kool-Aid lesson by studying student representations of the four recipes at different levels of sweetness and by seeing if their work indicated that they could scale down the recipes to make sample cups of Kool-Aid at the correct concentrations. Two students in the intervention group were absent on the day of the activity. Of the thirteen who completed the activity, three calculated proportions numerically to solve the mystery and make their cups of Kool-Aid, and nine used dots and boxes as models to solve the mystery and mix their Kool-Aid samples. One student did not complete the problem on her paperwork, even though she was in a group that had the correct answers. From these data, I concluded that the class as a whole had done the tasks and interpreted the information appropriately. Understanding that different solutions have different concentrations had become part of their conceptual model of density. Formatively, I concluded from their performance that my students were comfortable with the increasing complexity of the lessons. This meant that I was confident that I could continue with the research as planned and did not need to review this sort of density model.

Reflective lesson 2. In the second reflective lesson, I examined students' understanding of mass-to-volume relationships in terms of the "heaviness" of objects. All groups chose to differentiate the objects in set one either by gradations of shading or by drawing particles more or less compacted, keeping the volumes of the blocks constant. They drew the mystery cylinder as proportionally larger yet less dense than the blocks. The students presented accurate representations of the varying densities of the materials; no one depicted "weight" as a factor in the densities, such as by showing an uneven pan balance or the pull of gravity.

All groups drew dot-and-box models of their samples of clay and wood in set two, assigning each box a value of one cubic centimeter and each dot a value of one gram. Using those models as scale drawings, they were able to predict the volumes of any piece of clay or wood when given the mass. Rather than calculating using a formula or proportion, they made volume predictions by creating new scale drawings. Of the fifteen study participants who completed this reflective lesson, all successfully rendered models of both sets of objects that accurately reflected an understanding of mass compared to volume. I concluded that I had taught this appropriately.

Reflective lesson 3. This lesson assessed the modeling of relative densities from the sinking or floating of objects in water. The success of the lesson was measured by the success of students' models in predicting whether or not a small, glazed ceramic heart would sink or float in a basin of water and by their capacity to explain why. All intervention students accurately predicted that the ceramic heart would sink. They were also able to explain the sinking by comparing the density of

the ceramic heart to objects that were denser than water by means of a dot-and-box model. This lesson gave me evidence that students were comfortable with modeling and that their conceptual understanding of density, without the use of the density formula, was solid. This assured me that I could continue the study to its conclusion as planned.

This chapter has reported on the methodological choices that I made during my study of density instruction, including the development of my final research question. The first section of the chapter introduced my research design, setting, and participants. I described the intervention in the second section. The third section reviewed my methods of data collection to answer my research question and for formative assessment. In the last section, I discussed my methods for data analysis—again, methods both to answer my research question and for formative feedback on my teaching.

CHAPTER 4

RESULTS

In this chapter I report on my analysis comparing intervention and comparison students' responses from the interview, the written test, and the end-of-chapter test. I also present data from individual students to clarify and elaborate on the aggregate analyses of performance and gains on the instruments. Because the number of participants studied was small, 15 from the comparison classroom and 15 from the intervention classroom, the findings are suggestive rather than statistically significant. My results are consistent and clear, though, providing evidence supporting the intervention.

The chapter consists of five sections designed to compare the intervention and comparison groups. The first section presents the basic learning trajectory of each group of students from the beginning of the study to the end. The second introduces two "case-study students," one from each group, and I use their data to contextualize the aggregate learning trajectories of the two groups. The third section summarizes the interview results, and the fourth presents my analysis of the written test. Both instruments were administered before and after the density instruction, so the results in the third and fourth sections include performance and gains. The fifth section contrasts the performance of each group on the textbook's end-of-chapter test, given postinstruction only. These last three sections of the chapter report on students' responses to questions on the data collection instruments; the instruments, with the full wording of each question, appear in Appendices C, D, and E.

Learning Trajectories of the Intervention and Comparison Groups

The learning trajectory characterizing the intervention group was a bit uneven, but they consistently outperformed the comparison group (results presented in later sections of this chapter), which indicates that intervention students learned more about density than the comparison students, and that they developed a firmer and more consistent grasp of the variable nature of density than their peers. The preinstruction data collected on the students suggest that, at the start of the study, the intervention group knew slightly more about mass and density than the comparison group. Yet both groups demonstrated inconsistencies in their knowledge of mass and large gaps in their initial understanding of density. For example, even though 11 of the 15 intervention students knew enough about the conservation of mass at the start of the study to say that the mass of alcohol in a thermometer remains constant when heated up (interview, question 5), just five of them correctly ordered a set of objects by increasing mass (interview, question 3). After instruction, however, the intervention group distinguished between mass and density more consistently than before instruction and than their peers in the comparison group.

Being able to manipulate the density formula is the accepted standard for demonstrating an understanding of density in most textbooks and curricula. Importantly, despite having had no practice with word problems that required the calculation of density using a formula, *e.g.*, “What is the density of a metal with a mass of 10 grams and a volume of 2 cubic centimeters?”, almost half of the intervention group correctly interpreted and evaluated a diagram with similar

information. Following their instruction, the intervention group's responses on assessment instruments showed that they had grown more knowledgeable about density than the comparison group, and that they were comfortable with modeling as a means of communicating ideas and results related to density.

The learning trajectory of the comparison group was much less consistent than that of the intervention group, with both initial and continuing variation in their performance on the evaluation instruments. At the start of the study, the students had a confused understanding of mass; they knew how to measure the mass of an object using a pan balance and gram masses, but only four of the 15 students correctly ordered a set of objects by increasing mass (interview, question 3). A pan balance had been available for the students to use in this task, but few chose to use it. Students generally conflated mass and density, and few understood that density is a variable property of matter. After instruction, the ability of the comparison students to compare relative masses improved slightly. Throughout the density unit, the comparison students had practice in calculating answers to formulaic word questions regarding density (*e.g.*, "What is the density of a metal with a mass of 10 grams and a volume of 2 cubic centimeters?"), yet following the unit, most still could not correctly interpret and evaluate a diagram with similar information. At the end of the study, half of the comparison class still held that density was an immutable characteristic of matter, and many continued to conflate mass with density.

Case-Study Students

Two research participants, one from the intervention classroom and the other from the comparison classroom, help illustrate and elaborate on group differences and on the numerical results presented later in this chapter. These students were not part of the research design for my study. I did not collect more or different data from them, but I did analyze their data differently in order to write a narrative about each girl. I selected these “case-study students” when writing the dissertation because their data allowed me to describe the unfolding of the instruction and to examine its effects in a more holistic way than the tabled analyses in subsequent sections of the chapter. Whereas none of the students is a perfect representation of his or her group’s learning trajectory, the two case-study students are the best exemplars of their respective groups.

My case-study students are Maya, an intervention student, and Sofia, a comparison student. Sofia and Maya are real students, but the names are pseudonyms. Scholars disagree about what a case is, and researchers choose cases in different ways for different purposes (Ragin, 1992; Stake, 1995; Yin, 2009). These two case-study students provide detail that is not apparent in the larger data. My reason for selecting Sofia and Maya as case-study students is that they are representative or “typical” of participating students in their respective classrooms. Each one fit the basic academic profile of the students in her group (see Table 1): 1) they had a grade of B in my science class prior to the study, and 2) they were either advanced or proficient in their fifth-grade math and English Language Arts scores on

the California Standards Tests. Further, each demonstrated a conceptual trajectory that was typical of her respective group.

A Student in the Intervention Group, Maya

Maya was a student in the intervention classroom. The California Department of Education classifies Maya as Hispanic/Latina of any race, and she is a native speaker of English. She has a bubbly, warm personality, and she happily tackled the activities and challenges presented in science class. She was respectful of classmates and had a clear desire to collaborate with group partners. She relished the persuasion and argumentation that grew from discussions to determine the “best” answers to the problems posed. She was always quick to smile and laugh.

Maya’s learning closely matched the intervention group’s improvement trajectory. At the start of the study, her knowledge of mass and density was uneven. She ordered only three of four objects correctly by increasing mass and could not correctly rank them by increasing density (interview, question 3). Nonetheless she pointed out that the two objects made of aluminum should be equally dense. She correctly defined the word “density” as: “[h]ow much mass something has and how much it’s compacted or spread out” (interview, question 6), and she drew “compactness” diagrams (see Figure 5) to explain the different masses of equal-volume cubes of aluminum and steel (written test, question 4). Figure 5 represents the kind of visual model that was at the core of the intervention. It appears that Maya understood such diagrams from the outset and was ready for further modeling instruction. She was one of the 11 intervention students who initially knew that the

mass of alcohol stays constant in a thermometer that is being warmed up, but she did not realize that the density of the heated alcohol in the thermometer changes: “[t]he alcohol rises, and its mass and density stay the same because it’s still alcohol” (interview, question 5). In Maya’s way of thinking prior to the intervention, density was as immutable as mass, regardless of temperature or state. When asked to rank four objects (their mass and volume labeled) by increasing density, she appeared to order them instead by the thickness of the items (written test, question 7). Like others in the intervention group before instruction, Maya’s understanding of mass and density was spotty, a mixture of correct and incorrect notions.

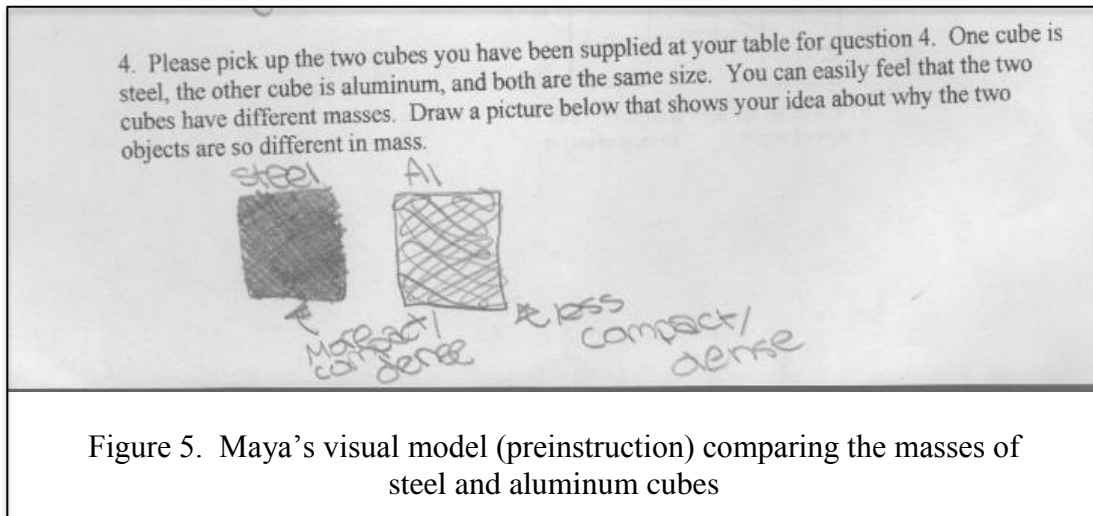


Figure 5. Maya’s visual model (preinstruction) comparing the masses of steel and aluminum cubes

During the intervention, Maya’s conceptualization of mass and of density grew deeper and more complete, and she also became adept at drawing density models and using them to solve problems. Rather than practicing terminology, measurement, and the density formula, the intervention students studied density through observations and models, and they came to decisions in student discussions.

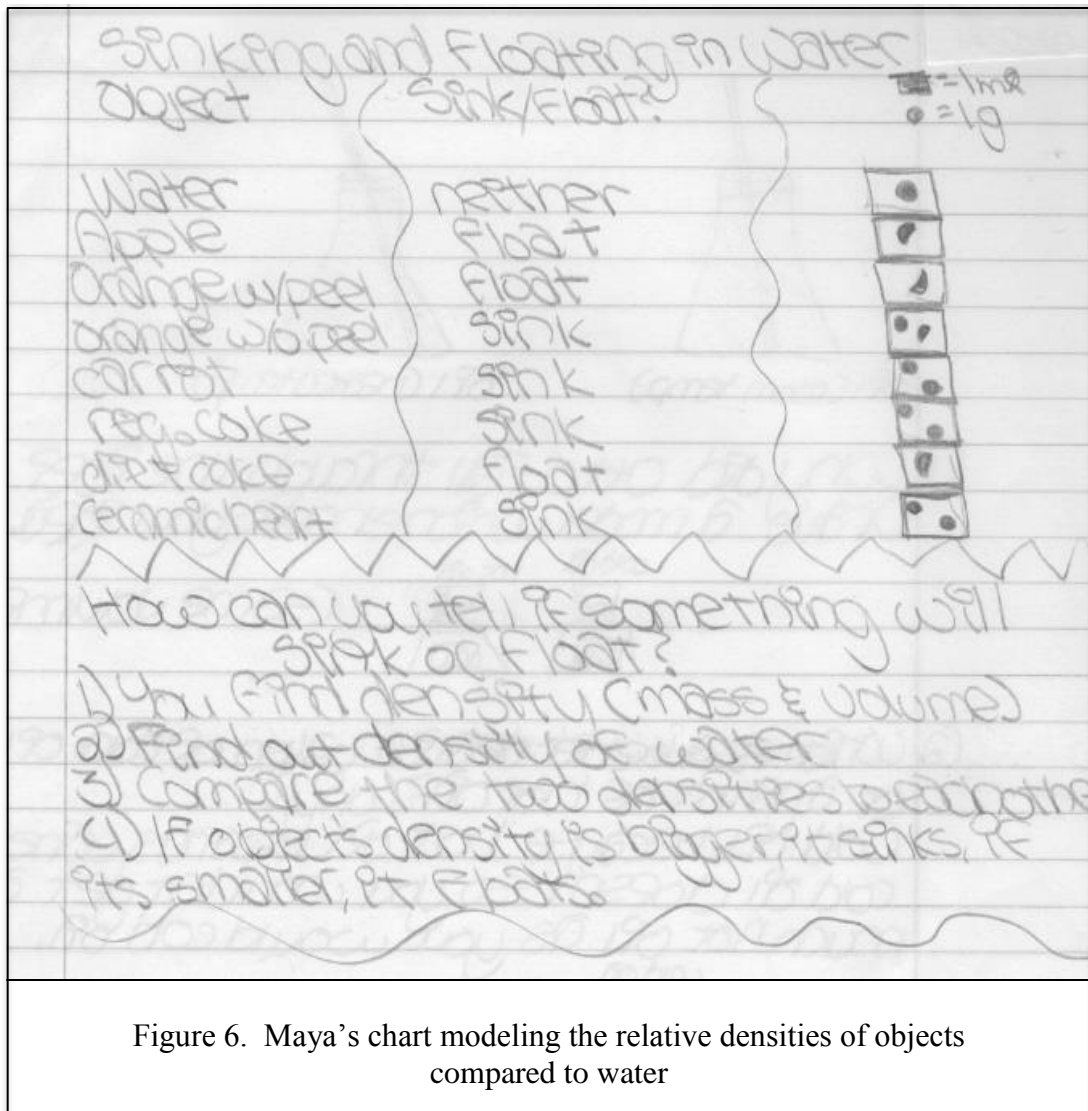


Figure 6. Maya's chart modeling the relative densities of objects compared to water

For example, Maya's group used a modeling technique to compare the relative densities of water and various objects (Figure 6). In Figure 6, a box represents one milliliter of water and a dot represents one gram. The density of water is 1 gram per milliliter. The students made no measurements of the mass or volume of the objects on Maya's list. After observing whether each object on the list except the last (the ceramic heart) floated or sank in water, and how it floated or sank, Maya and her

group made the model of their observations seen in Figure 6. They then predicted the behavior of the ceramic heart in water and added that prediction to the model.

Maya's group found that its prediction was correct when tested; the heart sank in water. They understood that the density of the ceramic heart was greater than the density of water.

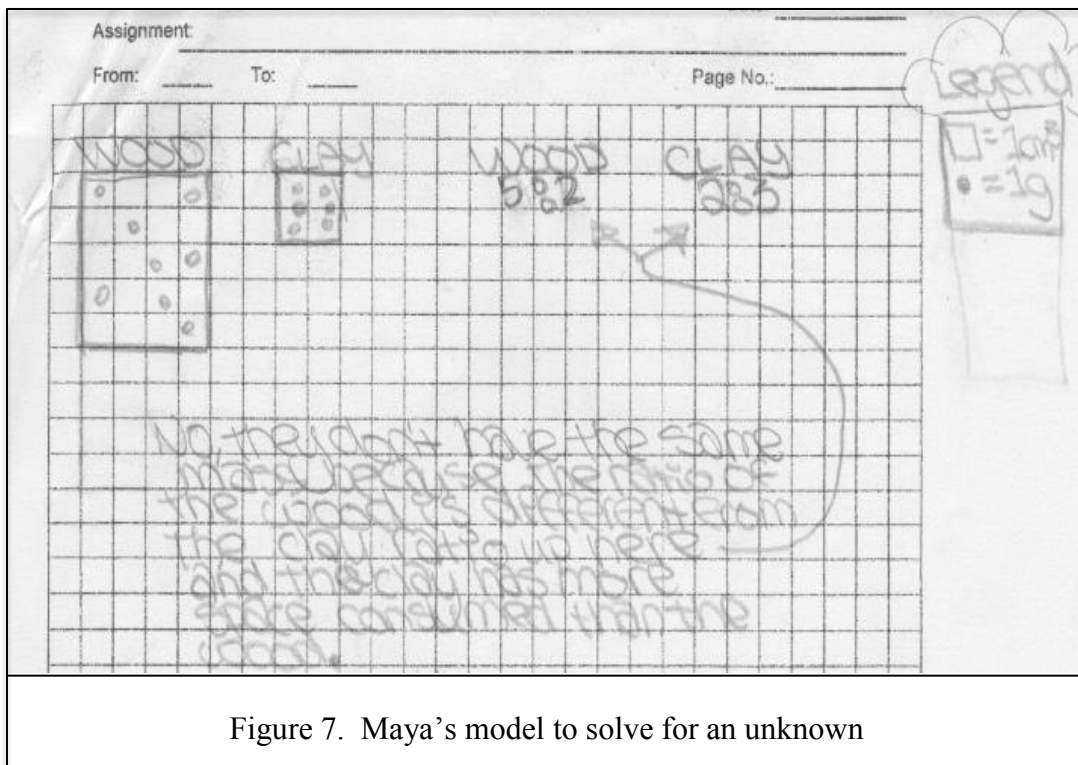


Figure 7. Maya's model to solve for an unknown

The models, such as visual models consisting of box and dot diagrams to represent density, developed by intervention students helped them conceptualize density in ways that the textbook and the density formula could not. In Figure 7, Maya created a model that can accurately predict the volume of any given mass of clay or of balsa wood. I gave the class the initial mass-to-volume ratios of clay (a two-cubic-centimeter chunk of clay has a mass of three grams) and of balsa wood (a

10-cubic-centimeter piece of balsa wood has a mass of four grams), and she drew diagrams to represent the volume taken up by six grams of clay and eight grams of balsa wood. Using her model, Maya correctly calculated that eight grams of balsa wood has a volume of 20 cubic centimeters, and that six grams of clay has a volume of four cubic centimeters. The intervention group learned to use this form of symbolic modeling to predict outcomes, find solutions, and build their understanding of mass, volume, and density (Gilbert, 2004).

Maya showed a generally improving conceptualization of mass and density throughout the course of the intervention. At its end, her understanding of density as a variable characteristic of matter had improved, but her knowledge of mass and of how to calculate density remained inconsistent. On the postintervention interview, she still did not order four objects correctly by increasing mass, but she did get them in the correct order by increasing relative density (interview, question 3). In response to the posttest questions about heating up the alcohol in a thermometer, Maya again showed her grasp of the conservation of mass, but this time she also revealed a revised, fuller comprehension of the variable nature of density: “[t]he alcohol molecules spread out when they warm up, and this means the density goes down” (interview, question 5). Rank ordering objects labeled with their mass and volume by increasing density was still challenging for Maya. Unlike her ranking by perceived thickness on the preinstructional test though, she seemed to use “felt-weight” on the posttest, which allowed her to get the first two objects into the correct order by increasing density (written test, question 7). Like other intervention students, Maya

retained some confusion about mass and calculating density at the end of the study, but she had developed a deeper, more complete understanding of density as demonstrated by her use of density models to solve problems and her improved responses to the postinstruction density items. In particular, Maya's explanation of the behavior of alcohol in a thermometer that is being warmed up showed that the intervention helped her grasp the variable nature of density.

A Student in the Comparison Group, Sofia

Sofia was in the comparison classroom. The California Department of Education classifies Sofia as Hispanic/Latina of any race. She was considered an English learner when she started school but was quickly reclassified as English-proficient at five years of age. In my class, Sofia was a hard worker. The work she turned in was very thorough, and she took care to answer questions as completely as possible, a characteristic that set her apart from most of her classmates. She was an active and vocal participant in class and worked well with classmates in small groups. She enjoyed discussions and was quite willing to consider others' viewpoints.

Sofia was a good example of the comparison group's trajectory of learning. Like most comparison students, she had inconsistent comprehension of mass, and she conflated mass and density at the start of the study. During her preinstruction interview, Sofia twice ordered four objects (their density did not covary with their mass) in the same way when asked to rank them first by increasing mass and then by increasing density (question 3). When asked if the mass and density of the alcohol in a thermometer changed when the thermometer was moved from a cold-water bath to

a warm-water bath, her response indicated that she thought the mass had increased when it had not; she also incorrectly regarded density as an immutable characteristic of matter: “[t]he alcohol grows because it’s warm, and there is more to take up space, [but its] density doesn’t change because you are not adding more alcohol” (interview, question 5). Although she was able to define density, her understanding was tied to weight: “[density] is something’s weight and how it fills its container – is it packed tightly or loosely” (interview, question 6).

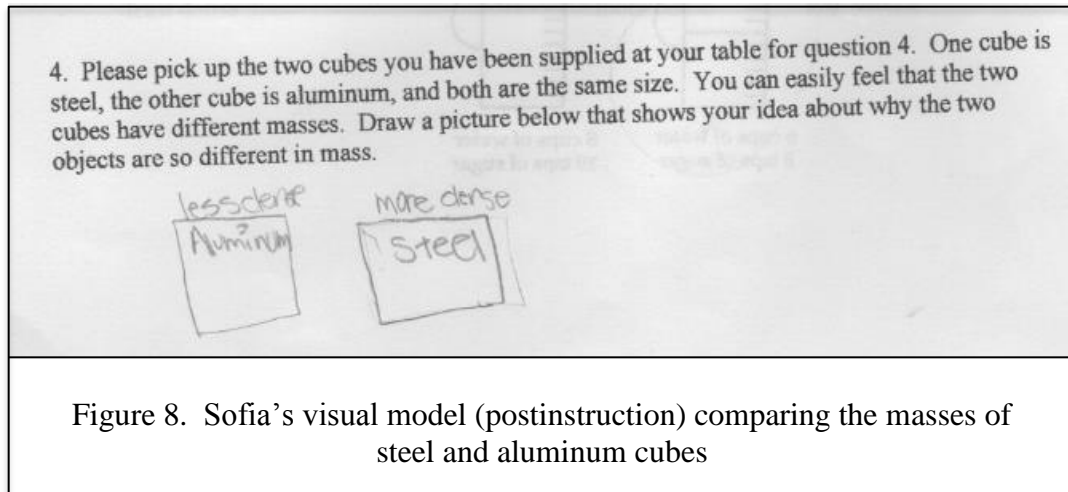
On her preinstruction written test, Sofia was unable to diagram the mass differences between a cube of steel and a cube of aluminum of the same size and shape (written test, question 4). She also ordered four objects with labeled mass and volume by increasing mass when the question asked her to rank them by increasing density (written test, question 7). At the beginning of the study, Sofia’s confusion about mass and density was typical of the comparison group’s level of understanding.

The instruction I provided to the comparison class during the study pushed them to develop better comprehension of density, but without modeling and dialogue-based decision making. For instance, Sofia’s class made underwater waterfalls one day. Students colored and then layered cold water, hot water, salt water, and tap water in specific ways and watched the resulting motion of the colored fluids. That day Sofia’s written explanation for why the cold water sank was: “[Cold] water molecules don’t have the energy to spread out, so they clump together and take up less space.” Her response, like many of the answers given by her classmates, was not incorrect, but it did not show an understanding of relative density. It did not say that

when particles of one substance clump together and take up less space, they become denser than the surrounding liquid or gas and then sink. After we studied relative density and hot-air balloons, Sofia's grasp of relative density improved. Her explanation for why a hot-air balloon rises compared the densities of air parcels and mentioned floating: "When heat rises above the cold air, it also picks up the balloon. The density of the hot air is less dense than the cold air. As the air expands, it becomes less dense." This is an accurate description of what happens as far as it goes, but heat might be seen as the agent that pulls the balloon up. She did not mention why expanding air becomes less dense, but her insights about relative densities were more complete than earlier in the unit. Sofia's response to my instruction was fairly representative of the comparison group. Their understanding of mass and density grew during the density unit but remained partial.

By the end of instruction, Sofia appeared to distinguish mass and density in some instances but not in all. She had a better grasp of mass. For example, on the question about moving a thermometer from cold into hot water, she accurately stated that even though the alcohol was taking up more space as it warmed up, the mass of the alcohol stayed the same (interview, question 5). Sofia demonstrated some continuing confusion about density, though, because she said that the density of the alcohol in the thermometer was not changing as it warmed up. She did not associate the increased volume and the decreased density of the alcohol. Without having benefitted from the type of visual modeling used in the intervention, Sofia did not use models to compare densities. On her postinstruction written test, she correctly

described steel as “more dense” and aluminum as “less dense,” but her diagram of the two substances did not illustrate their relative densities (Figure 8).



When asked to order items (their mass and volume labeled) by increasing density on the written test, she ranked them by mass instead, just as she had done before instruction (written test, question 7). However, Sofia did show growth in her understanding of relative density on the postinstruction interview when she correctly ordered the four objects by increasing density (question 3). Her definition of the word “density” also improved to focus on how compact the material is without mentioning weight (interview, question 6). Like the rest of the comparison group, Sofia had a better understanding of mass and density after instruction, yet her understanding of density as an intensive quantity remained incomplete.

Interview Results

The interview data came from the modified version of the clinical interview used by Smith and colleagues (1992) (instrument in Appendix C). Both intervention and comparison students were administered the interview before and after the density

unit. The modifications and scoring are fully described in the data collection and analysis sections of Chapter 3. The interview gave priority to assessing density (total score possible = 12) over assessing mass (total score possible = 8). On the tables, I have converted the interview scores into the percent correct for ease of comparison.

Table 3
Interview
Preinstruction Performance by Group (% correct)

	Comparison group	Sofia (comparison student)	Intervention group	Maya (intervention student)
Total	38%	20%	41%	40%
Mass questions	16%	0%	16%	50%
Density questions	20%	33%	37%	33%

Table 3 presents the preinstruction performance of the participating comparison and intervention students on the five questions scored from the interview. Before instruction began, the intervention group got three percent more of the interview questions correct than did the comparison group. The students still had plenty of room for improvement after instruction, however, as both groups got less than 50 percent of the questions correct.

Table 3 also breaks out the students' preinstruction performance on the mass and density questions on the interview. Two of the five questions dealt with mass and three with density. Both groups of students performed better on the density questions than on the mass questions. On the density questions, the intervention group got

seventeen percent more correct than the comparison group, indicating they may have had a slight edge in understanding density at the beginning of the study. The performance of the case-study students on the preinstruction interview roughly paralleled the performance of their respective groups, except that Maya, the intervention student, was more familiar with the conservation of mass (interview, question 5) than her peers, and Sofia was less familiar with mass than her group.

Table 4 displays the preinstruction and postinstruction performance and improvement on the interview for both groups of students. The total rows show that the intervention group outperformed the comparison group on the interview questions both before and after density instruction. They also had greater improvement—21 percent overall gains for the intervention group compared to just 14 percent for the comparison students. Both Sofia and Maya were at the top of their respective groups in terms of improvement on the interview questions after instruction. Despite the preinstruction results indicating that the intervention group may have known slightly more about density than the comparison students before the study, the intervention group's possible "head start" can be dismissed due to the intervention group's better performance and greater gains following instruction.

Student performance on the mass and density breakouts differed. Both groups of students got 16 percent of the mass questions correct at the start of the study, indicating similar knowledge of mass. After instruction, both groups had improved, with the intervention students having greater gains than the comparison students.

Sofia did better on the mass questions after instruction, but Maya stayed at the same level of performance.

Table 4
Interview
Preinstruction and Postinstruction Performance and Gains,
by Group (% correct)

	Comparison group	Sofia (comparison student)	Intervention group	Maya (intervention student)
Preinstruction total	38%	20%	41%	40%
Postinstruction total	52%	60%	62%	80%
Total gains	14%	40%	21%	40%
Preinstruction mass questions	16%	0%	16%	50%
Postinstruction mass questions	20%	50%	43%	50%
Mass question gains	4%	50%	27%	0%
Preinstruction density questions	20%	33%	37%	33%
Postinstruction density questions	55%	67%	73%	100%
Density question gains	35%	34%	36%	67%

The intervention group had stronger initial performance than the comparison group on the density questions, which suggests the intervention students knew slightly more about density before the study began. The percent of correct density

answers grew 35 to 36 percent for both groups following instruction, leaving the comparison group at 55 percent correct and the intervention group at 73 percent correct. Sofia's performance and gains on the density questions roughly mirror those of the comparison group, but after instruction Maya improved even more than her group as a whole on the density questions. The breakout performances on the mass questions and on the density questions parallel the overall trend of the interview results in Table 4, with better performance and greater gains by the intervention group.

Written Test Results

I made slight modifications to a written test by Smith and colleagues (1997) (instrument in Appendix D) and gave it to the comparison and intervention classrooms both before and after the density unit. Although the interview and the written test assess knowledge of both mass and density, the written test gives considerably more weight to mass (total score possible = 24) than to density (total score possible = 8). It also includes one question on volume, which figures into the overall totals. On the following tables, I report the results of the written test as the percent correct.

Table 5 displays the participating students' results on the written test before they studied density in my classroom. At the start of the study, both the intervention and the comparison group got three quarters or more of the items about mass correct, but they scored considerably lower (ten percent correct or less) on the density questions. This is a reversal of the breakout results from the preinstruction interview,

where both groups did better on the density questions than on the mass ones. Sofia and Maya performed at a level comparable to their respective groups. The total results for both groups were similar, although as was true of the preinstruction interview, the intervention group performed slightly higher overall, indicating they may have initially known more than the comparison group about mass and density.

Table 5
Written Test
Preinstruction Performance by Group (% correct)

	Comparison group	Sophia (comparison student)	Intervention group	Maya (intervention student)
Total	53%	58%	59%	58%
Mass questions	74%	71%	80%	88%
Density questions	3%	0%	10%	0%

Table 6 presents the performance and gains by the comparison and intervention groups on the written test. The performance figures in the total rows show that the intervention group had six percent more correct responses than the comparison group before instruction and 15 percent more afterwards. Their level of improvement over the course of the intervention, 15 percent, was also greater than the five percent comparison-group gains. Just as with the interview results, though, the slight edge that the intervention students may have had over the comparison students prior to instruction is more than offset by the combination of better performance and greater gains. Sofia and Maya are good examples of the performance and gains of

their respective groups on the written test. These overall results on the written test generally agree with the overall interview results, with the intervention group outperforming the comparison group.

Table 6
Written Test
Preinstruction and Postinstruction Performance and Gains,
by Group (% correct)

	Comparison group	Sophia (comparison student)	Intervention group	Maya (intervention student)
Preinstruction total	53%	58%	59%	58%
Postinstruction total	58%	64%	73%	72%
Total gains	5%	6%	15%	14%
Preinstruction mass questions	74%	71%	80%	88%
Postinstruction mass questions	80%	79%	85%	92%
Mass question gains	6%	8%	5%	4%
Preinstruction density questions	3%	0%	10%	0%
Postinstruction density questions	17%	0%	43%	0%
Density question gains	14%	0%	33%	0%

Table 6 indicates that both groups of students had high levels of knowledge about the mass questions on the written test prior to instruction, leaving them less

room for improvement. The mass questions were of variable difficulty, but most students did quite well on a set of yes/no items asking whether given things had matter or not. Sofia and Maya represent their groups closely on these questions. Despite their relatively high scores on the mass items before instruction, both groups also showed some posttest improvement—five or six percent.

Neither the intervention nor the comparison students performed well on the density questions prior to instruction. Sofia and Maya did not get the correct answers to these questions on either the pretest or posttest. The intervention group as a whole, however, showed solid improvement on these questions, getting 43 percent correct after instruction. The intervention group had stronger performances and higher gains on the density questions and on the written test overall.

End-of-Chapter Test Results

The end-of-chapter test was part of the teacher materials from the textbook used by the comparison class, *CPO Focus on Earth Science* (2007) (instrument in Appendix E). It was a multiple-choice assessment of density as it was presented in the textbook, and all the scored questions dealt with density specifically. I gave the test to both groups of students at the end of their instruction, and the results are reported here as the percent correct.

I expected the comparison group to do better than the intervention group on the end-of-chapter test. The comparison students read the textbook, and the intervention students did not. The comparison group also worked with the textbook's vocabulary and the types of problems it presented. Yet, as revealed in Table 7, the

intervention group got 79 percent of the answers correct, which was 10 percent more correct answers than the performance of the comparison group. Consistent with the results from the other instruments, the intervention group's percent of correct answers on the end-of-chapter test exceeded the comparison group's percent correct.

Table 7
End-of-Chapter Test
Performance by Group (% correct)

	Comparison group	Sophia (comparison student)	Intervention group	Maya (intervention student)
Total	69%	56%	79%	67%

The intervention group outperformed and demonstrated greater improvement than the comparison group on the interview and on the written test. In addition, on the end-of-chapter test they got 10 percent more of the answers correct than the comparison group. The assessment results are evidence that the intervention students learned more about mass and density from the intervention than the comparison students learned from their density instruction, indicating that the intervention was effective.

All of my students had some confusion and conflation of mass and density at the start of instruction. As a group, Sofia and the other comparison students scored a little lower on the preinstruction instruments than the intervention students. Their density unit focused on the textbook, problem sets, and labs, rather than on the modeling and discourse in the intervention unit. Their postinstruction performance

indicated continued conflation of mass and density. In particular, Sofia and her group demonstrated relatively little growth in their understanding of density.

Maya and the intervention group also confused mass and density at the start of the study, although they performed slightly better than their peers on the preinstruction interview and written test. From that initial slight advantage, the intervention group began to learn about density through models and discussion. Maya's classwork and postintervention performance show that, despite retaining some confusion about mass, the high level of student engagement and the density models helped her develop a deeper understanding of relative density and of density as a variable property of matter. Like Maya, the intervention group learned to grasp the complexities of density better than the comparison group.

CHAPTER 5

DISCUSSION AND CONCLUSIONS

In this concluding chapter, I first interpret the results of my study. Next I discuss the implications that my study has for the teaching of density, and I provide recommendations for teachers. Lastly I discuss the limitations of my study and list some possible next steps in the study of density instruction.

Interpretation of Results

As the number of participants studied was 30 (15 in the comparison group and 15 in the intervention group), my results are suggestive rather than statistically significant. Nevertheless the results are consistent; the intervention students outperformed and showed greater improvement on all assessments than the comparison students. The consistency of the results clearly supports one finding: instruction based on modeling, with opportunities for open-ended student dialogue, helped the intervention group develop a more sophisticated and transferable understanding of mass and density than that held postinstruction by the comparison group.

A consequence of the effective intervention strategies was that the comparison group and the intervention group had different learning trajectories. Data from the case-study students, Sofia and Maya, illustrate the improvement trajectories of the two groups studied. Both students began the density instruction with somewhat conflated notions of mass and density. Sofia, like the comparison group as a whole, seemed to know a little less about mass and density initially than Maya and most of

the intervention group, but each girl had some confusion about the concepts. In the comparison classroom, Sofia got practice with solving formulaic density problems, measurement, and labs that covered roughly the same curriculum as what the intervention class studied. In the intervention classroom, Maya discussed data and analyses with classmates. They modeled observations, made and tested predictions, and came to consensus about their models and their conclusions. After instruction, both girls demonstrated greater knowledge of mass and density. Yet at the end of the study, Sofia and about half of her comparison classmates still held that density was an immutable characteristic of matter and continued to conflate mass and density.

Maya, on the other hand, generally distinguished mass from density at the end of the study. Her density models helped her make predictions and solve problems. Without direct instruction in using the density formula, density equals mass divided by volume, Maya developed her own intuitive sense of how to express the density of an object as the ratio of mass to volume. She knew about relative densities and how to explain them. She came to regard density as a variable property of matter. Like her peers in the intervention group, Maya had a much greater understanding of density after instruction than most of the comparison students. She was also comfortable with modeling and ready to try it in new contexts.

In this study, modeling and student discourse were more effective ways to teach density than my usual methods. Not only did the intervention lead to superior performance and greater gains on every assessment instrument, but it helped students

start to disrupt the conflation of mass and density that is characteristic throughout the middle grades.

Implications for Teaching Density

When I began this study, I wanted to examine why many of my students conflated mass and density. I therefore focused on how students understand mass (an extensive quantity) and the role of mass in my students' understanding of density (an intensive quantity: the ratio of mass to volume). One problematic source of confusion for the comparison students turned out to be the textbook. The textbook used in the comparison classroom described density as "always the same" in a chapter subheading, and it explained:

The density of a material is always the same under the same conditions. This is true regardless of how much of the material you have. For example, the density of aluminum metal is always 2.7 g/cm^3 . Aluminum foil, aluminum wire, or an aluminum brick all have the same density. This is true as long as you have a sample of aluminum metal that is not hollow and does not have any other materials mixed with it (Hughes, *et al.*, 2007, p. 97).

This passage near the beginning of the chapter may have misled students from the start. After all, if density is "always the same," then how does it really differ from mass? What does volume have to do with density if density is "always the same"? Later in the chapter the textbook clarified what "under the same conditions" meant, but students may have instead remembered the more prominently displayed words: "always the same."

What became evident by the end of the study was that the concept of volume may, in fact, be the surprise culprit affecting students' understanding of density, perhaps as much as, or even more than mass. For example, the effect of volume on

density was an important factor in the thermometer question from the interviews. Students observed the rising column of alcohol inside a thermometer as it was warmed up in a hot-water bath. They were asked first whether the mass of the alcohol was changing and then whether the density of the alcohol was changing. In the postinstruction interview, nine of the 15 students in the comparison group replied that the alcohol's mass stayed constant as it warmed up, and 10 said that the density of the warming alcohol stayed the same, even as they watched the alcohol expand and take up more space. Those who believed, even after instruction, that both the mass and density stayed constant were probably still conflating mass and density by leaving out the effect of changing volume on the alcohol.

At the start of this dissertation, I described a scene from my classroom where I asked my students to imagine placing a tower of ten five-gram plastic pieces on one side of a pan balance and a small 50-gram brass piece on the other. Twenty students said the pan balance would balance. Those students were confident that different materials that are equal in mass can have unequal volumes. They were transferring the concept that mass is a property of matter from a lower density material (plastic) to a higher density material (brass).

Ten other students in the class said that the side of the pan balance with the brass piece would go down. They may have been thinking about the balance question this way: metal is heavier for its volume than plastic. Somehow they then dropped volume from their thinking, leaving them with the inaccurate notion that metal is heavier than plastic regardless of volume.

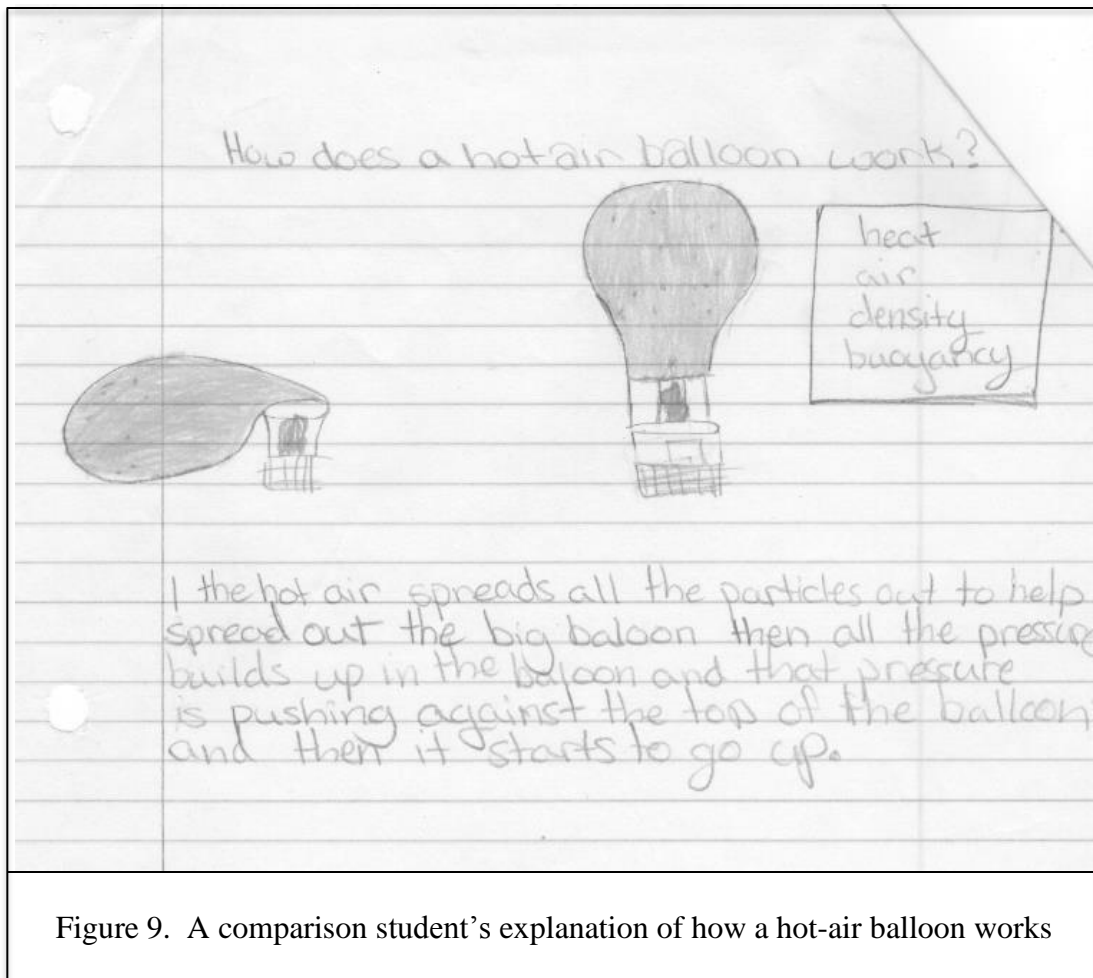
Two common practices may underlie and/or reinforce students' disregard for volume in the conflation of mass and density: 1) the choice of words for describing attributes of matter; and 2) the decision to hold the size or volume constant for objects or fluids used to teach about different densities. First, we often use the words "light" and "heavy" when comparing the density of objects—even in academic contexts. Some objects or gases are described as "lighter than air." Certain metals are called "heavy metals." In addition, students encounter language, even academic texts, equating "heavy" with "denser" and "light" with "less dense." For example, the following passage comes from one of the textbooks in my classroom:

Scientists believe the earth has three main layers: the crust, the mantle, and the core. The crust is the outer layer of the earth. It is mostly lighter-weight rocks such as basalt and granite (Silver & Wynne, 1989, p. 7).

The United States Geological Survey uses similar wording about tectonic plates:

Continental crust is composed of granitic rocks which are made up of relatively lightweight minerals such as quartz and feldspar. By contrast, oceanic crust is composed of basaltic rocks, which are much denser and heavier (USGS, 1999).

"Light" and "heavy" are accurate descriptors in those sentences only when the volumes of the objects are equal. Five cubic meters of continental crust have less mass, and are therefore lighter, than five cubic meters of oceanic crust, yet five cubic meters of continental crust are likely to have more mass and be heavier than one cubic centimeter of oceanic crust. Such uses of "lighter" for "less dense" and "heavier" for "denser" are misleading and tend to support student misconceptions that volume is irrelevant to density and that denser materials must be heavier.



Language or phrasing may also affect students' understanding of the relative densities of hot and cold air. A common saying is: *Hot air rises; cold air sinks*. One student in the comparison group assigned the power of levitation to hot air, expecting it to push a hot-air balloon up into the air (see Figure 9). The student was talking about thermal expansion, but volume was missing from his explanation. Hot-air balloons rise because the warmer air inside the balloon takes up more space than the surrounding cooler air. As volume increases, the density of the air inside the balloon

decreases, and the warm balloon floats in the relatively cooler air. The phrase “hot air rises” may have discouraged this student from considering volume in his answer.

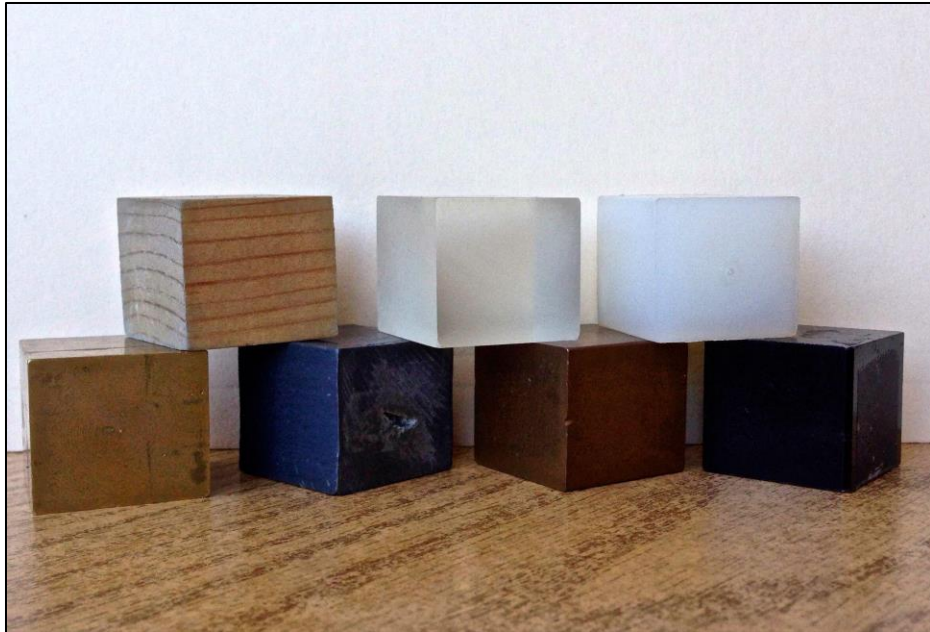
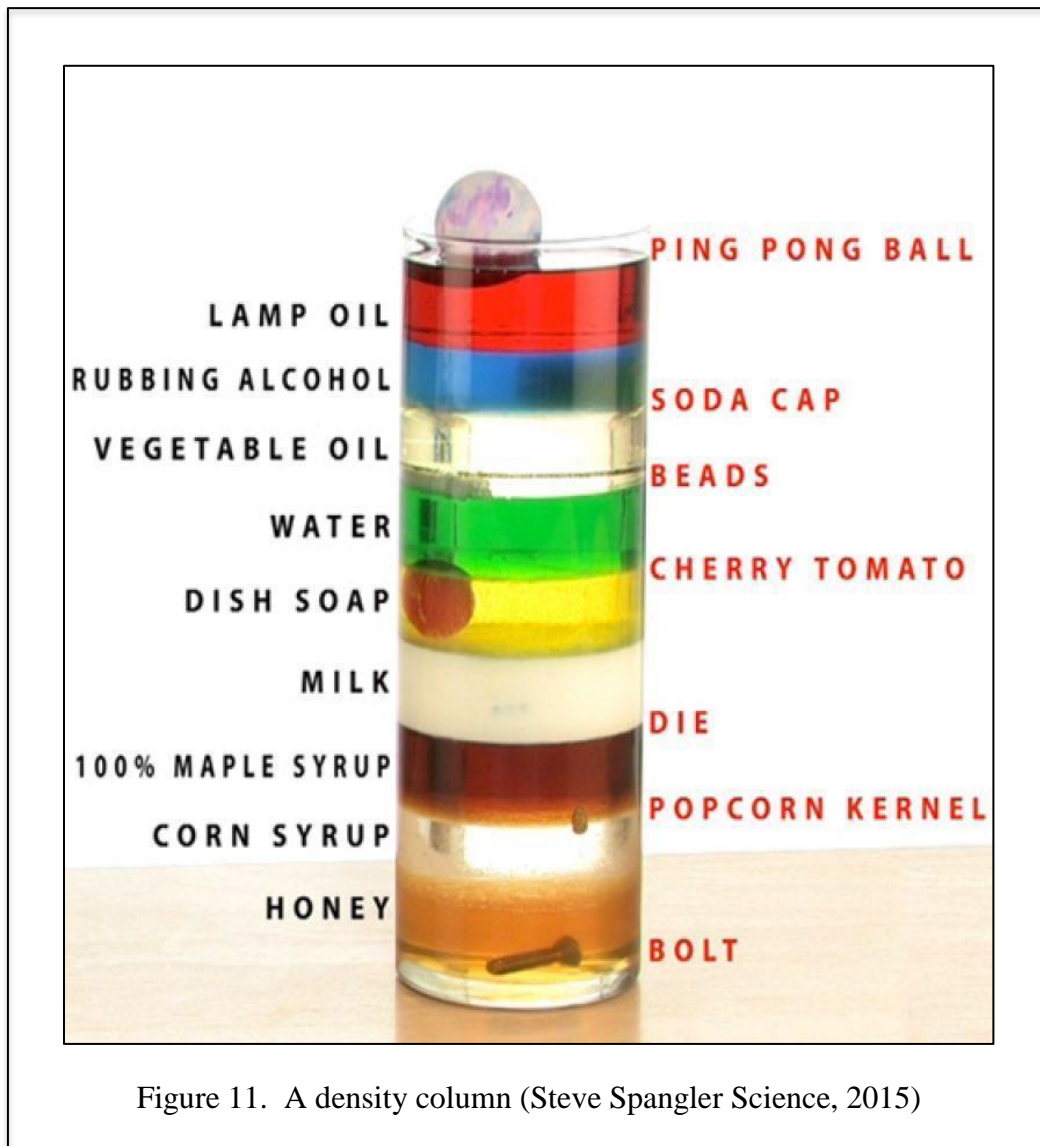


Figure 10. Density cubes. (Left to right: copper, pine, PVC, acrylic, brass, nylon, and steel)

The decision to “simplify” the teaching of relative densities by holding constant the shape or volume of objects and the volume of liquids may also promote the misconception that denser materials must be heavier, no matter the volume. A common practice in teaching relative density is to show students objects of equal volume but different densities. An example is “density cubes” (Figure 10), which are standard science-class equipment. Teachers ask students to measure the masses and calculate the densities of these one-inch cubes of different materials. Not surprisingly, students discover that the heavier the cube, the denser the material. Using objects of identical volume for such tasks may give rise to—or underscore—a

student's misunderstanding that mass and density are the same and that volume is irrelevant.



The same confusion is often reinforced in the construction of a popular science project, a “density column” (Figure 11). Usually the directions, easily found online, tend to require that strictly equal volumes of different-density liquids be used. For example:

HOW DOES IT WORK?

The same amount of two different liquids will have different weights because they have different masses. The liquids that weigh more (have a higher density) will sink below the liquids that weigh less (have a lower density).

To test this, you might want to set up a scale and measure each of the liquids that you poured into your column. Make sure that you measure the weights of equal portions of each liquid. You should find that the weights of the liquids correspond to each different layer of liquid. For example, the honey will weigh more than the Karo syrup. By weighing these liquids, you will find that density and weight are closely related (Steve Spangler Science, 2015).

The requirement that the volume of each liquid be the same removes any student observations about volume from the task, which may reinforce the notion that denser materials are just plain heavier. [The author of this project might have pointed out that the mass or volume of each specified liquid and solid is irrelevant in setting up a density column. An inverted pyramid of layers, for example, with one milliliter of honey and a one-gram steel bolt at the base, and 1000 milliliters of lamp oil and a 1000-gram ball with the same density as a ping-pong ball (which would be enormous) will settle out in exactly the same order as in Figure 11.]

Recommendations for Teachers

1. Use words carefully and consistently when teaching mass, volume and density concepts. Avoid words such as “size,” “amount,” “heavy,” and “light” because they are vague and, at times, misleading.
2. Teach density as an intensive quantity with many opportunities to observe, model, and predict how changing one variable at a time will affect the density of matter. Spend as much time as possible modeling, predicting, and observing the effect of different volumes on the density of matter.

3. Give students ample opportunities to discuss thought experiments and to develop solutions together in order to refine their understandings of how to measure matter. This is particularly important with problems that have nonobvious solutions, such as finding the mass of air or finding the volume of a drop of water.
4. When comparing the densities of materials, make sure that the volumes span a range. Comparing the densities of equal volumes of materials may encourage student conflation of mass and density.
5. When discussing thermal expansion of matter, ensure that students keep the concepts of conservation of mass and variable volume distinct.
6. Practice with the density formula, density equals mass divided by volume, is both useful and practical, but be sure that students have plenty of opportunities to model their answers diagrammatically as well. Further, using the density formula with diagrams to solve for unknowns (*e.g.*, determine the mass of 10 milliliters of molasses, given that its density is 1.4 grams/milliliter) is helpful for developing deeper understanding.

Limitations of the Study

This study was limited by a number of practical and methodological factors. The sample sizes were small due to the fact that I studied students in my own classroom. Given the research design was a quasiexperimental comparison of two small groups, statistical analyses were inappropriate, and so my findings are just suggestive. Second, several types of time constraints affected the study. I was a full-time teacher, so I did not have time to extend the study longer or collect data more

intensively. My students also had little time to participate in the study except during their science class. The nature of the school year plus the timing and duration of my usual density unit were also time constraints on the study. A third and lesser limitation arises from the subjectivity of being a teacher-researcher. The bulk of my data came from assessments where I acted as an impartial proctor, but I also analyzed the learning trajectories of the two classes. This analysis involved subjectively pulling together data from my dual roles as teacher and researcher to construct narratives. I believe that the learning-trajectory analysis and the assessment analyses complement each other to make my findings stronger, and so the subjectivity claim limited the study very little.

The instruments that I used for assessment were also somewhat problematic. My study was based on earlier research done with eighth-grade students, and so the assessments from that study were better suited to students who knew more math than my sixth graders. Further, the language of some of the questions on the assessments was different from what my students were accustomed to hearing in class (particularly the assessments' use of the words "size" and "amount" in place of "volume"). In addition, some items were phrased so that students might have believed that they were supposed to choose between two items of equal density when the actual expectation was that they rank order a set of objects by density. Each of these issues may have curbed student performance on the assessments in my study.

Next Steps

Now that the national science standards are undergoing rapid and profound changes, we have an opportunity to improve the way we teach density. Students need some practice in solving problems using the density formula. However, they need much more time for modeling and discussing their solutions and predictions in order to distinguish mass and density (and volume) and to develop a deep understanding of each concept. Using models to solve complex problems is an instructional goal of the Next Generation Science Standards (NGSS), which provides academic and political backing for the findings of this study.

We should also carefully examine how we teach the concept of volume in elementary and middle schools. Volume is three-dimensional and highly variable depending on temperature and pressure, which may make the concept particularly difficult for children. When discussing density, we must take care not to minimize or overlook volume in favor of the more tangible concept of mass.

Teachers and researchers need to learn more about how students make sense of the relationship of mass to volume in curricula involving density. More study is needed, particularly before we can expect middle-grade students to employ the concept of density as a scientist does. Yet that may be the expectation of the NGSS. Rather than address the teaching of density directly, the NGSS for middle school consider density as a defining characteristic of matter (*e.g.*, analyzing a substance by calculating its density to determine whether a chemical reaction has occurred) and as a driver of Earth systems (*e.g.*, knowing that varying levels of salinity drive ocean

currents) (NGSS, 2013). As the standards are implemented, teachers and curriculum designers will need the help of researchers to address students' varying abilities to make sense of density in this new context.

APPENDIX A

Description of the Intervention: Instruction and Instructional Purposes/Goals in Chronological Order

Intervention Instruction	Purpose/Goal
<p>LESSON 1</p> <p>Modeling density through crowdedness</p> <ol style="list-style-type: none"> 1. Observing/experiencing crowdedness. Half the class observes. Half the class enters a 12' x 12' box outlined on the floor; students move around in the box, keeping themselves equally distributed. Students switch places 2. Comparing crowdedness. The entire class enters box and attempts to move around, keeping themselves equally distributed <ol style="list-style-type: none"> 1. Discussion: does the space feel more crowded now? Why? 2. The second group leaves the space. Discussion: what could we do to make half of the class feel just as crowded as the full class? 3. Discussion: what changes would make half the class feel even less crowded? 4. Discussion: how can we describe this activity in diagram form? Student groups suggest further modeling crowdedness by using dots (students) and boxes of different sizes (area of square). 5. Discussion: what is crowdedness? Students define crowdedness as an intensive quantity: the number of children per one box. 	<p>LESSON 1</p> <p>To understand the difference between extensive and intensive quantities</p>
<p>LESSON 2: First Reflective Lesson</p> <ol style="list-style-type: none"> 1. Discussion: students work in groups of four to solve a mystery in which they must figure out which punch recipe creates the most concentrated solution by creating dot-and-box models 2. Using their dot-and-box models, students predict, observe, and explain (POE) their answers to the mystery. Observations are in 	<p>LESSON 2</p> <p>Formative assessment of students' understanding of proportionality & crowdedness; modeling</p>

the form of reducing the four large-scale punch recipes into four small cups and tasting to see if their concentration predictions were accurate. Explanations are in the form of simplified ratios of drink powder to water derived from student models.

LESSON 3

Class Discussion: what is matter?

Worksheet: What is matter?

1. Rock, idea, echo, water, grain of sugar, particle of chalk dust, air, tree, shadow, wish, heat, dog
2. I tally answers on a chart; the class discusses areas of agreement and disagreement
3. Discussion: what properties do the items that the class agrees on share that qualifies them as matter?
4. Discussion: what are reasons that you might think that something is or is not matter?
5. Discussion: class revotes on the areas of disagreement and students write answers individually to the following questions: *what are the properties of matter*; and *how can you tell if something is made of matter*?

LESSON 4

Activity: students compare two objects of similar mass and different volume

1. Students compare the two items by hefting and decide which item has more mass
2. Each item is placed in a plastic bag and students dangle a bag in each hand under the table and then decide again which item has more mass

LESSON 5

Lecture: finding the volume of regular solids using a ruler, and finding the volume of irregular solids using water displacement

LESSON 3

To allow the class as a group to refine its definition of matter.

LESSON 4

To experience that our senses can deceive us, showing the need to measure, to describe accurately, and to compare matter

LESSON 5

To reacquaint students with measurement techniques of extensive quantities and to review the terms “volume,”

“milliliter,” “cubic centimeter”

LESSON 6

Activity: measuring the mass and volume of a variety of solids. Students practice estimating and then measuring the masses of solids using the pan balance. Students then practice estimating and measuring the volumes of the same solids using rulers and/or graduated cylinders.

LESSON 6

To reacquaint students with measurement techniques of extensive quantities and to review the terms “mass”, “volume”, “gram”, “milliliter”, “cubic centimeter”

LESSON 7

Discussion: through *gedankenexperiments* (mental models), student groups develop strategies to measure “unmeasurable” volume and mass

1. Groups develop strategies by means of mental models to accurately measure the volume of a drop of water; strategies must rely only on measurement tools found in the classroom, and groups are encouraged to present their one “best” strategy to the class
2. Groups develop strategies by means of mental models with which to accurately determine the volume of a sheet of 8.5” x 11” paper; strategies must rely only on measurement tools found in the classroom, and groups are encouraged to present their one “best” strategy to the class
3. Groups develop strategies by means of mental models with which to accurately determine the mass of a lentil (this mass is too small to measure on a classroom pan balance); strategies must rely only on measurement tools found in the classroom, and groups are encouraged to present their one “best” strategy to the class

LESSON 7

To refine students’ understanding of the difference between mass and volume

LESSON 8

Lecture about materials and their properties

1. What are the characteristics of matter?

LESSON 8

To give students the opportunity to

2. How can we tell different materials apart?
3. How can you determine what a mystery material might be?

Discussion: students work in groups to develop a series of steps to determine the identity of a mystery material using only measurement equipment found in the classroom

use the intensive quantity of density as a predictive characteristic of an unknown material

LESSON 9: Second Reflective Lesson

Modeling: Draw ways to show the different “heaviness” of the following equal-volume items: acrylic, aluminum, wood; and a larger volume mystery material (a stack of 25-gram pieces covered with paper).

Modeling: Making a quantitative model that compares the mass of objects of different volumes. Students are asked to imagine 2 cubic centimeters of clay with a mass of 3 grams, and 10 cubic centimeters of balsa wood with a mass of 4 grams. Using their models, students predict the volumes of any given mass of clay or balsa wood.

LESSON 9

Reflective lesson on mass-to-volume relationship and to create model to represent “heaviness” of different materials

LESSON 10

Activity: Density of liquids.

Demonstration: Students observe room-temperature fresh water floating on top of room-temperature salt water in a beaker.

Discussion: Is there any way to make salt water float on top of fresh water?

Modeling: Draw a way to compare the densities of rubbing alcohol with a given density of 0.8 g/ml and molasses with a given density of 1.4 g/ml.

Modeling: Given that the density of water is 1g/ml, construct a model that shows this and can be used to predict the answer to: what is the density of 10 ml of water? Students test their predictions by finding the mass of 10 ml of water and explaining what they observe.

LESSON 10

To establish that liquids have density, and to model the density of water

LESSON 11: Third Reflective Lesson

Activity: Predict and hypothesize about sinking and floating using estimation and modeling. In groups, student discuss how to estimate the relative densities of the following materials: water, apple, orange with

LESSON 11

Reflective lesson to compare different densities using predictive models

peel, orange without peel, carrot, a can of soda, a can of diet soda, and a small ceramic heart, and create models that can be used to predict whether the solids will sink or float in in water.

that allow students to formulate a rule to predict whether objects will sink or float in a given liquid

LESSON 12

Demonstration: Erlenmeyer flask with a small glass tube stuck through a rubber stopper. The flask contains vegetable oil and is sitting in a warm-water bath which is slowly warming up. The mass of the oil-filled flask is taken at various times during the warming process. Students observe the behavior of the oil in the tube and discuss in groups how this might work as a thermometer and why the oil appears to be rising. In groups, students develop drawn models to show the mass and volume of the oil before and after heating.

Activity: Read and discuss the outcome of “The Man Who Fell Through the Ice” about a man who fell into a frozen lake when he walked home with a gallon of colder-than-normal oil.

Model: In groups, students devise models that explain why a gallon of warm oil has a different mass than a gallon of cold oil, and why a gallon of cold oil is a better deal financially than a gallon of warm oil.

LESSON 12

To observe the behavior of a liquid at different temperatures; to use a model to infer what has happened to the density of a liquid after heating.

LESSON 13

Activity: The Thermal Egg. In groups of four, students build a “thermal egg,” which is a small styrofoam ball covered with enough plasticine clay to make the entire mass neutrally buoyant in room-temperature water (in other words, the mass-to-volume ratio of the thermal egg equals one, which is equivalent to the mass-to-volume ratio of room-temperature water). Once the thermal egg has been constructed, students discuss and decide in their groups how to draw models to predict and explain what the thermal egg will do when dropped into icy water and into hot water. Students test their predictions and explain their results.

LESSON 13

To use the concept of relative density to solve a problem; to practice constructing models to predict and explain outcomes.

End-of-chapter multiple-choice test from the
classroom science textbook

To assess
understanding of
density

APPENDIX B

Description of the Intervention and Comparison Density Units:
Instruction and Instructional Purposes/Goals in Chronological Order

INTERVENTION CLASSROOM (see Appendix A for more detail)		COMPARISON CLASSROOM	
Instruction	Purpose/Goal	Instruction	Purpose/Goal
LESSON 1 Modeling density through crowdedness	LESSON 1 To understand the difference between extensive and intensive quantities	COMPARISON LESSON 1 Lecture: how to find the volume of regular solids using a ruler, and how to find the volume of irregular solids using water displacement (Compare with Lesson 5 of the intervention.)	COMPARISON LESSON 1 To reacquaint students with measurement techniques of extensive quantities and to review the terms “volume”, “milliliter”, “cubic centimeter”
LESSON 2 First reflective lesson	LESSON 2 Formative assessment of students’ understanding of proportionality and crowdedness; modeling	COMPARISON LESSON 2 Activity: measuring the mass and volume of a variety of solids. Students practice estimating and then measuring the masses of solids using the pan balance. Students then practice estimating and measuring the volumes of the same solids using rulers and/or graduated cylinders. (Compare with Lesson 6 of the intervention.)	COMPARISON LESSON 2 To reacquaint students with measurement techniques of extensive quantities and to review the terms “mass”, “volume”, “gram”, “milliliter”, “cubic centimeter”

LESSON 3	LESSON 3	COMPARISON LESSON 3	COMPARISON LESSON 3
What is matter?	To allow the class as a group to refine its definition of matter.	Read text on mass, weight, and volume; in groups, students complete written activities in the text on determining the volumes of regular and irregular solids (Compare with Lessons 5 and 6 of the intervention.)	To introduce the difference between mass and weight, to reinforce the concepts of mass and volume, and to allow additional practice in determining the volume of various solids through written exercises
LESSON 4	LESSON 4	COMPARISON LESSON 4	COMPARISON LESSON 4
Activity: students compare two objects of similar mass and different volume	To experience that our senses can deceive us, showing the need to measure to accurately describe and compare matter	Activity: determine the densities of equal-volume cubes by measuring their masses and calculating their densities using the formula: density equals mass divided by volume. Students express their answers in grams per cubic centimeter and order the cubes from least dense to most dense. (Compare with Lesson 9 of the intervention.)	To quantitatively compare the densities of 9 different materials: pine, oak, acrylic, PVC, nylon, aluminum, copper, brass, and steel; to introduce density as an intensive quantity
LESSON 5	LESSON 5	COMPARISON LESSON 5	COMPARISON LESSON 5
Lecture: finding the volume of regular solids using a ruler and finding the volume of irregular solids using water	To acquaint students with the concept of volume	Activity: determine density of solids of varying volume and evaluating whether different objects made of the same material have the same density	To use density as a quantifiable characteristic property of matter

displacement

(Compare with Lesson 8 of the intervention.)

LESSON 6

Activity: measuring the mass and volume of solids and liquids

LESSON 6

To reacquaint students with measurement techniques and terms

COMPARISON LESSON 6

Read text on density and answer text questions in table groups

COMPARISON LESSON 6

To review the first section of the chapter, to practice calculating volumes of regular solids, and to practice calculating densities using the formula $d = m/v$

LESSON 7

Discussion: through *gedankenexperiments* (mental models), student groups develop strategies to measure “unmeasurable” volume and mass

LESSON 7

To refine students’ understanding of the difference between mass and volume

COMPARISON LESSON 7

Demonstration: a spring scale is used to measure the weight of a rock both in and out of tap water, salt water, and rubbing alcohol
Read text on floating, sinking, and buoyant force; watch a video on buoyancy and ship design
(Compare with Lesson 13 of the intervention.)

COMPARISON LESSON 7

To observe the effect of buoyancy on the weight of an object, to observe that different liquids might have a different effect on an object’s buoyancy and weight, and to apply this understanding to constraints regarding ship design

LESSON 8

Lecture about materials and their properties
Discussion: students develop a series of steps to determine the identity

LESSON 8

To give students the opportunity to use the intensive quantity of density as a predictive

COMPARISON LESSON 8

Activity: Clay boats. Students create boats from 100-gram portions of clay and change the boat’s shape to accommodate more and more cargo in the

COMPARISON LESSON 8

To manipulate variables to create floating objects of different volumes and masses; to maximize a clay boat’s carrying capacity

of a mystery material using only measurement equipment found in the classroom

characteristic of an unknown material

form of plastic one-gram pieces.

(volume) by adjusting the shape of the boat to hold more and more cargo without sinking

LESSON 9

Second reflective lesson

LESSON 9

Reflective lesson on mass-to-volume relationship and to create model to represent “heaviness” of different materials

COMPARISON LESSON 9

Activity: Underwater waterfalls. Students create underwater waterfalls by layering colored samples of hot, cold, tap, and salt water. Students draw what they see in their beakers and explain why waterfalls are occurring. (Compare with Lesson 10 of the intervention.)

COMPARISON LESSON 9

To observe, compare, and explain what happens when fluids with different temperatures and solute concentrations are layered or mixed

LESSON 10

Density of liquids

LESSON 10

To establish that liquids have density, and to model the density of water

COMPARISON LESSON 10

Demonstration: students observe the behavior of a thin Mylar ribbon located within the column of air over a burning candle
Read text on heat, density, and buoyancy. Watch video on hot-air balloons

COMPARISON LESSON 10

To observe the behavior of warm air

LESSON 11

Third reflective lesson

LESSON 11

Reflective lesson to compare different densities using predictive models that allow students to formulate a rule to predict whether objects will sink or float in a given liquid

COMPARISON LESSON 11

Discussion: can we make hot-air balloons in the classroom?
 Activity: Students work in groups to experiment with tissue paper, lightweight plastic bags, tape, and hair dryers to see if they can create a floating container of warm air. Students draw models to explain how hot-air balloons work and write short explanations to accompany their models.
 (Compare with Lesson 12 of the intervention regarding thermal expansion)

COMPARISON LESSON 11

To apply the concept of thermal expansion in air

LESSON 12

Demonstration, activity, and modeling—heating liquids and density

LESSON 12

To observe the behavior of a liquid at different temperatures; to use a model to infer what has happened to the density of a liquid after heating.

LESSON 13

The Thermal Egg

LESSON 13

To use the concept of relative density to solve a problem; to practice constructing models to predict and explain outcomes

End-of-chapter multiple-choice test from the classroom science textbook

To assess understanding of mass and density

End-of-chapter multiple-choice test from the classroom science textbook

To assess understanding of mass and density

APPENDIX C

Interview Protocol

Date _____ Time start _____ Time stop _____

Name _____ Period _____

1. Please hold these two pieces of styrofoam. Do they have mass?

Does the big piece have a lot of matter, a little matter, or no matter?

Does the small piece have a lot of matter, a little matter, or no matter?

If a piece of Styrofoam is too small to see, does it exist?

If it exists, does it have mass? _____

Now, imagine that you have a special tool that allows you to cut very small pieces of matter. Could Styrofoam be cut in half repeatedly forever, or would there be a point at which no matter was left to cut?

2. Please hold these pairs of objects as I ask you about each pair. You may use the pan balance if you like for comparing the masses of the objects. For each pair, does one object have more mass?

1. PVC cylinder, wood cylinder
2. aluminum cube, copper cube
3. aluminum cube, copper penny
4. aluminum cube, aluminum cylinder
5. wood block, aluminum cube

Now, for each pair, is one item denser?

1. PVC cylinder, wood cylinder
2. aluminum cube, copper cube
3. aluminum cube, copper penny
4. aluminum cube, aluminum cylinder
5. wood block, aluminum cube

3. Can you put these four objects (mystery cylinder, aluminum cube, aluminum cylinder, and large wooden block) in order from the least mass to the most mass?



Now, can you put these four objects in order from the least dense to the most dense?

4. If I add a very small piece of clay to this ball of clay, do any of the following measurements change – the amount of clay in the ball, the mass of the ball, or the density of the clay? Please explain your answer(s).

5. If I move this thermometer from a cold-water bath to a warm-water bath, do you see that the alcohol in the glass tube rises? Do any of the following change – the amount of alcohol in the tube, the mass of the alcohol, or the density of the alcohol? Please explain your answer(s).

6. How would you define the word *density*?

APPENDIX D

Written Test

Name _____

Date _____

Period _____

1. Please decide whether you consider each item in the following list to be *matter* or *not matter*. That is, decide whether each item is made of some kind of physical material or not.

matter: yes or no?

- _____ a dog
- _____ a tree
- _____ a rock
- _____ water
- _____ a grain of sugar
- _____ a particle of chalk dust
- _____ air
- _____ heat
- _____ a shadow
- _____ an echo
- _____ an idea
- _____ a wish

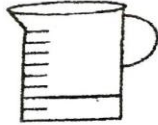
2. Please describe or list the properties of matter. In other words, what makes something qualify as matter?

3. How can you tell if something is made of matter?

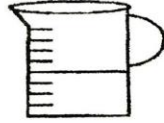
4. Please pick up the two cubes you have been supplied at your table for question 4. One cube is steel, the other cube is aluminum, and both are the same size. You can easily feel that the two cubes have different masses. Draw a picture below that shows your idea about why the objects are so different in mass.

5. Given the information below, please circle the beaker that has a sweeter liquid for each problem.

Problem 1

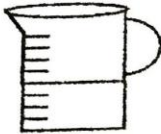


2 cups of water
6 tps of sugar

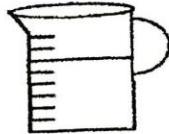


4 cups of water
3 tps of sugar

Problem 2

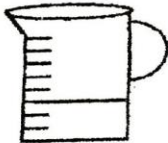


4 cups of water
12 tps of sugar

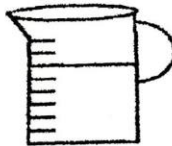


6 cups of water
12 tps of sugar

Problem 3

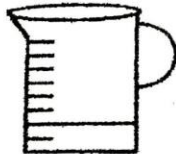


3 cups of water
9 tps of sugar



6 cups of water
18 tps of sugar

Problem 4

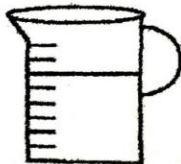


2 cups of water
8 tps of sugar



6 cups of water
18 tps of sugar

Problem 5

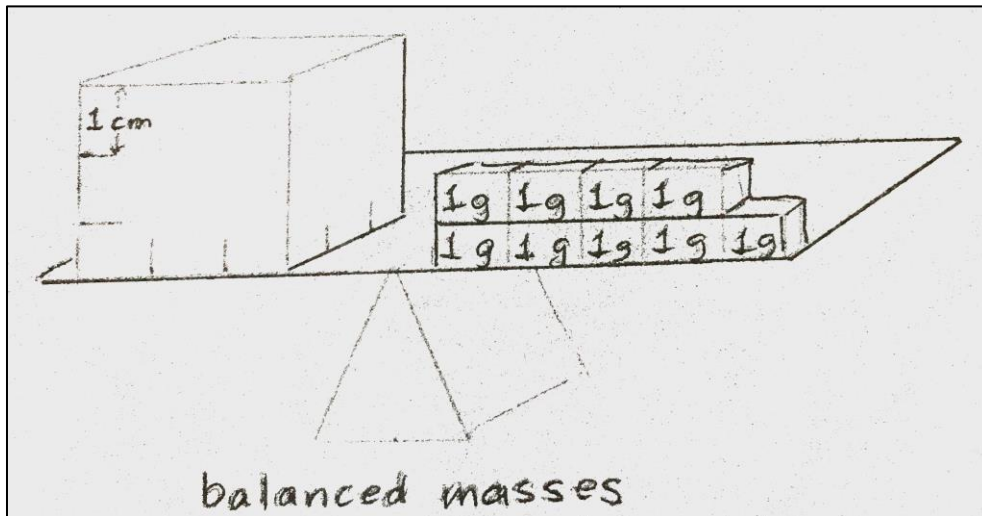


6 cups of water
8 tps of sugar



8 cups of water
10 tps of sugar

6. Can you find the volume, mass, and density of the cube shown below? Please explain how you arrived at your answer(s).



7. Please pick up the four objects labeled A, B, C, and D at your table for question 7. Each object is also labeled with its volume and mass. Can you put them in order from least dense to most dense? Write the letters below.


least dense -----> most dense



8. Can each pair of objects below be made of the same material?

Problem 1


A B



Objects A and B are the same size, but B has more mass than A.

Problem 2

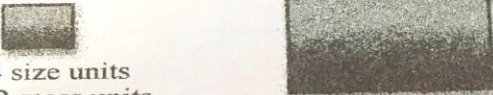
A B



Objects A and B have the same mass, but B is smaller than A.

Problem 3

A B

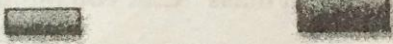


4 size units
12 mass units

10 size units
30 mass units

Problem 4

A B

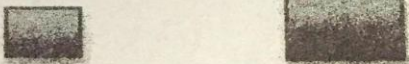


2 size units
8 mass units

3 size units
9 mass units

Problem 5

A B



3 size units
5 mass units

5 size units
7 mass units

APPENDIX E

End-of-Chapter Test*

1. The space that an object takes up is its:
 - a. density
 - b. volume
 - c. weight
 - d. mass
2. The density of an object depends on which of the following:
 - a. how closely the atoms are packed in the material
 - b. the size of the object
 - c. the object's temperature
 - d. both A and C
3. The density of an object is defined by:
 - a. mass divided by volume
 - b. mass times volume
 - c. volume divided by mass
 - d. volume plus mass
4. Density is typically measured in what units?
 - a. g/cm
 - b. g/cm²
 - c. g/cm³
 - d. g/cm⁴
5. Given the following densities (wood = 0.9 g/cm³, glass = 2.3 g/cm³, aluminum = 2.7 g/cm³, and iron = 7.8 g/cm³), what material could a block with a mass of 78 grams and a volume of 10 cm³ be made of?
 - a. wood
 - b. glass
 - c. aluminum
 - d. iron
6. Mass is measured in:
 - a. inches
 - b. pounds
 - c. grams
 - d. cubic centimeters

7. Which of the following measures the pulling force of gravity on an object?
- volume
 - weight
 - mass
 - A and C
8. What is the volume of a box with dimensions of 5 cm x 3 cm x 2 cm?
- 10 cm
 - 10 cm^3
 - 30 cm
 - 30 cm^3
9. Matter that has the ability to flow is a:
- fluid
 - gas
 - liquid
 - all of the above
10. If the buoyant force on a beach ball is greater than the weight of the ball, the ball will:
- float
 - sink
 - have neutral buoyancy
 - float and then sink
11. If the buoyant force on a beach ball is less than the weight of the ball, then the ball will:
- float
 - sink
 - have neutral buoyancy
 - float and then sink
12. If an object is less dense than the fluid it is placed in, it will:
- float
 - sink
 - have neutral buoyancy
 - float and then sink
13. If an object with a density of 2.0 g/cm^3 is placed in a fluid with a density of 1.9 g/cm^3 , the object will:
- float
 - sink
 - have neutral buoyancy
 - dissolve

14. If the force of gravity on Jupiter is greater than the force of gravity on Earth, how would your mass on Jupiter compare to your mass on Earth?
- it would be greater
 - it would be less
 - it would be the same
 - you can't tell without numbers
15. If the force of gravity on the Moon is less than the force of gravity on Earth, how would your weight on the Moon compare to your weight on Earth?
- it would be greater
 - it would be less
 - it would be the same
 - you can't tell without numbers
16. What is the density of a gold ring that has a mass of 6 g and a volume of 3 cm³?
- 0.5 g/cm³
 - 2 g/cm³
 - 1 g/cm³
 - 3 g/cm³
17. How does the density of a thin copper wire compare to the density of a copper ring?
- the wire is denser than the ring
 - the wire is less dense than the ring
 - the densities are the same
 - you can't tell without numbers
18. Warm air rises above cool air because
- warm air is less dense than cool air
 - warm air is more dense than cool air
 - warm air has the same density as cool air
 - warm air has more weight than cool air
19. The air near the ceiling of a classroom has a temperature of 90 degrees Fahrenheit, while the air near the floor has a temperature of 70 degrees Fahrenheit. What conclusion can you make about the air in the room?
- the air near the ceiling is more buoyant than the air near the floor
 - the air near the ceiling is less buoyant than the air near the floor
 - the air near the ceiling has the same density as the air near the floor
 - the air near the ceiling is more dense than the air near the floor

20. In order to change the density of an object, you can:
- change its volume, but keep its mass the same
 - change its temperature
 - change its shape
 - A or C
21. In order to make air float, which of the following can be done?
- decrease the air's density
 - heat the air
 - increase the air's volume
 - all of the above
22. When an object's volume is made smaller and its mass remains the same, its density:
- increases
 - decreases
 - remains the same
 - increases, then decreases
23. When an object is heated and increases in temperature, its atoms spread further apart, causing:
- the object's weight to increase
 - the object's weight to decrease
 - the object's volume to increase
 - the object's volume to decrease
24. If a low-density object is placed in a high-density fluid, the object will:
- displace fluid equal to the object's mass
 - not be able to displace fluid equal to the object's mass
 - increase in density
 - decrease in density
25. Which of the following is not a fluid?
- helium gas
 - maple syrup
 - brick
 - water

*From the textbook used by the comparison class: *CPO Focus on Earth Science* (2007), Chapter 5.

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