Implications of Research on Children's Learning for Assessment: Matter and Atomic Molecular Theory

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Introduction: Purposes and Overview

Our purpose in this paper is to suggest ways of using research on children's learning to improve assessments, including both large-scale assessments at the national and state levels and classroom assessments. We are convinced that this research has important implications for assessment.

We take it as given that what children learn in school should lead them to see the world in new ways: ways that are informed by both personal experience and foundational scientific theories. However, research on children's learning consistently shows discontinuities between the science that they learn in school and the ways that they think about and interpret physical phenomena. They learn to recite the answers to school questions without recognizing the connections between those school questions and their own ideas about the world. As a result, many children learn to "do school" without altering their underlying ideas about how the world works.

The results of these discontinuities between school learning and children's ways of thinking about the world are profoundly troubling. Although, in the short run, many children can learn to repeat what their teachers tell them, in the long run it is the ways of thinking that are grounded in their life experiences that endure. The result is the troubling patterns that we see in large-scale assessments of science learning. Even though students study the topics tested in the assessments repeatedly, because they do not understand these topics, they soon forget what they were told, and their performance remains frustratingly poor.

The authors of standards documents such as *Benchmarks for Science Literacy* (AAAS, 1993) and the *National Science Education Standards* (NRC, 1996) intended to include knowledge that would be useful to students both in school and out. However, large-scale and classroom assessments based on the standards commonly undermine this intent by focusing on school tasks that children do not connect with their life experiences or by sampling knowledge in scattershot manner. These assessments encourage teachers to focus on memorization and recitation of isolated science facts and procedures.

We believe that research on children's learning provides valuable tools and strategies for developing large-scale and classroom assessments that reveal students' ways of thinking about the world and the extent to which their thinking is (or fails to be) informed by the conceptual frameworks of scientists. Such assessments would enable teachers to gain insights about their students and to connect the content of science standards with children's life experiences.

Developing standards-based assessments that use tools and strategies from research on children's learning will require new approaches to *elaborating standards* and to *designing and interpreting assessments.* In the remainder of this paper we first suggest general strategies for accomplishing these goals. We then develop examples around an important topic in the school curriculum: matter and atomic molecular theory.

Using Research on Learning to Elaborate Standards

Assessments are generally based on standards that summarize the knowledge students should master, including *Benchmarks for Science Literacy* (AAAS, 1993) and the *National Science Education Standards* (NRC, 1996). These standards consist mostly of brief statements of propositional knowledge that students of different ages should understand. Since they do not provide operational definitions of understanding, they must be elaborated before they can be used as a basis for assessment.

Research on learning can be used as the basis for a principled strategy for developing elaborated standards that can support valid and useful assessments. This strategy includes (a) organizing standards around big ideas, (b) connecting standards to empirical evidence about children's learning, and (c) connecting children's knowledge and practice.

Organizing standards around big ideas

Because standards tend to be lists of propositions, we undertake to specify those central principles or "big ideas" that underlie understanding these propositions. Repeated focus on a comparatively small set of foundational principles and related concepts and practices can provide coherence for assessment and instruction. Central principles can be introduced early in schooling and progressively refined, elaborated, and extended throughout schooling. Teaching to big ideas provides coherence to the curriculum and helps teachers align curriculum tasks with learning performances. Assessments, too, can be made more valid and predictable by sampling from clusters of standards around big ideas rather than sampling randomly from standards at large.

Key characteristics of big ideas include the following:

- *Powerful ways of thinking about the world:* Big ideas are central to their discipline and have broad explanatory scope. They are the source of coherence among the various concepts, models, theories, principles and explanatory schemes to different classes of phenomena within a discipline. The also provide insight into the development of the field, and are links between disciplines.
- *Structure learning progressions.[1]:* Big ideas can be understood in progressively more sophisticated ways as students gain in cognitive abilities and experiences with phenomena and representations. They underlie the acquisition and development of concepts central to a discipline and lay the foundation for continual learning.

[1] We define a learning progression as a sequence of successively more complex ways of thinking about an idea that might reasonably follow one another in a student's learning. We agree on several caveats about learning progressions:

- Learning progressions are not developmentally inevitable. There is no single "correct order."
- Actual learning is more like ecological succession, with changes taking place simultaneously in multiple interconnected ways, than like the artificially constrained and ordered accounts that we can give in this paper.
- The learning progressions that we can suggest are partly hypothetical or inferential. We do not have long-term longitudinal accounts of learning by actual students.
- Describing students' reasoning is problematic because the available research uses many different methods and conceptual frameworks.

In this paper we suggest possible big ideas for matter and atomic-molecular theory and use them to organize our accounts of learning progressions and examples of assessment tasks.

Connecting standards to empirical evidence about children's learning

The standards prescribe what should be learned at different ages based on logic and personal experiences of the authors. In the years since the standards were written the body of available research on children's learning of these topics has been considerably enlarged. This enables us to elaborate on and sometimes reconsider the standards in the following ways:

- *Making judgments about age appropriateness.* The research can provide empirical evidence for the age appropriateness of standards, particularly in the form of teaching experiments demonstrating that typical students in a certain grade range can learn a standard with proper instruction.
- *Elaborating on necessary underlying knowledge.* The research can show that understanding an idea in the standards requires additional knowledge—ideas that are necessary prerequisites to those in the standards. With support from the research, we can suggest those ideas and explain why they are prerequisites.
- *Suggesting connections and learning progressions.* The research can also show connections among standards-- instances where ideas reinforce one another or where understanding of some ideas depends on the understanding of others. This enables us to cluster standards around big ideas and to suggest reasonable sequences or progressions across grade levels.
- *Resolving conflicts among standards.* Relevant standards documents, including the *National Science Education Standards, Benchmarks for Science Literacy,* and the *NCTM Content Standards,* do not always agree about appropriate expectations and learning progressions for students of different ages. Research can help to resolve these conflicts by suggesting which standards could be most accessible and useful to students.

Thus what we attempt to do in this paper is to show how research on learning can be used to elaborate on the standards in ways that support useful and valid assessments.

Enacting children's knowledge in practice

The research can also help us to develop operational definitions of what it means to "understand" a standard by suggesting connections between the conceptual knowledge in the standards and practices that can be observed and assessed. We define practice to mean the coordination of knowledge and skills to accomplish a goal/task. By defining the most important practices for which the knowledge is used, we can connect the conceptual statements in the standards with classroom and assessment performances in which students enact their understanding in ways importantly similar to scientists. Some of the key practices that are enabled by scientific knowledge include the following:

- *Defining and describing.* Defining and describing involves recalling from memory a definition of a concept or principle or describing how one concept relates to other ideas. For example, a student could describe the flow of energy in an ecosystem. Or, a student could describe how to use a light probe by telling a fellow student how to use it to measure light reaching a plant.

- *Representing data and interpreting representations.* Representing data involves using tables and graphs to organize and display information both qualitatively and quantitatively. Interpreting representations involves being able to use legends and other information to infer what something stands for or what a particular pattern means. For example, a student could construct a table to show the properties of different materials or a graph that relates changes in object volume to object weight. Conversely, a student could interpret a graph to infer which size object was the heaviest or a straight line with positive slope to mean there was proportionality between variables.
- *Identifying and classifying.* Both identifying and classifying involve applying category knowledge to particular exemplars. In identifying, students may consider only one exemplar (Is this particular object made of wax?) whereas in classifying students are organizing sets of exemplars. For example, they could sort items by whether they are matter or not matter; by whether they are solid, liquid, or gas; or by kind of substance.
- *Measuring*
    - *Ordering/Comparing along a Dimension.* Ordering involves going beyond simple categorization (e.g., heavy vs. light) to conceptualizing a continuous dimension. For example, they could sort samples according to weight, volume, temperature, hardness, or density.
    - *Quantifying.* Quantifying involves being able to measure (quantify) important physical magnitudes such as volume, weight, density, and temperature using standard or nonstandard units. Measuring is a simple form of mathematical modeling: comparing an item to a standard unit and analyzing a dimension as an iterative sum of units that cover the measurement space.
- *Predicting/Inferring.* Predicting/inferring involves using knowledge of a principle or relationship to make an inference about something that has not been directly observed. For example, students can use the principle of conservation of mass to predict what the mass of something should be after evaporation; or they may calculate the weight of an object from knowledge of its volume and the density of a material it is made of.
- *Posing questions.* Students identify and ask questions about phenomena that can be answered through scientific investigations. Young learners will often ask more descriptive questions, but as learners gain experiences and understanding they should ask more relational and cause and effect questions.
- *Designing and conducting investigations.* Designing an investigation includes: identifying and specifying what variables need to be manipulated, measured (independent and dependent variables) and controlled; constructing hypotheses that specify the relationship between variables; constructing/developing procedures that allow them to explore their hypotheses; and determining how often the data will be collected, and what

type of observations will be made. Conducting an investigation includes a range of activities – gathering the equipment, assembling the apparatus, making charts and tables, following through on procedures, and making qualitative or quantitative observations.

- *Constructing evidence-based explanations.* Constructing explanations involves using scientific theories, models and principles along with evidence to build explanations of phenomena; it also entails ruling out alternative hypotheses.
- *Analyzing and interpreting data.* In analyzing and interpreting data, students make sense of data by answering the questions: “What does the data we collected mean?” “How does this data help me answer my question?” Interpreting and analyzing can include transforming the data by going from a data table to a graph or by calculating another factor and finding patterns in the data.
- *Evaluating/Reflecting/Making an Argument.* Evaluate data: Do these data support this claim? Are these data reliable? Evaluate measurement: Is the following an example of good or bad measurement? Evaluate a model: Could this model represent a liquid? Revise a model: Given a model for gas, how would one modify it to represent a solid? Compare and evaluate models: How well does a given model account for a phenomenon? Does this model “obey” the “axioms” of the theory?

These practices are not only “scientific”, but also how students make sense of the world in everyday terms. This continuity between everyday and scientific practices is important. Students can learn how science provides conceptual tools for practices that they are already doing, as well as how the scientific and everyday enactment of those practices differ (in the same way it is important to teach student that “air” and “heat” do not mean the same thing in everyday and scientific language). These scientific practices link theoretical models to the observed world. Organizing assessment around these practices highlights that scientific theories have the goal of making sense of and acting on the world.

Using Research to Design and Interpret Standards-based Assessments

In addition to being useful for elaborating standards, the principles, practices, and results from research on children's learning can also be used to design improved large-scale and classroom assessments. We suggest a three-stage process:

1. Big ideas and important practices can be codified in *learning performances*: types of tasks or activities appropriate for classroom settings through which students enact their understanding of big ideas and scientific practices. Learning performances reflect the reasoning tasks we want students to be able to do with scientific knowledge (Reiser et al., 2003). Learning performances reformulate the big ideas in terms of scientific practices that use those ideas, such as students being able to define terms, describe phenomena, use models to explain patterns in data, construct scientific explanations, or test hypotheses. Learning performances can be developed by crossing big ideas (i.e., specific content) with scientific practices. Figure 1 from McNeill and Krajcik (2004) gives an example of how learning performance stem

from crossing practice with content (in this case, content is taken directly from the standards rather than being organized around big ideas, as we do in this report).

Figure 1: Developing Learning Performances

Content Standard	Scientific Practice	Learning performance
When substances interact to form new substances, the elements composing them combine in new ways. In such recombinations, the properties of the new combinations may be very different from those of the old (AAAS, 1990, p.47).	Develop…explanations… using evidence. (NRC, 1996, A: 1/4, 5-8) Think critically and logically to make the relationships between evidence and explanation. (NRC, 1996, A: 1/5, 5-8)	Students construct scientific explanations stating a claim whether a chemical reaction occurred, evidence in the form of properties, and reasoning that a chemical reaction is a process in which old substances interact to form new substances with different properties than the old substances.

2. Learning performances can be used to develop clusters of *assessment tasks or items*, including both traditional and non-traditional items that are (a) connected to standards in principled ways, and (b) analyzable with psychometric tools.
3. The research can be used as a basis for *interpretation of student responses,* explaining how responses reveal students' thinking with respect to big ideas and learning progressions

We feel that assessments developed according to these principles will have a number of advantages over most current large-scale and classroom assessments, including the following:

- Assessments can be developed to reflect the big ideas underlying the standards as embodied in key scientific practices.
- Because of the link through learning performances, the interpretation of standards and the relationships between standards and assessment items can be clearer and more explicit.
- The assessments and their results will help teachers to understand and respond to their students' thinking.

Overview of the Paper

In the remainder of this paper we outline an approach to developing assessments for an important topics in the school curriculum: matter and atomic molecular theory. We identify a coherent set of big ideas and suggest learning progressions that organize and elaborate on the current national standards around big ideas and scientific practices.

For each grade range we use available research to produce a version of the big ideas that are suitable for the experiences, knowledge and cognitive abilities of students in that grade range, generate appropriate learning performances, and suggest possible assessment tasks or items that meet the following criteria:

1. They enact the national standards (in the form of big ideas and related practices) for that grade range.
2. There is evidence that students can perform well with appropriate instruction.

3. Both correct and incorrect student responses inform teachers, curriculum developers, and policymakers about students' thinking.
4. Student responses are potentially analyzable with psychometric tools, based on scoring rubrics that order responses or classify them into groups.

We accompany the assessment tasks with commentaries explaining how the tasks are useful in revealing students' thinking and (when available) with research results from studies that have used those tasks. We conclude with a section revisiting the claims made in this introduction, discussing how those claims are illustrated by the learning progressions, learning performances, and example tasks.

Learning Progression for Atomic Molecular Theory

Richard Feynman wrote about atomic theory:

> If, in some cataclysm, all of scientific knowledge were to be destroyed, and only one sentence passed on to the next generation of creatures, what statement would contain the most information in the fewest words? I believe it is the *atomic hypothesis* (or the atomic *fact*, or whatever you wish to call it) that *all things are made of atoms - little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into one another*. In that one sentence, you will see, there is an enormous amount of information about the world, if just a little imagination and thinking are applied. (Feynman, Leighton, & Sands, 1963, chapter 1, page 2)

Why did Feynman ascribe such value to this insight about the constitution of matter? The answer lies, in part, in the capacity of atomic theory to provide deep and satisfying answers to questions we all ask about the world around us:

- What are things made of and how can we explain their properties?
- What changes and what stays the same when things are transformed?
- How do we know?

Children entering school can respond to these questions, albeit in incomplete and naïve ways. If we are to accomplish the goal of helping students to connect school learning with the observable phenomena around them, we must find the pathways—the learning progressions—that connect children's naïve ideas with the powerful insight that Feynman wrote about. The research shows that learning progressions connecting the questions above to atomic molecular theory are challenging; those learning progressions involve macroscopic understandings of materials and substances as well as nanoscopic understandings of atoms and molecules.

Children's ability to appreciate the power of the atomic theory requires a number of related understandings about the nature of matter and material kinds, how matter and materials change, and the atomic structure of matter. These understandings are detailed in the standards documents. We organize them around six big ideas that form two major clusters: the first two form a *macroscopic level* cluster and the last four form an *atomic-molecular level* cluster. The first cluster is introduced in the earliest grades and elaborated throughout schooling. The second is introduced in middle school and elaborated throughout middle school and high school. The atomic-molecular theory elaborates on the macroscopic big ideas studied earlier and provides deeper explanatory accounts of macroscopic properties and phenomena. These big ideas are:

M1. Macroscopic Properties: We can learn about the objects and materials that constitute the world through measurement, classification, and description according to their properties.

M2. Macroscopic Conservation: Matter can be transformed, but not created or destroyed, through physical and chemical processes.

AM1. Atomic-molecular theory: All matter that we encounter on earth is made of less than 100 kinds of atoms, which are commonly bonded together in molecules and networks.

AM2: Atomic-molecular explanation of materials: The properties of materials are determined by the nature, arrangement, and motion of the atoms and molecules of which they are made.

AM3: Atomic-molecular explanation of transformations: Changes in matter involve both changes and underlying continuities in atoms and molecules.

AM4: Distinguishing data from atomic-molecular explanations: The properties of and changes in atoms and molecules have to be distinguished from the macroscopic properties and phenomena they account for.

In the next section we provide an overview of a possible learning progression based on the research on children's learning. This learning progression suggests how, with appropriate instruction, children's thinking about matter and material kind could be transformed so that they understand the big ideas of the atomic-molecular theory and use them to answer the key questions above. We then have sections focusing on learning and assessment at each of three grade ranges: K-2, 3-5, and 6-8. In each section we (a) suggest which of the big ideas could be understood by children in that grade range, (b) suggest and justify learning performances—ways of enacting the big ideas in practice—appropriate for that grade range, (c) suggest specific assessment tasks or items that sample those learning performances, and (d) discuss common student responses to those tasks and what those responses reveal about student thinking. Developing specific assessment items for grades 9-12 was beyond the scope of this report. However, Appendix A outlines how these six big ideas could continue to be elaborated and extended at grades 9-12.

Overview of a Possible Learning Progression

Our overview of a possible learning progression is based on our reading of the research on children's thinking about materials, matter, atoms, and molecules. Some of the specific studies are referenced in the following parts on specific grade levels. A more complete, though still selective, review of the research on students' understanding of matter and molecules is provided in our Interim Report. Two key tables from that report are reproduced in Appendix B.

We organize our account of a learning progression around the three key questions above. Answering these questions engages learners in the scientific practices described in the introduction. We see several key trends, described below, in the long-term process by which children can develop more scientifically sophisticated answers to these questions.

1. Experiences with a wider range of materials and phenomena. Children extend the range of their experiences with materials, properties of materials, and changes in materials. New experiences often help them to see the limitations of their earlier ideas and to accept new ideas that account for a wider range of phenomena.

2. Increasing sophistication in describing, measuring, and classifying materials. Children learn about the limits of their sense impressions and master the use of a wider range of instruments to measure and classify properties of materials and changes in materials. They become aware of properties of materials that are not revealed by casual observation and learn to measure them. They also become aware of the composition of many materials, understanding that even homogeneous materials are mixtures of substances, including different elements and compounds.

3. Development of causal accounts focusing on matter and mass. Children move from explanations of changes as events caused by conditions or circumstances to explanations that focus on mechanisms of change and on tracing substances through changes. They come to appreciate that mass is a fundamental measure of the amount of matter, so that changes in mass must be accounted for in terms of matter entering or leaving a system. They learn that gases are forms of matter like solids and liquids; thus gases have mass and can be used to account for otherwise unexplainable mass changes.

4. Increasing theoretical depth. Children develop accounts of properties of matter and changes in matter than make increased use of hidden mechanisms and atomic molecular theory. They are increasingly able to make use of all six big ideas (listed above) and to develop accounts that coordinate four different levels of description:

- *Impressions or perceptual appearances*—what we see and feel—are related to
- *Measurable properties or variables*—mass, volume, density, temperature, pressure, etc.—which are related to
- *Constituent materials* and chemical substances, and finally to
- The *atoms and molecules* of which those substances are composed.

Throughout elementary school students are working to coordinate the first two levels as they develop a sound macroscopic understanding of matter and materials based on careful measurement. From middle school onward they are coordinating all four levels as they develop an understanding of the atomic-molecular theory and its broad explanatory power.

5. Understanding the nature and uses of scientific evidence and theories. Children learn to distinguish between data and models or theories, which can be used to account for many different observations and experiences. They become increasingly able to develop and criticize arguments that involve coordinated use of data and theories. They also become increasingly sophisticated in their understanding of sources of uncertainty and their ability to use conditional and hypothetical reasoning.

We call this a *possible* learning progression because it does not represent the learning of most students in American schools, who are taught in ways that do not recognize and respond to their ideas. In general, though, the suggested progression is consistent with national standards and supported by studies demonstrating successful learning with appropriate instruction.

What are things made of and how can we explain their properties?

Young children live in a world where objects and events are more salient than materials. They see many objects around them, which they learn to describe by function (spoons, toys, chairs, etc.) and by perceptual appearances (the big spoon, the red spoon, the hot spoon, the plastic spoon). They notice early in their lives that objects are made of different materials, which have different perceptual appearances and properties. Yet they are still in the process of recognizing material kind as an important basis for classification.

The experiences of young children with liquids and gases are quite limited. Although children have extensive experience with liquid water, labeled in many different ways (water, rain, mist, fog, dew, puddles, etc.) and with liquids made mostly of water, also labeled in different ways (milk, juice, soda, etc.), they have little experience with liquids other than water (gasoline, alcohol, antifreeze) and do not differentiate between them and water-based liquids. Young children's experiences with gases are even more limited. Although they are familiar with a gas mixture—air—that also contains suspended solids and liquids (smoke, dust, fog, "steam"), young children (and many older ones) do not think of air and other gases as material, typically saying that "air is nothing," a belief that interferes with grasping the conservation of matter and with acquiring the atomic-molecular model, as discussed in the next sections.

Thus, children entering school are just beginning to appreciate the meaning and significance of the key question: What are things made of and how can we explain their properties? As they go through school, successful students learn to answer this question in progressively more sophisticated ways through (a) classifying objects and materials, (b) distinguishing matter from non-matter, (c) identifying constituents of materials, and (d) explaining properties of materials.

Classifying objects and materials. As discussed above, recognizing the distinction between objects and the materials of which they are made is an important intellectual achievement for young children. Through schooling, children's descriptions of objects and materials become systematized and more sophisticated in several ways. They learn to measure important properties, a process that allows them to transcend more limited sensory definitions of those properties (e.g., weight as felt weight) as they construct an underlying mathematical model of the property in question (e.g., weight as additive physical magnitude that can be mapped to number and explicitly symbolized as the sum of equal-size units). Recognizing the advantages of measurement, they come to distinguish among properties that were initially confounded, and to sort out which are properties of objects (e.g., weight and volume) and which are properties of the materials they are made of (e.g., density). Finally, as they learn about the atomic-molecular theory, middle and high school students can classify materials in more subtle ways: distinguishing among elements, compounds, and mixtures.

Distinguishing matter from non-matter. Having a concept of specific materials is not the same as having a general concept of matter. Given the definition of matter that many students are taught in school ("Matter is anything that has mass and takes up space.") distinguishing matter from non-matter would seem to be straightforward. However, research shows that statement does not make sense to most students as long as they have alternative sense-based conceptions of matter, mass, space, and weight (see Appendix B). Further, students may not classify gases as matter because they do not believe that gases have mass or occupy space. They also often misclassify forms of energy such as heat and light as matter because they have physical effects. Hence it is important that elementary and middle students build a solid understanding of mass, volume, and weight so they can make the distinction between matter and non matter reliably. Establishing a general concept of matter provides a framework for identifying the reactants and products in physical and chemical changes and for understanding phase change, chemical change, conservation of matter, and the atomic-molecular theory.

Identifying constituents of materials. Ultimately, the question about what things are made of is about the underlying constituents of materials. Is a particular material all the same substance or a mixture of different substances? If we broke an object up into little pieces, would the pieces still be the same material? How small could we make the pieces before they stopped being the same material? Even young children can answer these questions at some level; even chemists with the resources of research laboratories cannot answer these questions completely for all materials. The most sophisticated answers to questions about the constituents of materials involve relating knowledge and observations at the four different levels mentioned above: sense impressions, measurable properties, chemical substances, and atoms and molecules.

Explaining properties of materials. Children notice early in their lives that different materials have different perceptual appearances and properties: Metals are hard and heavy and feel cold when you touch them, Styrofoam is light, glass is clear and breaks, and so forth. By learning to appreciate the difference between sense impressions and measured properties, and the greater reliability of the latter over the former, elementary students lay the groundwork for distinguishing among properties that were initially confounded (e.g., weight and density) and associating some of those properties (e.g., density) with material kinds. These more sophisticated descriptions of materials motivate explanations of *why* different materials have different properties. As students develop knowledge of atoms and molecules in middle and high school, they can use this knowledge not only to more clearly identify the underlying chemical substances, but also to explain the properties of materials in terms of the mass, arrangement, and motions of the atoms and molecules of which these substances are composed.

What changes and what stays the same when things are transformed?

By the time they enter school children have witnessed thousands of transformations—occasions when objects or materials change form or appearance. Some transformations are fictional: Cinderella's pumpkin is transformed into a coach and her mice into horses. Other equally marvelous transformations actually happen: Seeds sprout and become plants; caterpillars become moths; ice melts into water. Many involve objects becoming bigger, or smaller, or disappearing altogether: Children grow; matches "burn up;" pieces of fruit "rot away."

Young children are aware that most changes are not magical—objects do not simply appear and disappear. There is usually some continuity between what was there before and what is there later. However, accounts of changes based on impressions can be quite different from accounts based on careful measurement or chemical analysis. For instance, children watching a burning candle may see that the candle changes but the flame stays the same. A s they grow, they see that their weight changes but they stay the same. It takes a profound shift to see our bodies as mere way stations for the materials that come into them. (That is, food, water, oxygen are transformed, and leave in a different form.)

During the elementary school years as children learn to measure weight and volume and to identify materials based on some of their properties, they can begin to engage in systematic investigations of what changes and what stays the same across various transformations. For example, they can determine that weight and kind of material is conserved across shape changes, freezing, or melting. During the middle school years as they learn about atoms and molecules and to identify substances (both visible and invisible) that play a role in transformations, they can understand what changes and stays the same across a broader range of transformations including evaporation, condensation, burning and rusting. Thus, atomic molecular theory enables them to relate changes in appearance to underlying constancies in measurable variables, chemical substances, and/or atoms and molecules. In relating changes in appearance to underlying constancies, they can classify changes into types (e.g., phase change, chemical reaction, dissolving), identify the laws to which those changes are subject (e.g., conservation of mass during phase change), and explain the mechanisms by which those changes take place. This process can never be complete; research chemists today continue to investigate questions about laws and mechanisms that no one can answer. Deeper understanding, though, involves developing more thorough and detailed accounts of how changes in appearance are related to underlying constancies.

How do we know?

People of all ages face the problem of deciding what to believe and the related problem of persuading others that their beliefs are correct. Young children's decisions are typically dichotomous (ideas are true or false) and supported by simple arguments based on sense impressions (what they saw, felt, heard, smelled) and authority (what they were told). As they learn more about materials, measurement, and underlying (and hidden) chemical substances, children's beliefs and arguments can become more sophisticated in several ways:

- Recognizing tentative or conditional knowledge and hypothetical reasoning.
- Distinguishing among kinds of knowledge claims.
- Constructing arguments that coordinate evidence and theories or models.

Recognizing tentative or conditional knowledge and hypothetical reasoning. Learning and reasoning about objects and materials require students to understand that many statements are not simply true or false. For example, some statements are true within a margin of error ("this object weighs 22 grams"). Other statements are conditionally true ("a steel object is heavier than an aluminum object if they are the same volume"). Still other statements are inherently probabilistic ("the chance of rain this afternoon is 30%"). As children learn to measure and apply mathematical ideas to physical phenomena, they are increasingly able to formulate more specific hypotheses and thus have more opportunities to recognize the conditional and testable aspects of knowledge.

Hypothetical reasoning, although difficult, is especially important for science learning and scientific argument. Students need to consider the consequences of statements whose truth they do not know and test those consequences against observation. ("If matter has mass and cannot appear nor disappear, then, although I cannot see it, what is escaping from this boiling water must be matter and have mass.") Learning about atoms and molecules provides an important context for engaging and developing students' capacity for hypothetical reasoning.

Distinguishing among kinds of knowledge claims. Children also need to learn that scientific arguments include different kinds of knowledge claims that play different roles in reasoning. The first of these involves distinctions between *everyday and scientific concepts.* Most of our everyday physical concepts are sensory in origin (heat as hotness, cold, felt weight, whiteness of surfaces). Underlying these percepts/concepts, are physiological mechanisms that involve several scientific concepts (e.g., hotness is a function of heat, temperature, area of contact with the skin, and temperature; felt weight is a function of weight, density, and area of the body being affected.) Hence, sense impressions do not provide reliable data about scientific concepts; instead, scientists rely on measuring tools and instruments. Clarifying those sensory mechanisms, in a simple fashion, as students learn to measure helps students understand the difference between perceptual and physical variables, and grasp the scientific concepts more easily.

Central to an understanding of modeling in science and its role in inquiry is a basic differentiation between *theories* and *data* and knowledge of forms of argumentation that relate theories to patterns in data. There are several aspects to this differentiation that include: (a) recognition that science is concerned with developing theories about the world, not just producing good results; (b) realizing the forms of argumentation for theories are based on deriving testable implications from one's theories, and arranging for systematic observation that can distinguish among alternative plausible hypotheses; and (c) understanding that theories guide all aspects of inquiry and that, although well-tested, they are always revisable based on both new data or new explanatory ideas.

Constructing arguments that coordinate evidence and theories or models. Successful scientific arguments both differentiate theories from evidence and use them in a coordinated way to construct an account of the objects or systems being studied. For example, an account of what happens when a nail rusts requires coordination between the appearance of the nail, data about the mass, density, and chemical properties of the nail and the rust, and use of atomic molecular models to explain how the materials of the nail are changing. The ability to construct such arguments is hard-won. There is a long tradition of research (using a variety of different types of tasks) that indicates that students do not consistently differentiate theories and evidence, and that even by college age most students still do not understand the role of indirect data and argument in the construction of scientific theories. At the same time, there is increasing recognition that these results are more an indictment of current practices in science education than of students' learning capacities. Research has shown that even young children can engage in investigations with appropriate scaffolding provided by the teacher, and that involving them in designing and conducting investigations and making arguments for conclusions is one of the best ways of developing their understanding of scientific thinking.

Possible and actual learning progressions

Learning to use the atomic molecular theory systematically to account for properties and transformations of matter and materials, is a long, difficult process. Research shows that for many people receiving traditional instruction, that learning process actually never happens: many students in high school and college science courses continue to provide narrative accounts for common transformations even after they have studied atomic molecular theory. Furthermore, research shows that students who do learn to provide atomic molecular accounts do so gradually. It takes a long time and substantial intellectual effort to build up the knowledge base and associated practices that scientifically literate people use to link changes in appearance to underlying processes that involve both systematic constancies and transformations.

Research as yet provides few longitudinal studies documenting this process developmentally, but studies of conceptions of matter, material kind, and related physical and chemical entities in students of different ages, as well as the results of intervention studies, enable us to piece together a learning progression culminating in the mastery of the basic tenets of the atomic molecular theory. In particular, students cannot systematically relate changes in appearance to atomic-molecular theory without developing a strong understanding of matter and related variables at the macroscopic level: mass, weight, volume, and density, as measurable variables; kinds of materials and their characteristics properties. With appropriate instruction one can expect students to go through this learning progression successfully as they move from grades K to 12.

The learning progression we propose, and on which we base assessment items for different grade ranges, reflects the necessary progression from scientifically sound macroscopic accounts to atomic/molecular ones, as well as children's developing cognitive abilities. In this learning progression, students move from more specific phenomena (e.g., focusing on specific substances such as water, and on a specific phase change, such as melting) to a more general and abstract understanding of those phenomena (properties of all substances, all phase changes). They also move from comparing and ordering to quantitative measurements; from explaining and representing data to modeling; and from accounts closer to the surface of phenomena to accounts based on invisible and/or abstract physical entities (e.g., from material kind to substance).

The assessment items and accompanying discussions below are based on a sampling of the research on students' conceptions of matter, volume, weight, density, material kinds, and the atomic/molecular model, their resistance to traditional instruction, and their evolution in carefully designed intervention studies. In some cases, there are items that most students at those grade levels will currently answer incorrectly because of problems in their instruction; we include them because there is evidence that these items are within their grasp with appropriate instruction. Our discussions will focus on what we can learn from those incorrect answers that could inform large-scale assessment, classroom assessment, and curriculum development. Please note these items are really only *ideas* for assessment items, not perfected assessment items, as members of our committee are not assessment specialists. They are meant to illustrate some of the kinds of understandings and practices that it would be important to find ways to assess at the different grade levels.

Assessment Suggestions for Grades K-2 (ages 5-8)

Versions of Big Ideas for Young Elementary School Students

M1. Macroscopic Properties

- **Objects** are **made of** specific **materials** and have certain **properties**. The **properties of objects** can be carefully described, compared and measured.

M2. Macroscopic Conservation

- **Some properties change** and some **stay the same** when objects are **transformed in simple ways**

Learning Performances that Integrate Big Ideas and Practices

What are things made of and how can we explain their properties? Before engaging in explanations of the properties of objects and materials, K-2 children need to become familiar with making principled distinctions between the two and making careful measurements and systematic descriptions. At the K-2 level children can study the properties of materials while engaging in practices that include *identifying* and *classifying*, *ordering* and *measuring*, *representing data* and *posing questions*[2]. They can learn to learn to *describe* **objects** both in terms of (a) the **kinds of materials** they are made of and (b) their **properties** (such as size, weight, shape, color, temperature, texture, etc.) Using this knowledge, students can *classify* objects in different ways: (a) by **kind of object**; (b) by **kind of material**; and (c) by specific **property**. From K to 2, students can become more systematic in their descriptions of the properties of objects not only by distinguishing between the general attribute and its specific value, but also by *ordering* a set of objects along specific dimensions and developing ways of *measuring* certain dimensions (**length, area, volume, weight**). They can create inscriptions that *represent their data* about object properties either with pictures, data tables, or simple graphs as well as *interpret representations* in order to make inferences about the properties of objects. Examples of learning performances based on the above practices that can be translated into specific assessment items are:

- Classifying by type of object vs. type of material.
- Ordering a set of objects (qualitatively) by weight or length.
- Measuring the length, area, volume, or weight of a given object.
- Representing data about the properties of a set of objects in a data table.

Examples of specific assessment items for these learning performances will be provided at the end of this section along with a discussion of how student performance on these items can be interpreted.

What changes and what stays the same when things are transformed? Students can begin to *describe* whether and how the properties of objects and materials are affected by various **transformations**. Important transformations that they can explore in

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[2] In the sections that follow, we use the convention of italicizing the key practice and bolding the big idea to which it applies.

this grade range are **reshaping**, **breaking into pieces, melting, and freezing**. These transformations are of interest because they bring into focus the distinctions among the properties of kinds of objects (shape changes), the amount of matter it contains (weight does not change), properties of material kind in a specific phase and across phase change (texture and color stay the same when a solid object is broken into pieces but not necessarily when it is melted; texture and color change when wax is melted but other properties stay the same, e.g., being water repellent and smell). These distinctions, brought out in specific contexts, are part of constructing an understanding of material kind. Thus, in reasoning about transformations, the child can engage in the practices of *posing questions, predicting/inferring, designing and conducting investigations, representing data and interpreting data representations,* and *making arguments* for a conclusion. Some specific learning performances for reasoning about transformations based on these practices would include:

- Inferring that breaking into small pieces affects object identity but not material kind identity.
- Predicting whether changing the shape of an object changes the amount of stuff in or weight of an object.
- Predicting whether melting something changes the amount of stuff or kind of material.
- Conducting an investigation and making an argument about what changes or stays the same when an object is reshaped or melted.

How do we know? One of the foremost issues facing K-2 students concerns how they know about the properties of objects and what factors affect the reliability and validity of their assessments. They can *pose questions* about the **reliability** of **common impressions** of physical properties (e.g. perceived length of a line, felt weight) vs. data based on careful **measurement**, *conduct investigations* of these issues, and *make arguments* about the greater precision and reliability of data based on careful measurement. They can also begin to *identify* the characteristics of a **good measurement**, including using units of uniform size and fully "covering" the measurement space. In this way, they can begin to distinguish between common (sense) impressions and scientific data and realize the importance of learning to use objective measuring devices in order to obtain reliable information about the properties of objects. Two examples of learning performances that assess practices relevant to these issues include:

- Making arguments about the greater reliability of assessments of length or weight based on measurement rather than common impressions.
- Identifying the characteristics of a good measurement of length.

Justification for Big Ideas and Learning Performances

Existing Standards propose that K-2 children should describe objects in terms of their properties (such as shape, size, and weight) and the materials that they are made of. They should also be aware that transformations can affect the properties of objects. Research supports the reasonableness of these Benchmark standards for K-2 children. For example, during preschool, children are learning words for specific properties and materials. They can also make a preliminary distinction between kind of object and kind of material (Au, 1994; Smith, Carey, & Wiser, 1985). Thus, it is reasonable to ask them to order, compare, and classify objects in these ways.

The existing standards propose that K-2 children should be exploring what happens during various physical transformations and observe that the properties of objects can change. In translating this standard into learning performances and assessment items, we confine ourselves to transformations in which materials remain visible, such as dividing into small pieces, reshaping and melting. (Transformations such as evaporation, dissolving and burning which involve processes invisible to the naked eye, and ideas about matter not accessible to most second graders, are better reserved for the later grade levels.) Further, we note that students should be encouraged to ask about what properties may *change* and which may *stay the same* during transformations. The research of Piaget & Inhelder (1974) and Stavy & Stachel (1985) has demonstrated that during the years 6-8 children are able to engage with the questions of what changes and what stays the same across simple transformations (such as pouring liquids from one container to another, reshaping or subdividing pieces, melting) and even develop an intuitive notions that the *amount of material* and the *kind of material* are conserved across these transformations. Thus, it is reasonable to expect not only that students experiment with some transformations, but also that they begin to form meaningful generalizations about what changes and what stays the same.

Existing Standards (*Benchmarks, NSES, NCTM*) are somewhat inconsistent in their expectations of K-2 children in the area of measurement. The mathematics (*NCTM*) standards explicitly state that K-2 children should be developing nonstandard and standard measures of length, volume, area, and weight as well as gaining familiarity with inscriptional practices such as creating simple data tables or pictorial representations. In contrast, the Benchmarks science standards describe learning to measure volume, length, and weight as goals for Grades 3-5 rather than K-2. (The *NSES* science standards written for the broader age range of K-4 simply state that students should be learning to measure during this time.) We reconcile this discrepancy by arguing K-2 students should *begin* learning about measurement, although noting that learning to measure weight and volume is a protracted process that continues throughout the elementary and middle school years. At the K-2 level, we expect that children will have rich experiences with constructing measures of length and area (including nonstandard measures) so that they can develop a solid metaconceptual understanding of the process of measurement and of what makes a good measure. They can then build on this foundational understanding as they grapple with the even more challenging tasks of constructing measures of weight and volume. By grade 2 children may begin having some experiences with measuring weight and volume (e.g., based on iterating and counting manipulable units, not using formulas). Recent research supports the *NCTM* standards by demonstrating that young children are indeed capable of developing a robust understanding of many aspects of measurement during this time with appropriate instruction (Lehrer et al, 1998, 1999). At the same time, this research also argues for depth (constructing metaconceptual understanding and an explicit theory of measure) rather than superficial breadth (simply teaching measurement procedures). Given the centrality of measurement in science and the ways measurement can contribute to conceptual understandings, it is important to start early in developing a rich understanding of measurement.

Finally, we note the coherence among the two big ideas we are working on with students at the K-2 level. Engaging students with describing objects calls their attention to different types of properties and characteristics of objects (e.g., descriptions in terms of object kind, material kind, and extensive variables such as weight and size). Further, work with measuring and exploring transformations encourages them to begin to move from perceptually centered definitions of weight, size, amount to more quantitative, theoretically based analyses.

Possible Assessment Items Based on Learning Performances

What are things made of and how can we explain their properties?

(A) Classifying by type of material vs. type of object:

Performance Item: Give students a set of objects (forks, spoons, knives) made of different materials (plastic, metal, wood). Ask students to sort (a) first by type to object and (b) then by type of material. In each case, they should explain the basis for their groupings.

Interpretation: This task calls for students' ability both to (a) distinguish type of objects from types of materials and to (b) form exhaustive classifications based on this distinction. Students who confuse objects and materials might inappropriately list some object names for types of materials--i.e., spoons, knives, forks--or list both the material and object name "plastic spoon". Students who do not understand classifications will fail to systematically pick out all the items of a given type.

(B) Ordering a set of objects (qualitatively) by weight or length:

Pencil and paper item (for weight): Show 3 same size objects of different colors (object A, B, and C). Then show A and B on a pan balance (with A tipped lower) and B and C on the balance (with the pans level). Which of the following reflects the correct ordering of the three objects by weight?

A. A is heavier than B and C. B and C weigh the same.

B. A is heavier than B but not C. B and C weigh the same.

C. A is lighter than B and C. B and C weigh the same.

D. A is lighter than B but not C. B and C weigh the same.

Performance item (for weight). Give 3 same size objects and a pan balance. Ask students: Which is the heaviest? Next heaviest? Are any the same weight? How do you know?

Performance item (for length): Give students 5 paper strips of different lengths. Ask them to order them from shortest to longest. (Note: Because they can't just stand these up on a table, they must be careful to line them up equally at the bottom to correctly compare their lengths, which calls for a deeper understanding.)

Interpretation: The weight ordering task tests whether they understand how to infer weight relations from a pan balance (the side that goes down has the heavier object) and whether they understand the transitivity of weight (if A is heavier than B, and B and C are equal, then A is also heavier than C.) Students who select answer A understand both principles; those who select answer B understand how to interpret the scale, but not transitivity; and those who select C understand transitivity but not how to interpret the scale, and those who select D understand neither. The length ordering task tests whether they understand that one has to line the items up (holding the starting point for the bottom constant) in order to compare lengths. Research provides evidence that children can make simple transitive inferences about length (Bryant & Trabasso, 1971) and learn to systematically order during this time (Piaget & Inhelder, 1967).

(C) <u>Measuring the length, area, weight, and volume of one or more objects:</u>

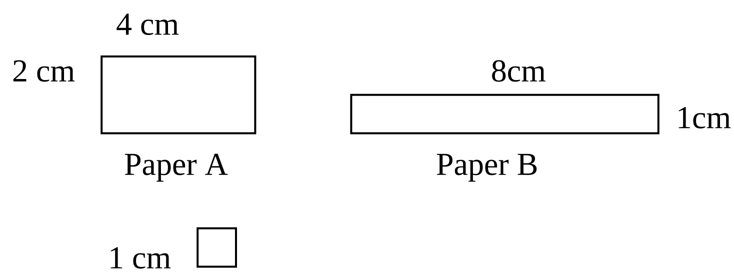
Paper and pencil item (length): (Assumes students have ruler available to use.) Show students 3 sticks of different lengths on the page. Have the sticks arranged so that they are not all going in the same direction and are not evenly lined up. Ask them to use their ruler to find out:

How long is Stick A? _________.

How long is Stick B? _________.

*How long is Stick C?*_________.

Paper and pencil item (area): Show students outlines of two pieces of paper (A and B) of different shapes and a little square.



How many 1 cm squares will cover Paper A? ________________

How many 1 cm squares will cover Paper B? _________________

Do Paper A and Paper B cover the same amount of space? ______________

How do you know?

Paper and pencil item (weight): Show 3 objects (of different size), each on a pan balance in balance with different numbers of gram weights. (Object A is smallest, object B is medium size, and object C is the largest). Object A balances with 4 gram weights, object B with 6 gram weights, and object C with 4 grams weights. Ask them to determine the weight of each object and to answer the following questions.

How much does Object A weigh? ___________.

How much does Object B weigh? ___________.

How much does Object C weigh? ___________.

Performance item (area): Ask students to figure out a way to measure the amount of space covered by their open hand.

Performance item (volume): Give the child a rectangular block (4 cm x 2 cm x 3 cm) and a set of cubes (each 1 cm^3). Ask the child to use the cubes to figure out how much space the object occupies.

Interpretation: The paper and pencil tasks assess their ability to use a given tool (a ruler, a 1 cm square piece, a pan balance in balance with certain number of gram weights) to measure a given dimension. The paper and pencil task about weight also assesses the extent to which the child realizes the information from the pan balance is *more central* to determining weight than information about size. An important part of the child's learning about weight is *reprioritizing* which cues are more central (pan balance trumps felt weight or perceived size). It is important for assessment items to be designed in order to detect whether this reprioritization has taken place. The performance item for volume reflects one form of volume measurement that might be appropriate at this age level: measuring by using the cubes to build another object with the same dimensions and then counting the cubes. The pencil and paper area item also probes whether students distinguish the shape of an object from the area it covers; they need to realize that two items could have different shape yet still cover the same amount of space. The performance area item (measuring the area of one's hand) is a challenging problem calling for them to consider fractional units. (See Lehrer et al., 1998, for evidence that grade 2 children can successfully deal with these and other tasks with appropriate instruction.)

(D) Representing data about the properties of objects in a data table.

Pencil and paper item (qualitative): Show the child a picture of a set of objects (labeled A, B, C, etc.) that differ in color (red, blue), shape (cube, sphere) and size (large, small). Ask the child to make a table that describes each object with respect to the properties of color, shape, and size.

Performance item (quantitative) linked to above measurement task: Give students a set of objects that vary along a given dimension (length, area, weight, or volume). Ask them to measure the dimension in question and make a data table that shows the values of each of the objects for that dimension

Interpretation: In keeping the *NCTM* standards, these items call for students to construct simple, but organized tables to represent their data in clear ways. An important aspect of their performance would be their ability to describe each object accurately and completely according to all the properties or dimensions in question and to have separate columns (or rows) for each property or dimension.

What changes and what stays the same when things are transformed?

(A) Inferring that breaking into small pieces affects object identity but not material identity.

Pencil and paper item: Here is a picture of a wooden airplane. If I break it into many pieces, is it still an airplane? Is it still wood? (Show picture of "it" broken into pieces).

A. It is still an airplane and it is still wood.

B. It is still an airplane but it is not wood.

C. It is no longer an airplane but it is still wood.

D. It is no longer an airplane and it is not wood.

How do you know?

Performance based item: Show students a wooden airplane. Now cut the airplane up into smaller pieces. Ask: Do I still have an airplane? Is it still wood? How do you know?

Note: to insure validity of these items it is best to ask about several (3 or 4) different objects, so that student consistency in judgments can be determined.

Interpretation: If students understand that identity of object type but not material kind is affected by breaking into pieces, they will systematically judge that "It is no longer X (the type of object), but is still Y (the type of material)" across a variety of items. Relevant justifications include: "It no longer flies, has the parts of, or looks like an airplane." "It still looks like wood, because it is *made* of wood and breaking doesn't change whether it is wood, it's still a tiny piece of wood, etc." Research by Smith, Carey, & Wiser (1985) and Au (1994) that even preschoolers realize that material kind identity is preserved with breaking into small pieces (although they have more difficulty with extreme transformations--wood ground into sawdust or metal ground into fine metal powder). It is recommended at this level the "pieces" be small enough to destroy the integrity of the object, but not so small as to look like possibly different stuff (metal powder).

(B) <u>Predicting whether changing the shape of an object changes the amount of stuff in and weight of the object</u>.

Pencil and paper or performance item (weight): Students see picture of two round balls of clay that are in balance on a pan balance. One is rolled into a sausage. They are asked to select which picture depicts how the pan balance will look after the sausage is placed on the balance.

A. The two objects still balance.

B. The side with the ball is further down.

C. The side with the sausage is further down.

D. There is no way to predict what will happen based on the information given.

How did you know that?

Performance item (clay amount/weight): Students are given a round clay ball. They are asked to roll it into a sausage. They are asked: Is there the same amount of clay/more clay/less clay in the sausage as in the round ball? How do they know? Does the sausage weigh more/less/or the same as the round ball? How do they know?

Performance item (liquid amount): Students have two beakers of different heights and widths. Juice is in poured into the first beaker. Then students pour the juice into the second beaker (taller and thinner beaker, so the water level is higher). They are asked: Is there more /less/same amount of juice in the tall thin beaker as there was in the original beaker? How do they know?

Interpretation: The performance items are classic Piagetian conservation of amount and weight items (Piaget & Inhelder, 1974). In general, the majority of 1st and 2nd graders should be able to answer the conservation of amount items. The conservation of weight items tend to be more difficult, as they involve the related issues of coming to understand weight as tied to amount of matter and distinguishing objective weight from felt weight. However, given that students will be working on these issues with the measurement of weight, we believe it may be appropriate to give students simple conservation of weight problems by the end of 2nd grade. (Note we would postpone asking them whether a very tiny piece has weight until grades 3-5 when they are working on issues surrounding very tiny pieces and fractional units and numbers.)

(C) <u>Predicting whether melting something changes kind of material</u>.

Pencil and paper: Here is a chocolate bunny. We put it in pan on the stove and heat it (show picture). What will happen to it after it is thoroughly heated?

A. It will be warmer but it will still be hard and shaped like a bunny, and it will still be chocolate.

B. It will be warmer and melted into a puddle of chocolate. It will no longer be shaped like a bunny.

C. It will be warmer and melted into a puddle of stuff that is no longer chocolate.

D. It will be unchanged.

How do you know?

Interpretation: This item assesses whether students understand that heating (a) changes an object's temperature; (b) changes its state (from solid to liquid); yet (c) does not change the kind of material it is. We suggest giving children an "easy" item such as chocolate at this grade level because the item still retains its characteristic color during the phase change. Children's answers can be analyzed to determine which of the above understandings are present. Children who select D understand none of the three ideas; those who select B understand all of them. Those who select C understand the points about temperature and state, but do not realize material kind is conserved. Research of Goswami & Brown (1990) suggests that first grade children have some understanding that melting preserves material kind in at least some simple cases.

(D) <u>Conducting investigation and making an argument about what changes and what stays the same when an object is reshaped or melted</u>.

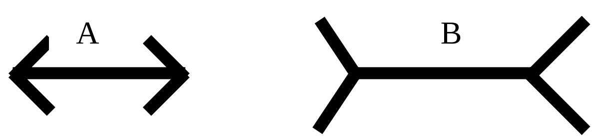
Performance item: Same as above (B or C) except that students are asked after making a prediction to gather some data and make an argument for a conclusion.

Interpretation: It would be expected that students could place the clay ball and sausage on a pan balance to determine the weight hasn't changed. Or that students could taste the chocolate before or after the transformation to determine the kind of material hasn't changed. This allows students to bring their new skills to bear on solving an interesting problem or puzzle.

How do we know?

(A) <u>Making arguments about the greater reliability of assessments of length or weight based on measurement vs. common impressions</u>.

Pencil and paper item (for length): Joe and Sam want to compare the length of the following two lines, excluding the end arrows.



Joe stared at the lines very carefully for a long time. He then argued: B is longer than A (between the arrows) because it *looks* much longer to my eyes!

Sam cut out a strip of paper the same length as A, and then placed the strip on B. He then argued: B and A are the same length because *B is the same length as the cut out strip*.

If you wanted to be sure about the length of the lines, would you do what Joe did, and look carefully at the arrows, or would you do what Sam did, and use a strip of paper? Why?

Pencil and Paper (for weight): Mary and Linda want to compare the weight of two objects: a small metal cube and a large wooden cube (show picture of objects).

Mary looks at the objects and says "The large cube is obviously heavier. I can tell by just looking."

Linda says*:* "I can't tell which is heavier. I think you would have to compare them on a balance scale in order to know for sure."

Who do you think is right? Why?

Interpretation: This task assesses whether students understand that appearances can be misleading and that simple measurement (comparison to a standard) gives more reliable information. Students who understand this for length should not only think Sam has the better approach, but also be to explain that how long something "looks" can be affected by other things (such as the surrounding arrows); using a comparison strip allows one to not be distracted by this context. In contrast, students who do not have this understanding may prefer Joe's measurement because "he studied it carefully" or may think they both are equally good because they each tried hard and had good reasons. The weight item assesses whether they distinguish weight and size, realize that size is an unreliable predictor of weight, and realize that balance scales are good instruments for measuring of weight.

(B) Identifying the characteristics of a good measurement of length.

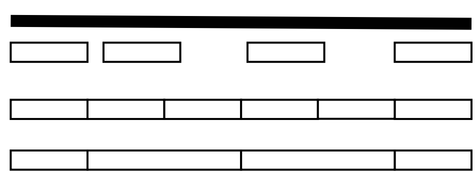
Pencil and paper item: Three students (Joan, Jenny, and Sarah) each made measurements of the same line (by cutting out paper strips) but measured the line in different ways.

Line:

Joan's measurement: 4 length units

Jenny's measurement: 6 length units

Sarah's measurement: 4 length units



Open ended version: Who do you think had the best measurement? Why?

Multiple choice version: Who do you think had the best measurement?

(A) Joan had the best measurement because she spaced hers out.

(B) Jenny had the best measurement because each unit was the same size and touching.

(C) Sarah had the best measurement because each unit was touching.

(D) Joan and Sarah had the best measurements because they got the same answer.

(E) Joan and Jenny had the best measurements because they both used the same size units.

Interpretation: This item assesses whether students realize that in measurement you need to use uniform units and fully cover the measurement space. Jenny has the best measurement because she has met both criteria. Joan uses uniform units but does not cover the measurement space and Sarah covers the measurement space but does not have uniform units. It also assesses whether students see these characteristics as more important than simply "agreeing" with each other. The work of Lehrer et al (1999) shows that children this age are capable of understanding these principles with appropriate instruction.

Assessment Suggestions for Grades 3-5 (ages 8-11)

Versions of the Big Ideas for Older Elementary Students

M1. Macroscopic Properties

- There are some **properties** that characterize **all matter**; others characterize specific **types of materials**.
  - Matter **takes up space** and **has weight.** Non-material entities do not.
    - **Air** is **matter** and takes up space and has weight.
    - There can be **pieces of matter** that are **too small to see** with the naked eye.
  - **Materials** have **characteristic properties** that are independent on the size of the macroscopic sample (e.g., color, texture, malleability, hardness, heaviness for size, etc.).

M2. Macroscopic Conservation

- **Matter** is **conserved** across certain **transformations** that radically change appearance.
  - **Matter continues to exist** across transformations in which it **no longer is visible** (e.g., dissolving).
  - **Amount of matter and weight** are **conserved** across melting, freezing, and dissolving**.**
  - Materials can be changed from **solid** to **liquid** form by heating, but are still the **same kind of material**.

Learning Performances Integrating Big Ideas and Practices

What are things made of and how can we explain their properties? The early work in K-2 on identifying specific kinds of materials, measuring volume and weight, and predicting and evaluating what stays the same and changes across simple transformations prepares students to move up a level of abstraction and develop an explicit, macroscopic concept of **matter** at the Grade 3-5 level. Whereas some concept of matter was implicit in young children's notion of "kinds of material", their early focus was on differentiating specific materials rather than considering what general characteristics all matter has. (The notion of "wood" or "metal" is less abstract than "matter".) Further, we think it is important to delay explicit discussion of the nature of matter until students are in a position to go beyond using commonsense perceptual properties and conceive of volume and weight as objective, quantifiable properties distinct from "perceived size" and "felt weight." These distinctions are beginning to be constructed during K to 2.

Practices at this level become more complex in several ways. First, they involve concepts at a more abstract level (e.g., *classifying* by **matter vs. not matter** rather than by specific kind of material or kind of object; *identifying* **air** as matter because it has volume and weight, even though one cannot see it). Second, they involve more complicated forms of *measuring* and graphical *representation* (e.g., using elementary formulas to calculate the volume of rectangular solids, developing greater precision in measurement through more general understanding of fractional units, constructing graphs that show the relation between **volume** and **weight**[3] instead of displaying each property separately.) Third, students can start to *predict* the value of one property in terms of knowledge of other properties. For example, making underlying relations explicit allows students to *predict* (for a given material) what happens to the weight of an object as its volume is doubled or tripled; it also allows them to discover that equal volumes of different materials have different weights. Thus, they can come to *explain* the weight of a whole object in terms of the sum of the weights of its parts and to understand that the **weight** of an object is a joint function of the **kind of material** it is made of and its **volume**. As students become more familiar with some of the distinctive properties of materials, they may be able to *design and conduct investigations* to determine if objects are made of the same materials. Examples of specific learning performances based on the above practices that can be translated into specific assessment items are:

- Classifying by matter vs. not matter.
- Measuring the volume of a rectangular solid using the formula (L x W x D) and standard units.
- Collecting and representing data about the relation between two variables (e.g., volume and weight) for objects made of one (or more) kind of material.
- Interpreting graphs that show a simple linear relation between two variables.
- Predicting how the weight of an object (of a given kind of material) changes as a function of its volume.
- Inferring whether two objects could be made of the same material from qualitative knowledge of their relative volumes and weights.

What changes and what stays the same when things are transformed? As students develop more skills of measurement, an explicit understanding that there can be pieces of matter too small to see, and more knowledge of some of the characteristic properties of different materials, they can deepen their exploration of what changes and what stays the same across various physical transformations. Students at this age can continue to engage in the practices of *posing questions*, *predicting/inferring*, *designing* and *conducting investigations*, *representing* and *interpreting data*, and *making arguments* for a conclusion as they investigate transformations, and these practices become more complex in several ways. First, students can now understand **conservation of matter**

[3] We use “weight” rather than “mass” intentionally at this level. The distinction between weight and mass can more properly be assessed in older students who have learned about gravitational attraction.

and material kind across **transformations** in which **perceptual appearance** is more **radically transformed** (as when the solute appears to "disappear" in dissolving, or when the color of a material changes upon melting). Second, students can *conduct investigations* in which they have to *collect data* about a set of properties of materials (rather than consider just one) and *make arguments* from a pattern of data. Some specific learning performances for reasoning about transformations based on these practices would include:

- Inferring that matter continues to take up space and have weight as it is broken into tiny pieces.
- Inferring that substance identity but not object identity is maintained across melting.
- Predicting increases/decreases in weight when air is added/removed from an object.
- Predicting how the weights of two objects will compare when repeatedly halved.
- Predicting that solutes (e.g., salt, sugar) continue to exist and have weight when dissolved in water.
- Predicting and explaining what happens to the weight of an ice cube during melting.
- Identifying a bar graph that shows lack of change over time.

How do we know? Students can continue to critique common sense impressions (e.g., perceived size, felt weight, and felt hotness) as measures of properties and to investigate the greater validity, reliability, and sensitivity of data based on formal measurements. At the same time they can begin to realize that different measuring instruments vary in precision and that one needs to select a measuring instrument that is appropriate for a task. They can use mathematical reasoning to predict values of variables on the basis of measurements and begin to realize that this is one way mathematics is a powerful tool of science. They can learn to use simple microscopes and can consider how these tools extend the range of events that we can directly observe. Finally, they can begin to realize that science often involves making conjectures or inferences about unseen entities in order to explain a pattern of results and that one needs to evaluate a hypothesis by considering a pattern of data. They can also begin to realize that some statements are only true under certain conditions and start to identify what those conditions are. Examples of learning performances that assess students' deepening understanding of scientific practices include:

- Explaining why we get different weight measurements with different measuring instruments.
- Designing an investigation and making an argument to convince someone that dissolved sugar has not really disappeared.
- Conducting an investigation and making an argument about how they know the identity of a material has been maintained during melting.
- Evaluating the claim: If Object B is bigger and heavier than Object A then it is made of the same material.

Thus, the big ideas studied in this grade range underlie a coherent and powerful set of practices that allow students to engage in more abstract, more general, and more theoretically grounded construction of the concepts of **matter, material kind, and physical transformation** at the macroscopic level. The initial concept of matter as what can be detected by the senses changes into what takes up space and has weight, whether directly accessible to the senses or not. This **new concept of matter**, the **additive nature of weight**, the **material nature of air**, and **conservation of matter and weight across visible and certain invisible transformations**, mutually support each other. These ideas also prepare students for engaging with an important issue at the next level: whether matter is fundamentally continuous or particulate. At that level, macroscopic ideas and the atomic/molecular theory will support each other in the same way that the core macroscopic ideas support each other at this level.

Justification for Big Ideas and Learning Performances

The existing standards (*Benchmarks*, *NSES*, *NCTM*) all acknowledge the importance of continuing to work on developing students' skills of measurement during these middle elementary years (e.g., volume, weight, length, surface area, time, temperature). They also advocate enriching students' understanding of the properties of materials (e.g., the properties of strength, hardness, flexibility, imperviousness to water and fire, ease of conducting heat, buoyancy, and response to magnets are specifically mentioned as appropriate for grade 3-5 by *Benchmarks*). In addition, *Benchmarks* puts special emphasis on deepening students' conception of weight as an additive physical magnitude (i.e., having students recognize that however parts are arranged, the weight of the whole is the sum of the weight of the parts) and having students appreciate that materials may be composed of parts that are too small to see without magnification. Finally, both *Benchmarks* and *NSES* state that during the elementary school years, students should be learning that materials can exist in different states or phases--solids, liquids, and gas --and become familiar with the phase changes that occur in the water cycle.

Curiously, the existing standards do not say that children should develop an explicit macroscopic concept of *matter* at this (or any point)[4] as something that takes up space and has weight--yet we would argue this is precisely the "big idea" that links and organizes many of the above understandings. Indeed, research by Smith (2004) has shown that developments in students' concepts of matter, volume, and weight go hand in hand and support their learning about weight and volume measurement. Central to developing an understanding of weight as an additive physical magnitude and to understanding the logic of weight measurement is reconceptualizing weight as a fundamental property of *matter* rather than defining it more perceptually as *felt weight*. At the same time, linking the ideas of weight and matter only supports thinking of weight as an additive quantity if students are already thinking of *the amount of matter* in an object as an additive physical magnitude. This realization in turn requires that they conceive of matter as the underlying constituent of objects that continues to exist and

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[4] The only time the word "matter" is used in a *Benchmark* standard is with reference to the atomic-molecular theory introduced in grades 6-8 where it is stated "All matter is made of atoms." Prior to that time only the word "materials" is used. We would argue that students need both: the general concept of matter and the idea of material kinds.

take up space even when divided into pieces too small to see, rather than defining matter simply as something that is perceptually accessible--that is, something that you "can see, feel, and touch". Finally, in order to understand that air (and other gases) are matter *because* they take up space and have weight, students need to recognize the centrality of these properties for being matter in the first place.

Thus, we argue that assessing students' general concept of matter is important at grade 3-5 both because it is central to students' successful learning about measurement and the material nature of gases (two agreed upon goals for this grade level) and because it lays the foundation for later learning in grades 6-8 about density and the atomic-molecular theory. Existing research suggests that those students who have come to reconceptualize weight and volume as properties of matter are more successful in understanding weight and volume measurement (Smith, 2004) and the material nature of gases (Smith, Maclin, Grosslight, & Davis, 1997) than those who have not. They are also developing an intuitive precursor of density (acknowledging that objects vary in their heaviness for size as well as in their total weight or size) that in combination with their measurement skills contributes to their construction of a more formal concept of density in later grades. Finally, existing research has shown that students are more likely to understand the basic tenets of the atomic-molecular theory if they have a sound macroscopic theory of matter in which the concepts of matter, volume, weight, and density are differentiated and inter-related (Snir, Smith, & Raz, 2003).

In keeping with the standards, we believe that students this age can extend their understanding of conservation of matter and material kind, especially across transformations such as melting, freezing, dissolving, and breaking into tiny pieces. Investigations and assessments of dissolving are particularly timely and challenging as they involve a transformation in which the solute becomes invisible and because there is easily accessible data that students can gather in order to argue for the continued existence of the solute, including the evidence from qualitative taste tests. However, we question whether students this age are fully prepared to understand the evaporation phase of the water cycle given the newness of their understanding of air (and other gases) as material, their lack of knowledge of the atomic molecular theory (to visualize what is conserved), and the difficulty of making precise enough measurements to detect conservation of weight. Consequently, we suggest assessment of evaporation and condensation might be more profitably undertaken at grades 6-8 when they are also learning about the atomic-molecular theory.

Possible Assessment Items Based on Learning Performances

What are things made of and how can we explain their properties?

(A) <u>Classifying by matter vs. not matter</u>

Pencil and Paper Item:

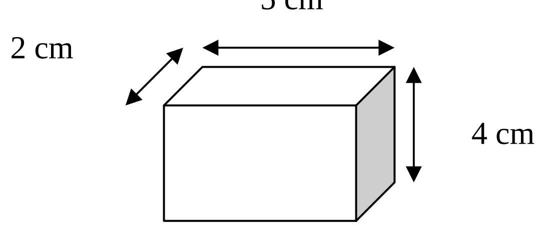
1. Decide whether you consider each item on the list to be matter of not matter. That is, decide whether each item is made of some kind of physical material. Circle your answer. (The list of items to be considered would include: a rock, an idea, an echo, water, a grain of sugar, a particle of chalk dust, air, a tree, a shadow, a wish, heat, a dog.)

2. How do you know? What are the properties of matter?

Interpretation: The questions engage students with the practice of classifying entities as either matter or not matter and providing justifications for their classification based on (at least) their macroscopic conceptions of matter. An important feature of how the assessment item was crafted was that it includes a wide array of kinds of entities (inanimate and animate objects, solids, tiny particles, liquids, gases, forms of energy, mental entities) and asks students to justify their responses. In general, prior to instruction students have difficulty picking out just the set of entities that scientists would consider "matter:" solids, powders, liquids, and gases) while excluding others (Smith et al, 1997; Stavy, 1991). Some students underextend (most commonly omitting air and tiny particles, but sometimes even living things or water); others overextend (including heat or light or electricity)—physical phenomena associated with matter but not themselves matter. Still others have classifications that include both over and under extensions. These under and over extensions go hand in hand with having different ideas about the properties of matter or ways of telling what is matter. Prior to instruction students commonly describe matter as something that you can sense (i.e., see, feel, or touch), although some have more idiosyncratic ideas (i.e., it is something that is natural or non-living) or may not understand what is meant by a "property" (instead giving other examples of matter); it is very rare for students to identify matter as something that has mass or weight. (Taking up space is more commonly associated with being matter than having weight.) Overall the task is a good one for assessing their current conceptions of what is matter and not matter. The task can also be done in interview form as a sorting task where they sort items into piles and provide justifications for their sorts.

(B) Measuring the volume of a solid using the formula (L x W x D) and standard units.

Pencil and paper item: Consider the following solid that is 5 cm long, 4 cm high, and 2 cm deep. What is its volume



This could be done either as an open-ended item (where students have to calculate the volume); alternatively, it could be done as a multiple-choice item with the following choices:

A. Its volume is 11 cm.
B. Its volume is 10 cm^2.
C. Its volume is 20 cm^2.
D. Its volume is 40 cm^3.
E. Its volume is 76 cm^3.

Interpretation: This item calls for students to distinguish volume from other measures of spatial extent (length, area, surface area,) both in selecting and applying the appropriate formula and units. It is common for students to confuse volume with other measures of spatial extent and to be sloppy in selecting units. However, students who have had experience constructing measures of volume from unit cubes, measures of area by tiling with squares, and measures of length by using rulers, should now understand the differences in spatial measures. Further, their increasing mathematical sophistication should allow them to construct and understand this first simple formula for volume. Some may conceive of this as pulling an area through a distance to get the volume (Lehrer, Jaslow, & Curtis, 2003); others may visualize the number of cubes in each layer and multiply by the number of layers. An alternative way of presenting this item would be as an open-ended response rather than multiple-choice response. In that format, students would be asked to find the volume of the object (from information in the picture) and explain how they found it. They could be scored for having the correct magnitude, unit, and explanation of procedure.

(C) Collecting and representing data about the relation between two variables (e.g., volume and weight) for objects made of one (or more) kinds of material.

Performance item: Students are given a set of 4 regular solids of different volume all made of the same material. They are asked to measure: (a) the volume of each solid and (b) the weight of each solid and plot the resulting data on a graph.

Interpretation: This task assesses students skills at simple measurement of volume and weight and their skills at constructing graphs that relate two variables (plotting one variable on the x axis and the other on the y axis). Lehrer, Schauble, Strom, & Pligge (2001) have shown that 5^{th} grade students are able to do this with appropriate instruction. In addition they have shown that in this context students are able to discuss issues about measurement error (why there may be slight differences in repeated measurements of the same object and why they might not all lie on the same line.) An interesting extension is to have them then plot the data for a second set of objects made of a different kind of material.

(D) Interpreting graphs that show a simple linear relation between two variables.

Pencil and paper item: Show a graph that plots the weight of an object (of a given kind of material) as a function of its volume. Ask them to explain in words what this graph tells them about how volume and weight are related.

Alternative version: Ask them to identify which graph shows that "as the volume of an object increases, so does its weight". (Have 4 contrasting graphs: a horizontal line, a line with positive slope, a line with negative slope, and a line with an initial positive slope followed by negative slope.)

Interpretation: These items assess whether students can translate between verbal and graphical expressions. At this age, one is looking for a general understanding, such as "increases in one variable go with increases in the other" rather than a full ability to articulate direct proportionality. Some may begin to have this notion by saying "Doubling the volume doubles the weight."

(E) Predicting the weight of an object (of a given material) as a function of its volume.

Pencil and paper item: Here is an aluminum cylinder that has a volume of 10 cm^3 and weighs 30 g.

1. What would be the weight of an aluminum cylinder twice its volume?
2. What would be the weight of an aluminum cylinder three times its volume?

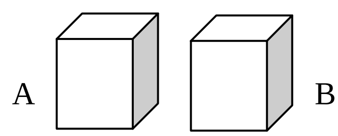
3. What would be the weight of an aluminum cylinder half its volume?
4. What would be the weight of an aluminum cylinder 1/10 its volume?

Interpretation: This item simply assesses that children realize the simple proportionality between volume and weight (for a given kind of material): an object of a given material that is twice the volume of another object must be twice the weight, etc. Young children start with vague intuitive generalizations such as big things tend to be heavier or increasing size increases weight (that are supported by their common sense impressions). One advantage of learning to measure is that one can detect much more precise relations among variables such as simple proportionality. Learning and investigating the proportionality between volume and weight for a given kind of material helps prepare students for learning more formally about density in grades 6-8. At issue in this item is whether students just give some bigger or smaller number or realize that the more precise mathematical relations.

(F) <u>Inferring whether two objects could be made of the same material based on qualitative information about their volumes and weights</u>.

Pencil and paper item:

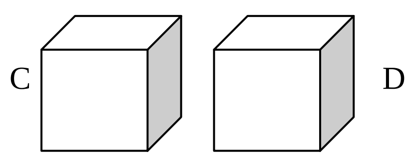
1. Consider the two objects below that are both the same volume and weight. They are each made of one material and they are completely solid inside.



A and B both weigh same

Could they both be made of the *same material*? Explain your reasoning.

2. Consider two objects shown below that are the same volume but different weights. They are each made of one material and they are completely solid inside.



C weighs more than D

Could they both be made of the *same material*? Explain your reasoning.

Interpretation: This task taps whether students are beginning to develop an intuitive sense that objects made of different materials have a characteristic heaviness for size. This is an early precursor for the concept of density that is introduced more formally in grades 6-8. Students who have this beginning understanding of density would say that the objects in problem 1 could be the same material, but not those in problem 2. Further, they could explain that if you take same size pieces of the same material they should have the same weight. Other students might say that both items could be the same material, because anything is possible, revealing that they have not yet begun to develop this precursor concept. Although this task can be done as a pencil and paper item, it is probably even more compelling for students this age when done as a performance item and they are allowed to heft the items in question. Still another interesting version of this task is to pit surface appearance differences against heavy for size differences in judging whether something can be the same material. For example, hand students two same size/same weight pieces of brass one of which is shiny and the other made dull (e.g., by using a rasp) and ask "Could these objects both be made of the same material?" Then hand them two same size/different weight objects that are both painted the same color, and ask "Could these objects be made of the same material?" Smith, Carey, & Wiser (1985) used the latter task and found that many students in this age range had the intuition that heaviness for size differences were more critical than appearance differences in determining that objects were made of different materials.

What changes and what stays the same when things are transformed?

(A) <u>Inferring that matter continues to take up space and have weight as it is broken into tiny pieces</u>.

Pencil and paper item. A large sack of sugar is very heavy and large. It contains millions of grains of sugar.

1. Does a pile of 10 grains of sugar take up any space? How do you know?
2. Does a pile of 10 grains of sugar weigh anything at all? How do you know?
3. Does one grain of sugar take up any space? How do you know?
4. Does one grain of sugar weigh anything at all? How do you know?

Interpretation: This task assesses whether students realize that even very tiny objects take up space and have weight, intuitions that many children are developing during this time. A strong pattern of answers to these questions would be to say yes to all the items arguing that it is still matter so it must take up space and have weight or making the additive argument that if the large sack is heavy each piece must contribute to the weight. Some students deny that small things (either 10 grains or 1 grain) take up any space or have weight because they are too tiny, revealing that they don't think of taking up space and having weight as fundamental properties of matter. In general students realize that small objects take up space prior to their realizing that they also have weight (Carey, 1991).

(B) <u>Inferring that substance identity but not object identity is maintained across melting</u>.

Pencil and Paper Item: Here is a candle made of wax. The candle is placed in a frying pan on the stove and heated. Now it melts and becomes a clear liquid. (Show picture of melted candle). Is it still a candle? Is it still wax?

A. It is still a candle and it is still wax.
B. It is still a candle but it is not wax.
C. It is no longer a candle but it is still wax.
D. It is no longer a candle and it is not wax.

How do you know?

Interpretation: This item assesses whether students realize melting changes object identity (it is no longer a candle) but not material kind (it is still wax). Children might explain their answers saying that it no longer has the shape of a candle and can no longer be used as a candle, but it is still wax because that is what it is made of and you can't change what it is made of by melting. Alternatively, some students may think the melted candle is no longer a candle or wax, because they think the melted wax has become liquid water (arguing it looks clear like water; or it's a liquid so it must be water). These answers show that students do not have a good understanding that material kind is preserved across melting. Stavy and Stachel (1985) found that children this age can understand material identity in this context.

(C) Predicting that an object will increase/decrease in weight as air is added/removed.

Pencil and Paper Item: Here are two empty balloons in balance. (Show picture of two uninflated balloons in balance, each hanging from the end of a rod that is suspended with a string tied to its midpoint). Which of the following pictures shows what will happen when we fill one balloon with air?

A. Picture shows the uninflated and inflated balloon are both still in balance.

B. Picture shows the inflated balloon is heavier (tips down)

C. Picture shows the inflated balloon is lighter (tips up)

D. There is no way to predict from the information given.

How do you know?

Interpretation: This item assesses whether students realize that air has weight and hence adding air will make the balloon heavier and the rod tip down. If students understand this, they should select B, and explain that air has weight, so it should make the rod go down. Common alternative ideas are that air is weightless (hence adding air will not change how things balance) or that air has negative weight (things rise when air is in them, hence the side of the rod with the balloon will go up). Other items could be created asking about the weight of a ball (or tire) as air is added/removed.

(D) Predicting how the weights of two objects will compare when repeatedly halved.

Pencil and Paper Item: This cube of clay is heavier than this (same size) cube of Plasticene (show picture of two same size objects on a scale with the clay side going down). Imagine that we repeatedly cut each cube in half and in half again until we had a very tiny piece of each (each about the size of a BB). How would the weight of the very tiny pieces of clay and Plasticene compare?

A. The clay piece would still be heavier than the Plasticene piece.

B. The Plasticene piece would now be heavier than the clay piece.

C. The two pieces would both be so tiny that they would weigh the same tiny bit.

D. The two pieces would both be so tiny that they would weigh nothing at all.

Why do you think that?

Interpretation: This item assesses students' understanding that all matter has weight and thus that weight differences between objects made of different materials are preserved with successful halving (answer A). In contrast, students who conceptualize weight as felt weight should select either Answers C or D (i.e., they both feel same--hence a tiny bit; or they both so small they exert no pressure on the hand and thus weigh nothing at all.). Thus, this item is a good test that students are moving from conceptualizing weight as felt weight to thinking of it as a property of matter. Both Bovet, Domahidy-Dami, & Sinclair (1982) and Smith, Carey, & Wiser (1985) have used a similar item (in clinical interviews) with children of these ages.

(E) Predicting that solutes (sugar, salt) continue to exist and have weight when dissolved in water.

Pencil and Paper Item: Three cubes of sugar (weighing about 3 grams) are dissolved in a large cup of hot water. What do you predict will happen to the sugar when dissolved?

A. The sugar will completely disappear and turn into water.

B. The sugar will still be there but will no longer weigh anything at all.

C. The sugar will still be there but will now weigh much less than 3 gram.

D. The sugar will still be there and will still weigh 3 grams.

How do you know?

Interpretation: This item assesses children's understanding of conservation of matter (and weight) in the context of dissolving. Very young children often think that the sugar either completely vanishes or becomes weightless because it is so tiny. In general, most students in this age range realize that the sugar is till there (Holding, 1987); the biggest challenge is whether they conserve weight. To the extent that children are able to see weight as a property of matter, however, they should be able to conserve weight as well.

(F) Predicting and explaining what happens to the weight of an ice cube during melting.

Pencil and paper item: A piece of ice is melted to liquid water. How would the weight of the water compare with the weight of ice?

A. The water would weigh less than the ice.

B. The water would weigh the same as the ice.

C. The water would weigh more than the ice.

Explain your answer.

Interpretation: This item assesses whether students can use a belief in conservation of matter (nothing was added or taken away during melting) and a belief that all matter has weight to reason that the weight of the water is unchanged during melting. Students who are thinking about the changed perceptual properties of the ice cube, rather than thinking about the fact that no matter has been added or taken away during the transformation, might mistakenly think that the ice cube weighs less (because it floats) or it weighs more (because it is harder and heavier). Stavy (1987) studied this problem with 5-10 year old children and found increasing understanding of conservation of weight in this context during this time (going from only 5% who understood the problem at age 5 to 75 percent at age 10).

(G) Identifying the graph that shows lack of change over time.

Pencil and Paper item: Show 4 graphs of the relation between weight of ice cube as a function of time: one shows a straight line with a positive slope; one a straight line with a negative slope; one a straight line rise followed by a straight line fall; and one a horizontal line. Which graph show shows no change in weight over time?

Interpretation: This item assesses a form of representational competence or literacy: that is, being able to interpret graphical data as conveying information about change or no change. This involves understanding some of the conventions of graphs and interpreting them meaningfully.

How do we know?

(A) Explaining why we get different weight measurements with different measuring instruments.

Pencil and paper item: Three children were given a piece of rice and asked to determine if it weighed anything. Linda picked up the piece of rice, noticed it exerted no pressure on her hand, and declared "It weighs nothing at all." John put the piece of rice on a plastic balance scale that he found in the kindergarten classroom. He noted that the balance scale did not move when the rice was placed on it, so he too concluded that the piece of rice "weighs nothing at all." Luis put the piece of rice on a metal balance scale that was used in a high school chemistry class. He found that the rice grain made the scale tip down a little bit when he put the grain on the left side. He then repeated the experiment by putting the grain on the other side, and found that again the grain made the scale tip down a bit. He concluded that the grain of rice weighed a tiny amount.

Why do you think they got different answers? Who do you think is most likely right? Why?

Interpretation: This item assesses whether students have an understanding that differing measuring instruments can have different sensitivities and therefore produce different results. It also assesses students' belief that even tiny pieces of matter must have some weight. Students should be able to explain that although little things may be too light to have their weight detected by our hands (or some crude scales, especially if they are sticky or gummy from dirty hands of kindergartners), they actually do weigh something and their weight is often detectable with scales of greater precision. In crafting this item, it could also be useful to have good visual depictions of the two scales that show thicker and thinner fulcrum points for the less sensitive and more sensitive scales, respectively. This visual depiction would give students a further way to reason about why the scales produced different results.

(B) Designing an investigation and making an argument to convince someone that dissolved sugar has not really disappeared.

Pencil and paper item: Two students are arguing over what happens to sugar when it dissolves in water. Ben thinks that when sugar dissolves it disappears because you can no longer see it. Sarah, on the other hand, thinks that when sugar dissolves it is still there because the water still tastes sweet. Ben, however, is not convinced by Sarah's argument because he thinks that although the sugar may have left its taste, the sugar itself is no longer there. How might you convince Ben he is wrong by gathering further data? Describe a further study that you could do in order to convince Ben that the sugar is really still there. Then explain what you would say to Ben in trying to convince him of this point.

Interpretation. This item is relevant to assessing whether students realize that if the sugar is still there it should still have weight, so they could compare the weight of the water before they add the sugar, immediately after the lumps of sugar are placed in the water (and hence the sugar is not yet dissolved) and when the sugar is fully dissolved. If the weight increases when the sugar is put in, but stays the same during dissolving, that argues that the sugar is still there. It also assesses whether they realize that in making an argument they need to consider multiple pieces of evidence and offer explanations for apparent counter-evidence. For example, they might also argue against Ben's position by raising questions about how sugar might leave its taste without being there (How can that happen?) or by noting that when things get small they are hard to see even though they are still there.

(C) Conducting an investigation and making an argument about whether the identity of a material has been changed during melting.

Performance task: Two students are arguing about whether, when wax melts, it turns to liquid wax or to liquid water. Conduct an investigation of the properties of the liquid and make an argument about which student you think is right. In conducting your investigation you might consider that water has some of the following properties: it is clear, odorless, soaks things placed in it, is cold when it melts, mixes with water but not oil, etc.

Interpretation: This task assesses whether students realize that they need to evaluate a claim against a pattern of evidence. They can't decide whether the colorless liquid is wax or water just by appearance (it's clear or colorless, it looks like water), but need to gather more information about the properties of the liquid upon melting (e.g., its temperature upon melting, what happens when you immerse a piece of paper in the liquid, its smell, how it reacts when mixed with water, etc.)

(D) Evaluating the statement: If Object B is both bigger and heavier than Object A then it is made of the same material.

Interpretation: This task assesses whether students realize that this statement is not always true, but only under certain conditions. One qualification would be to say it could be true if it were twice as big and twice as heavy, but not if it were twice as big but only a little bit heavier. It needs to be the same amount bigger and heavier. Alternatively, students may simply say the statement is true or false without qualification.

Assessment Suggestions for Grade 6-8 (ages 11-14)

Version of Big Ideas for Middle School Students

M1. Macroscopic Properties

- There are **properties** that characterize all **matter**, **specific materials,** and **phases of matter** that can be quantified and related.
  - **Mass** measures the **amount of matter** and is constant across location**. Weight** is proportional to mass and varies with the gravitational field.
  - **Materials** have **characteristic properties** such as density, boiling point, and melting point**. Density** is quantified as **Mass/Volume.**
  - Matter exists in three general phases, **solid, liquid, and gas,** that vary in their properties.

M2. Macroscopic Conservation

- Some transformations involve **chemical change** (e.g., burning, rusting) in which new substances, as indicated by their different properties, are created. In other changes (e.g., changes of state, thermal expansion) materials may change appearance but the substances in them stay the same.[5]
- **Matter and mass are conserved** across both types of changes.
  - **Conservation of mass** is a fundamental law.
    - The volume, but not the mass of the gas, is changed when compressed.
    - Heating changes the volume, but not the mass of the object.
    - Dissolving, phase change, and chemical change involve conservation of mass but not volume.

AM1. Atomic-molecular theory

- **The basic tenets of the atomic/molecular model are:**
  - All matter is made up of discretely spaced particles (called **atoms**) which are far too small to see directly through an optical microscope. There are empty spaces (**vacuum**) between atoms.
  - Each atom takes up space, has **mass**, and is in constant **motion**.
  - There are over a hundred **different kinds** of atoms. Each kind has distinctive properties, including mass and the way it combines with other atoms or molecules.
  - Atoms can be joined (in different proportions) to form molecules or networks--a process that involves forming **chemical bonds** between atoms. Molecules have different characteristic properties from the atoms of which they are composed.

AM2. Atomic-molecular explanation of materials

- **Macroscopic properties can be explained in terms of atoms and molecules**
  - Some substances (**elements)** are composed of just one kind of atom. Other substances (**compounds**) are composed of clusters of atoms bound together.
  - Materials are mixtures of two or more (often many more) substances. Some materials are predominantly a single substance.
  - In solids, atoms or molecules move rapidly, but usually within spaces constrained by their neighbors. In liquids, atoms or molecules are also closely packed, but are more loosely associated, and constantly collide as they move past one another. In gases, atoms or molecules move freely in straight lines except when they collide with each other or their container.

AM3. Atomic-molecular explanation of transformations

- **Macroscopic transformations can be explained in terms of atoms and molecules** :

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[5] While many curricula suggest that middle school students could make a general distinction between chemical and physical changes, we prefer introducing the distinction in terms of a few canonical examples at this age. Because there are no simple procedures that allow students to reliably distinguish physical from chemical changes on the basis of macroscopic observations, we also propose introducing the distinction in the context of the atomic-molecular theory.

- ❑ Changes in matter include physical changes, in which molecules change arrangement and/or motion but remain intact, and chemical changes, in which atoms are rearranged (disconnected and reconnected) into new molecules but the atoms remain intact.
- ❑ Within a phase, adding or removing heat modifies the speed of atoms or molecules, but not their type of motion. During phase change, adding or removing heat causes a change in type of motion but not speed.

AM4. Distinguishing data from atomic-molecular explanations

- The **properties of atoms** and changes in atoms have to be **distinguished** from the **macroscopic properties and phenomena** for which they account.
  - ❑ At the atomic-molecular level, matter is discrete although macroscopically it appears continuous.
  - ❑ Although elements, compounds, and mixtures can look equally homogeneous at the macroscopic level, they can be distinguished at the atomic-molecular level
  - ❑ Atoms have some properties of macroscopic objects (mass, volume and weight) but not others.

Learning Performances that Integrate Big Ideas and Practices

The learning performances reflect the two major foci for this grade range: the atomic-molecular theory and quantifiable, properties of matter and material kinds.

What are things made of and how can we explain their properties? *Measuring* is now enriched in several ways: it can be combined with calculations to derive new variables (e.g., density) and it can be linked to the **atomic/molecular model**. Students' mathematical abilities and the concept "heaviness for size," as distinct from weight and as related to material kind, that they developed in late elementary school support understanding the algebraic formula for density. Students can be asked to *measure* the weight and volume of an object (including an irregularly shaped one, to be measured with water displacement) in order to *calculate* the density of the material it is made of. Students can *relate their measurements and calculations* to the kind of *graphic representations* developed at the previous level: they can plot the weights of a series of objects made of different materials as a function of their volumes, *infer* that weight and volume measurements for objects made of the same material kind fall on a straight line, and that the slope of a line is related to density.

A central achievement in this grade range is understanding **the particulate nature of matter** and *representing the basic tenets of the atomic-molecular model*. This is a demanding task because students need to *imagine* matter on a scale far removed from experience. In addition, using the atomic-molecular model involves making theoretical commitments that violate everyday experiences—the experience that matter is continuous is deeply entrenched, and the experience that the kinds of materials in the world are infinitely varied is not easily reconciled with the notion that there are only about 100 different kinds of atoms on earth--and metaphysical beliefs (e.g., that there is no vacuum). Students are asked to adopt the atomic-molecular theory in part on the basis of indirect evidence (e.g., gases are compressible) and on the strength of epistemological knowledge they are in the process of developing (e.g., a clear distinction between observations, data, and models and an appreciation of broad explanatory power)[6]. The learning performances in this grade range reflect practices that will help students meet those challenges.

Students can be assessed on their ability to *draw, label, and interpret* simple models of different materials in gas, liquid, and solid states. Their models should represent the major features of atoms being emphasized are this grade range--different elements are made of atoms which differ in mass, are at different distances from each other, are in perpetual motion in the vacuum, and are connected by forces of different strengths. In creating models, students need to *selectively represent attributes*, depending on the modeling goal. E.g., molecules can be represented as composed of atoms when their composition matters (e.g., accounting for the conservation of particles and mass during burning); or by single symbols when what matters is the distinction between different substances.

Relating the molecular/atomic model to observations and measurements in order to account for them is the core of the practices in this grade range. Regularities (of properties and relations) observed and measured at the macroscopic level can be accounted for by the atomic/molecular model, and in turn, give it credence. Modeling practices link the mass of an object to the number and mass of the atoms it is made of, and therefore strengthen the concept of mass as amount of matter and its additive nature. This allows introducing the distinction between mass and weight, and the prediction that objects have different weights in different geographical locations or on different planets. Students can be asked to *model* the liquid state of a substance given the model of the solid state and two objects made of the same material but with different volumes. They can *categorize* models as representing solids, liquids, gases; and elements, mixtures and compounds. They can *explain* why two models represent the same material kind in two different phases, different material kinds in the same phase, or different material kinds in different phases. They can *pose questions* about models presented to them, e.g., discuss whether two models could represent two substances with the same density or a phase change vs. a chemical transformation. They can *reflect* on the difference between macroscopic attributes that hold for atoms (weight, mass, volume) and those that don't (e.g., hardness) and learn to modify the basic models to account for differences in some of those macroscopic properties. These practices will foster *differentiating* between impressions, data, and models.

In this grade range, modeling practices focus on the basic tenets of the atomic-molecular theory, and on the general properties of matter and material kinds that it accounts for, rather than on modeling specific substances and finding experimental evidence for substance-specific models. Students can *design and conduct investigations* of selected substances (e.g., water, air, oxygen, hydrogen, wood, aluminum, iron, oil,

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[6] Advanced technology (Scanning Tunneling Microscope or STM; Scanning Electron Microscopy or SEM; Atomic Force Microscopy or AFM) allows scientists and students to construct visualizations of matter at the atomic scale and provides powerful evidence for the existence of atoms. Some researchers are beginning to explore its usefulness in the teaching of middle school students (Margel et al, in press). However, whether one can rightfully claim that the images provided by this technology show "atoms" rather than being evidence for them is a complicated epistemological issue. Moreover, they do not provide evidence for other tenets of the theory, such as there being space between them not filled with matter, nor for the distinction between atomic and macroscopic properties.

carbon, iron oxide, iodine, and carbon dioxide), mostly focusing on physical changes (the water cycle, evaporation of iodine, compression of air, thermal dilation of iron and oil), and a few selected chemical transformations. In grades 9-12, students will be involved in practices that build on these beginning understandings and generalize them, as they study, e .g., the periodic table and general principles of chemical reactions.

Examples of learning performances include:

- Measuring weight, mass, and volume of a sample; calculating the density of a sample using a formula.
- Given the weight of an object on earth, predicting its weight and its mass on a planet with a different gravity.
- Predicting the mass, weight, and density of a sample knowing the weight and density of another sample made of the same material.
- Graphing the relation between weight and volume of objects made of different material kinds. Inferring that all samples made of the same material fall on a straight line and linking the slopes of the graph to material kinds and their heaviness for size. Measuring the volume of a new sample made of one of the materials and predicting its weight using the graph.
- Conducting an investigation to determine whether two samples could be made of the same material.
- Predicting sinking and floating for samples made of different sizes and materials.
- Identifying the tenets of the atomic-molecular model. Describing the properties of atoms and molecules.
- Identifying the general properties of solids, liquids and gases, and relating them to properties of the atomic-molecular models for the three states.
- Categorizing atomic-molecular models according to states of matter, according to material kinds, or according to types of substances (elements, mixtures, compounds).

What changes and what stays the same when things are transformed? Students' stronger measurement skills; understanding of **mass**, **volume**, **weight**, and **density** as physical variables; and basic knowledge of the **atomic-molecular model**, can be put at the service of understanding the mechanism of **phase change**, and other phenomena related to **heat and temperature**, and the conservation of mass and weight across those changes. The atomic-molecular model also allows students to start making sense of the distinction between **physical transformations such as phase change and thermal dilation,** and **chemical reactions**.

Students can make *predictions* about mass, weight, volume, and density during physical and (some) chemical transformations. *Measuring* weight and volume before and after transformation allows students to test their predictions. They can also be engaged in *reflecting* on material kind identity across various transformations and in *designing investigations* to decide whether the identity of substances changes or not during transformations. Students can *use the atomic-molecular model* to *justify predictions* and *explain* experimental findings about weight, mass, and material kind during transformations. The atomic-molecular model gives them a way of *visualizing* gases even when they are invisible to the naked eye and thus to explore meaningfully not only melting and freezing but also transformations involving invisible substances—gas compression and expansion, boiling, evaporation, condensation (in particular in the water cycle), dissolving, and burning. *Experimenting* with various substances and transformations, and relating experimental findings to the atomic-molecular model, reinforce the belief that gas is matter. Given that belief, students can *infer* that all material kinds can exist in all three phases, although not necessarily in conditions possible on earth; and that the **conservation of mass and weight** is a general principle, while the conservation of volume is not.

The atomic-molecular theory also greatly enhances the macroscopic concept of material kind. *The practices of drawing models of* changes of state and of *contrasting* them to models of some chemical transformations, make salient that atoms keep their identity in all transformations whereas the grouping of atoms into molecules changes in chemical reactions. Through these modeling activities students can also demonstrate their understanding that molecules are constituted of atoms held together by chemical bonds; exist in much greater number than atoms; are the fundamental constituents of compounds; and have properties that differ from the properties of their atoms.

Examples of learning performances include:

- Predicting the weight of a sample of iodine after sublimation.
- Predicting that oil expands when heated and interpreting representations of weight, volume, and density of a sample of oil while heated.
- Predicting conservation of mass and material kind during boiling.
- Drawing the atomic-molecular model of a sample of gas in a syringe for two positions of its plunger.
- Predicting the weight and volume of a mixture of alcohol and water. Drawing an atomic-molecular model that could account for the results.

How do you know? The practices outlined in the previous two sections rely on epistemological understanding of the atomic-molecular model and in turn help students develop this understanding. Giving atomic-molecular accounts of material kind, phase change, thermal dilation, gas compression and expansion, conservation of weight and mass across physical and chemical transformations, and conservation of material kind across phase change, can support guided reflections on epistemology. The practices involving the atomic molecular model will encourage students to differentiate between the properties of atoms and molecules and the properties of objects and materials that are observable at the macroscopic level and develop understanding of the principles linking the former to the latter. More generally, they start developing an appreciation of the nature, function, and revisability of scientific models.

Students can be asked to reflect on what makes a good scientific model; to decide why a particulate model gives a better account of a phenomena than a continuous model of matter, whether a particular model obeys or violates the atomic-molecular postulates, and whether or not a set of models accounts for observed differences between a set of objects, or for a particular transformation; and to modify a model to account for a newly explored phenomenon (e.g., thermal dilation). These practices are pedagogically useful ways to teach students to construct arguments that coordinate evidence and models, to distinguish between knowledge claims, and to recognize hypothetical reasoning.

Examples of learning performances include:

- Using mathematical argument to obtain a measure for something indirectly.
- Evaluating competing models in light of data
- Reflecting on possible atomic-molecular models for density
- Conducting an investigation of condensation to test hypotheses and make an argument about where the water came from

Thus, the big ideas studied in this grade range underlie a coherent and powerful set of practices that theoretically ground the macroscopic concepts of **matter, weight, volume, and material kind** in the atomic-molecular model and express their relations quantitatively via graphs and simple equations. At this level, macroscopic ideas and the atomic/molecular theory support each other in the same way that the core macroscopic ideas support each other in the earlier grade range. In particular, the atomic-molecular model allows students to construct a concept of gas as a form of matter, and an abstract and general understanding of phase change that includes evaporation and boiling. Density, boiling point and other properties of substances cluster to support a concept of material kind, supported by the atomic model. The atomic-molecular model also allows students to start exploring the distinction between physical and chemical transformations, a distinction that is difficult to teach at the macroscopic level only. Finally, increased flexibility in measurement, calculation, interpretation of graphic representation, and use of models, and a growing appreciation of their inter-relations, make classroom practices similar to actual scientific practices.

Justification for Big Ideas and Learning Performances

The difference between our target ideas and the Standards for this age range is a matter of emphasis and coherence, more than content, with a few exceptions. The speed of chemical reactions and the idea that there are groups of elements with similar properties are in the Standards for this grade range but seem more appropriate for the high school level, when chemical reactions are studied extensively and the structure of the atom itself is discussed. For the same reason, we prefer addressing the difference between physical and chemical transformations at the macroscopic level in the context of a few familiar phenomena (e.g., rusting, burning, changes of state), rather than at a general level. The difference is an issue of debate among chemists, and will be more meaningfully addressed in high school, when students become familiar with chemical reactions.

On the other hand, we propose a richer set of postulates for the atomic model, one that includes the idea of vacuum between the atoms, scale, and of forces holding them together. Research shows that the idea of empty space between atoms is strongly resisted by students when it is taught, and that most students internalize the atomic model as atoms embedded in some continuous substance or closely packed together with no space (Pfundt, 1981). It is therefore crucial to address this issue explicitly. But in order to accept the idea of atoms with no matter in between, one needs to have some sense of what holds atoms together. Without the concept of bonds between atoms, the atomic model cannot be reconciled with the experience that matter coheres, and one cannot account correctly for the difference between solid and liquid state at the atomic level (Dow et al., 1978). Students'most common justification for drawing atoms packed together or embedded in a substance is that solids would not hold their shape otherwise (Chomat, Larcher, & Meheut, 1988). The concept of bonds between atoms is also necessary to the distinction between atoms and molecules, and to start understanding the difference between chemical and physical changes. The idea of scale plays a similar role in making the atomic molecular model "acceptable." For example, knowing that an atom is many, many times smaller than a speck of dust helps explain why matter looks continuous although it is not; and knowing the relative size of the gaps between atoms in solids helps students accept the atomic molecular model for solids (Scott, 1987). We believe that the benefits of having a coherent model that can satisfactorily explain a wide variety of phenomena (an explicit recommendation of the Standards) and prevent the development of deeply entrenched misconceptions, far outweighs the cost of making the model more complex[7].

For similar reasons, we also place more emphasis on a coherent view of matter at the macroscopic level, particularly on the relations between the concepts of weight, volume, mass and density; and on the connections between macroscopic and microscopic levels of description. The distinction between weight and mass on the one hand and volume on the other is relevant to understanding conservation of matter in physical and chemical transformations. Conservation is a core concept running through the K-12 curriculum. An important achievement in this grade range is understanding that conservation of mass/weight is central to physical and chemical transformations whereas conservation of volume is not. The atomic/molecular model provides a powerful explanation for why that is so, but at the same time depends on a solid distinction between mass/weight and volume at the macroscopic level. Research shows the deep connections between macroscopic beliefs about matter and components of the atomic/molecular model in this regard (Snir, Smith, & Raz, 2003).

We believe it is important to introduce some ideas which students cannot yet test empirically, grasp to in all their complexity, nor develop general principles about. For example, middle school students should not be asked to how they could tell, empirically, whether a substance is an element or a compound but can understand the distinction at the representational level; this understanding will pave the way for systematic investigations of this issue in later grades. They will not be able to decide whether a particular pair of models account for the different density of two materials but can be asked to judge whether certain models might account for such difference. In doing so, they will start appreciating relations between theory and evidence and the role of models in scientific understanding. We also believe that thinking of a few familiar chemical reactions in molecular terms will act as a place holder for a principled understanding of chemical reactions in high school chemistry.

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[7] We believe that one can introduce the idea of bonds and forces between atoms without specifying that atoms in molecules share electrons, and thus without depending on knowledge about the structure of atoms, a topic that is introduced in high school. Historically, the notion of chemical bond emerged early in the 19th century, about a century before the notion that electrons were involved in bonding. Our view is in agreement with the Benchmarks standards, which make bonding a topic of the 6-8 grade curriculum, i.e., before atomic structure is formally introduced in high school.

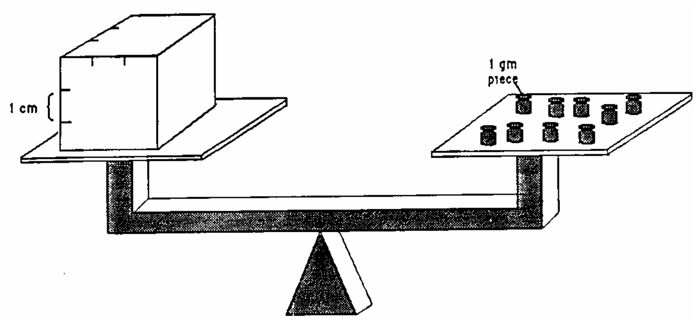
Finally, we believe that 6-8 is the appropriate grade range at which to introduce the distinction between mass and weight, because it is supported by students' work on force and gravitation in Mechanics.

Possible Assessment Items Based on Learning Performances

What are things made of and how can we explain their properties?

(A) Measuring Volume, Weight, Mass, and Density

Pencil and paper item: Here is an object that is in balance on the scale. Answer the following questions about the object giving the appropriate numbers and units.



1. What is the volume of the object?
   How did you figure that out?
2. What is the weight of the object?
   How did you figure that out?
3. What is the mass of the object?
   How did you figure that out?
4 What is the density of the object?
   How did you figure that out?

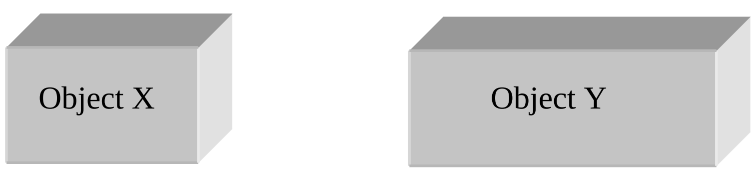
If the object was on a planet where the gravitational pull were twice what it is on Earth,

5. Its mass would be
   (A) Twice what it is on Earth
   (B) Half what it is on Earth
   (C) The same as it is on Earth
6. Its weight would be
   (A) Twice what it is on Earth
   (B) Half what it is on Earth
   (C) The same as it is on Earth
7. Its volume would be
   (A) Twice what it is on earth
   (B) Half what it is on earth
   (C) The same as it is on earth

Interpretation: These questions engage students with the practice of measuring and call on their macroscopic concepts of volume, weight, mass, and density, their knowledge of balance scales, as well as their knowledge of standard units for measuring each quantity. Students are asked both to make a calculation and explain the basis for their calculation. The questions can be scored for both having correct magnitudes and units for each quantity as well as a relevant, appropriately explained procedure. An important feature of how this assessment item was crafted is that students must *select* which information is most relevant for a given question and explain their reasoning, thus assessing if they make crucial differentiations as well as if they know relevant procedures and units for measuring each quantity. Some students give responses that indicate that they may be conflating different physical magnitudes. For example, in response to the volume question, students might give a length (3 cm) or an area (9 cm^2) or a surface area (54 cm^2) rather than the volume (27 cm^3). Alternatively, they may conflate mass with volume (e.g., giving a volume measure on both) or conflate weight and mass with density (e.g., giving a mass measure on both). This item is an adaptation of one used by Smith, Maclin, Grosslight, & Davis (1997) with a group of 8^{th} grade students. In general students find the weight questions easiest, followed by volume and mass, and then density. This task can also be given in interview form (with balance scales, rulers, gram masses, etc. present) to see if they can determine the volume, weight, mass, and density of an object in that context. We added the gravity question to further probe the differentiation between weight and mass, and the understanding that mass is an inherent property of an object, not dependent on gravity.

(B) Predicting weight, mass and density

Pencil and paper item: Object X and Object Y are made of the same material. Object Y is twice as big as object X (its volume is twice the volume of object X).

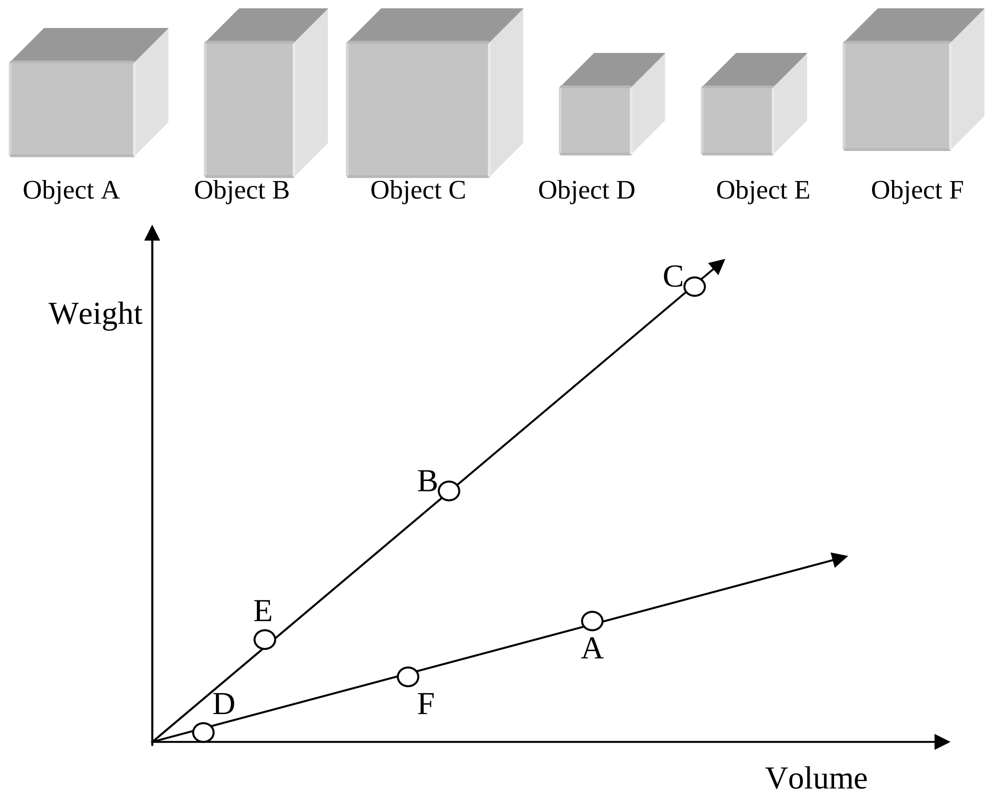


1. The mass of Object Y is
    A. Twice the mass of Object X
    B. The same as the mass of Object X
    C. Half the mass of Object X
2. The density of Object Y
    A. Twice the density of Object X
    B. The same as the mass of Object X
    C. Half the density of Object X
3. The weight of Object Y is:
    A. Twice the weight of Object X
    B. The same as the weight of Object X
    C. Half the weight of Object X

Interpretation: This item probes qualitatively for student understanding of mass and weight as extensive magnitudes and density as an intensive property of material kinds. If students have this understanding then they should realize that doubling an object's volume doubles both is mass and weight; however, the density is unchanged. Students who conflate weight and density often think that the density would also increase.

(C) <u>Interpreting representations of weight, volume, and density</u>.

Pencil and paper item: The graph represents the weights and volumes of 6 objects, A to F.

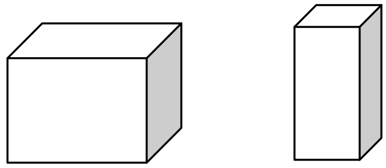


1. Order the objects from lightest to heaviest
2. Order the objects from smallest to biggest (some samples have the same volume)
3. Order the objects according to density (some samples have the same density)

Interpretation: This item tests students' understanding of density and their ability to read graphs. To order the objects according to weight and volume, they need to relate the points to the proper axes. To answer the density question they need both to know that density is the ratio of mass (or weight) and volume, and that a ratio relationship is represented by a straight line. We expect some students to answer the density question in terms of weight or volume, for reasons detailed in Item A.

(E) <u>Conducting an investigation to determine whether two samples are made of the same material</u>

Pencil and Paper Item. These two blocks are both solids and made of stuff that you can cut. They may or may not be made of the same kind of material.



Explain how you could determine whether they are made of the same material or not. Some suggestions are to measure their volume and weight; to handle them; to heat them, and to put them in water. You may think of other ways to investigate what they are made of. For each observation, manipulation, or measurement you suggest, explain why that will help you determine whether they are made of the same kind of material or not.

Interpretation. To be successful, students need to differentiate between properties of the objects (e.g., weight and volume) and properties of the material they are made of (e.g., density). Students who fail to differentiate weight and density or object and material kind might mistakenly suggest that weighing the objects, without taking their volumes into account, will help decide what they are made of. Students who draw conclusions from a sinking and floating test will give evidence that they understand that sinking and floating depend on material kind and not on weight, shape, or size. Students can also give evidence of understanding that directly observable properties such as malleability and measurable properties such as melting points are specific to material kinds.

(E) <u>Predicting sinking and floating</u>

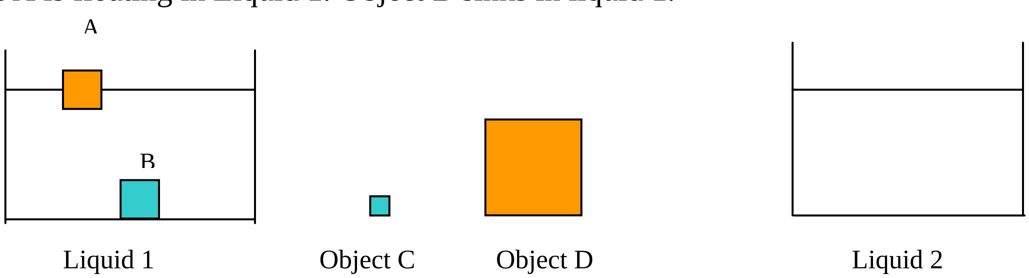
Pencil and Paper Item: These two jars contain the same volume of two different liquids. Liquid 2 is denser than Liquid 1.

Objects A and B are the same size but are made of different materials.

Objects C is made of the same material as Object B.

Object D is made of the same material as Object A (as indicated by their color).

Object A is floating in Liquid 1. Object B sinks in liquid 1.



1. Do you have enough information to tell whether Object A would sink or float in Liquid 2? Explain
2. Do you have enough information to tell whether Object B would sink or float in Liquid 2? Explain
3. Do you have enough information to tell whether Object C would sink or float in Liquid 1? Explain

4. Do you have enough information to tell whether Object D would sink or float in Liquid 1? Explain

Interpretation. This item assesses students' qualitative understanding of floating and sinking as depending upon relative density rather than absolute weight. Research has shown (Inhelder & Piaget, 1958; Smith, Snir, & Grosslight, 1992) that not all 6^{th}-8^{th} graders understand that sinking and floating depends on relative density. If students understand that sinking and floating depends upon relative density, they will understand that Object A must also float in Liquid 2, but that they do not have enough information to make a prediction about Object B. They will also understand that Object C will sink in Liquid 1 and Object D will float because they have the same densities as Objects B and A, respectively. If students base their answers on the absolute weights of the objects, in contrast, they will answer that Object A will float and Object B will sink in Liquid 2, ignoring the density of the liquid. In addition, they may say that Object C will float (because its small and light) and Object D will sink (because its much heavier), failing to realize that the density of the material is independent of the volume of the sample.

(F) <u>Explaining and describing the postulates of the atomic-molecular model</u>

Pencil and paper item (scale of particles): Which do you think is bigger, a molecule or a speck of dust?

A. They are the same size

B. The molecule. How many times bigger?

C. The speck of dust. How many times bigger?

D. I don't know.

Interpretation: Many students being taught about atoms and molecules, on the one hand fail to grasp their size and, on the other, believe that molecules exist *in* matter rather than constitute matter (Lee, et al., 1993). Consequently, some believe that bubbles in ice and dust in air are molecules (Ault, Novak, & Gowin, 1984). Part of reconciling the atomic-molecular model with sensory evidence that matter is continuous depends on understanding, not necessarily the absolute size of molecules, which has little meaning, but their size relative of very small visible objects such as a speck of dust.

Pencil and paper item (properties of atoms and molecules): The following are possible characteristics of atoms and molecules. First decide whether each sentence is true or false. Write T for True and F for False in the blank.

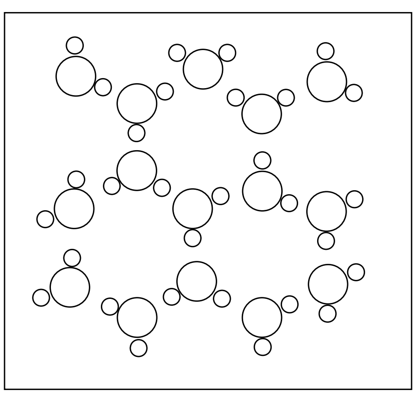
Statement	T or F
1. Molecules and atoms are always moving	
2. Molecules and atoms are all the same size	
3. Molecules in ice cream are very cold	
4. Molecules and atoms have mass and weight.	
5. Molecules can move at different speeds	
6. Only things you can see are made of molecules	

7. Molecules in a rock are not moving	
8. Two substances can be made of the same kinds of atoms but different kinds of molecules	
9. Two substances can be made of the same kinds of molecules but different kinds of atoms	
10. Molecules in liquids are always further apart than in solids	
11. Molecules in liquids move differently from molecules in solids	
12. Cells are kinds of molecules.	
13. There is empty space between the atoms and molecules of solids and liquids.	

Interpretation: These questions assess basic tenets of the atomic-molecular models that students should understand by the end of 8^{th} grade. Research shows that they are all challenging. Some students believe that only some subset of material kinds are made of molecules. For example, many believe that solids and liquids are made of molecules, but gases are not; others believe that living things are not made of molecules (Stavy, 1991). Most students wrongly attribute macroscopic properties such as hardness or temperature to molecules themselves (Ben-Zvi, Eylon, & Silberstein, 1986). Mis-attributing macroscopic properties to molecules similarly make it difficult for students to accept that molecules move in solids (Chomat, Larcher, Meheut, 1988). They also have difficulty accepting the idea of vacuum between atoms and molecules. The relationship between atoms and molecules is not always clear to students (Andersson, 1990); in particular, the idea that, if a substance is made of molecules, it is the molecules, not the atoms, that determine the macroscopic properties of the substance. This item is a modified version of items developed and used by Lee et al (1993) to assess the effectiveness of a 6^{th} grade curriculum unit. Students made significant progress in understanding many of these important ideas as a result of their curriculum unit.

(G) Explaining the properties of solids, liquids, and gases with atomic-molecular model

Pencil and paper item: This drawing represents the atomic-molecular model of a piece of ice.



1. What is in between the molecules?
   - A. Nothing (vacuum)
   - B. Air
   - C. Water

2. What makes ice harder than liquid water?

A. Molecules of ice are hard because they are frozen whereas molecules of liquid water are liquid

B. Molecules of ice are made of solid atoms whereas molecules of water are made of liquid atoms

C. The water in between the molecules of ice is frozen

D. The forces between the molecules are stronger in ice than in water

E. Molecules of ice are vibrating around a fixed point whereas molecules of liquid water move more freely

F. Both D and E

Interpretation: This item (modified from Lee et al., 1993), like the previous one, assesses whether students accept the idea of matter being constituted of molecules in a vacuum. It also asks students to differentiate between macroscopic properties to be explained (solidity of ice vs. liquidity of liquid water) and the properties of molecules that explain the macroscopic properties (forces and modes of motion). Students are prone to think of molecules of solids as hard and molecules of liquids as liquid (de Vos & Verdonk, 1987). The instructional unit used by Lee et al. (1993) with sixth-graders produced very significant improvement in students' molecular understanding of the states of matter. A case study by Wiser and Amin (2001) also finds that, with specific instruction, 8th-graders are able to master the atomic-molecular explanation of states of matter. Meheut and Chomat's (1990) study shows more generally that with a curriculum focusing on this important epistemological distinction students can learn to use the properties of atoms and molecules, to explain the properties of macroscopic samples.

(H) <u>Using the molecular-atomic model to make an argument</u>

Pencil and paper item: Two students were arguing about how they could treat dirty rain water so they could drink it.

Gerry suggested pouring it through a coffee filter.

Pat said "I still would not drink that water!"

1. What do you think was in the dirty water?

2a. If you agree with Gerry, draw a model of the dirty water, the coffee filter, and the filtered water that shows why the filtered water would be OK to drink.

2b. If you agree with Pat, draw a model of the dirty water, the coffee filter, and the filtered water that shows why the filtered water would not be OK to drink.

Interpretation. This item comes from an interview used by Lee et al (1993) with 6th graders. To evaluate the protagonists' arguments, students need to imagine invisible particles with causal powers, i.e., to use a concept of matter as particulate and whose core is not that it is directly accessible to the senses. They also need to think of the scale of what pollutants there are in the dirty water, and how the size of the pollutants compare to the size of the holes in the coffee filter. Thus several components of the concept of matter and several tenets of the atomic molecular model have to be recruited in order to reflect on this problem. Research shows that those concepts are not mastered by all students in this grade range (Stavy, 1990; Meheut & Chomat, 1990). Lee et al. (1993) found that students often failed to differentiate between water that appears pure and water that in fact lacks harmful substances. Similarly, students were typically vague about the relationship between the size of potentially polluting molecules and the size of pores in filter paper. The idea that "pollution" was made of molecules was also new to some students.

What changes and what stays the same?

(A) <u>Predicting the weight of a sample after sublimation</u>

Paper and Pencil Item. A piece of solid iodine is placed in a closed container. The container weighs 200g and the piece of solid iodine weighs 50 g. When it is heated the iodine sublimes and becomes a purple gas that fills the container.

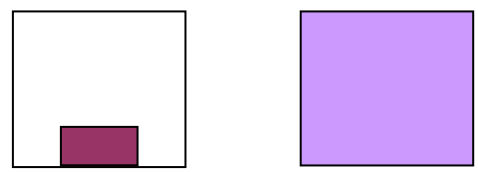
What is the total weight of the container on the right?

A. 250g

B. 200g

C. more than 200g but less than 250g

D. more than 250g



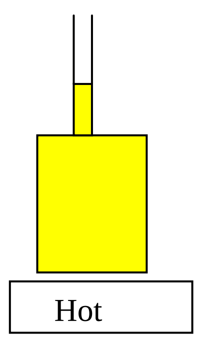
Weight of container 200g   Total Weight?

Weight of solid iodine: 50g

Interpretation. To answer this question, students have to apply conservation of weight to a sublimation phenomenon. Iodine is colored in its gaseous form. Stavy (1990) compared children's conservation of matter and weight in an acetone evaporation and iodine sublimation demonstrations. She found that the visual information facilitates thinking of the gas as material, and therefore as having weight, in 6th and 7th graders. Some students who think iodine gas does have weight may nevertheless think the weight of the sample in its gas form is less than the weight of the solid sample. Other students may think that the iodine gas weighs nothing at all, in spite of its having color (Stavy, 1990).

(B) <u>Explaining thermal dilation. Interpreting representations of thermal dilation</u>.

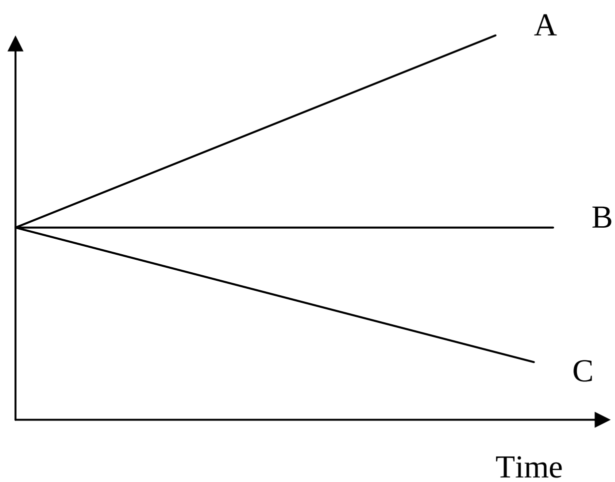
Pencil and paper item: A flask containing oil is being heated for 5 minutes.



1. What will happen to the level of the oil as the oil gets heated?
   A. It will rise up in the tube.
   B. It will stay at the same level in the tube.
   C. It will go down in the tube.

Why does that happen?

2. Which line on the graph represents the weight of the oil at the different points in time?
3. Which line on the graph represents the volume of the oil at the different points in time?
4. Which line on the graph represents the density of the oil at different points in time?

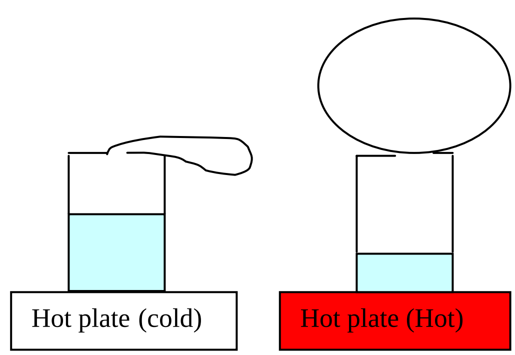


Interpretation. This item tests whether students know about thermal dilation, and whether they spontaneously invoke an atomic-molecular explanation for it. It also tests for the conservation of weight and mass of a substance being heated and whether students differentiate between weight (mass) and density, and are able to reason that, if volume increases while mass (weight) stays the same, density is decreasing. Studies (Wiser, 1986) shows that, prior to receiving a teaching unit on heat and temperature, students do know about thermal dilation but do not invoke molecular explanations, even when they know about atoms and molecules; they usually explain thermal dilation as due to the heat pushing the level of oil up. Studies also show that, with specific instruction, 8th graders find the atomic-molecular explanation of thermal dilation convincing and can extend it to understanding how a thermometer works (Wiser & Amin, 2001).

(C) <u>Predicting and explaining conservation of weight during boiling. Identifying substances during boiling</u>.

Pencil and Paper Item: A container with a little hole at the top is placed over a hot plate. There is water in the container. A deflated balloon is attached to the hole. The hot plate is turned on. The water starts boiling and the balloon inflates (see picture below):

1. What is the balloon filled with?
   - A. Air
   - B. Oxygen and hydrogen gas
   - C. Air and water vapor



D. Heat

2. Consider the combined mass (amount of stuff) of the container, water, and balloon (deflated or inflated), and what the balloon contains. When the water boils:

   A. Mass (amount of stuff) stays the same because ____________

   B. Mass (amount of stuff) decreases because ________________

   C. Mass (amount of stuff) increases because ________________

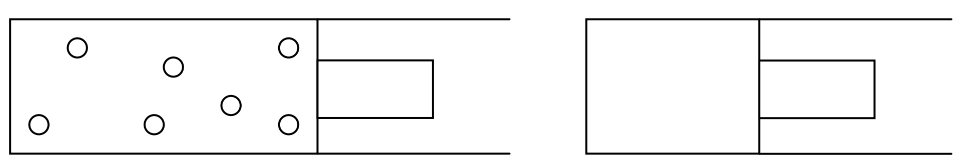
   D. There is no way to predict

Interpretation. These questions test whether students believe that what escapes from the boiling water is material, whether they apply conservation of mass to this situation, and what they think escapes from the water. Bar & Travis (1991) found that the proportion of students who believe that what escapes from boiling water is still water increases through middle school, from 40% from 60%. Some students believe that what escapes from the boiling water is air and or they might say that the water breaks down into oxygen and hydrogen (evincing a confusion between chemical and physical transformations) (Andersson, 1990; Osborne & Cosgrove, 1983; Salomonidou & Stavridou, 2000). Students may correctly apply conservation of mass (Bar, 1987; Bar & Galili, 1994) and predict that when the liquid water changes state, there is no change in mass. Alternatively, they may believe that the mass of the gas will be less than the mass of liquid (because gases are thought to be light or weightless) (Stavy, 1988). The influence of context (Stavy, 1991b) makes it important to ask students to consider phase changes in various situations. As their knowledge of conservation and of the mechanism of phase change deepens, we expect them to become more impervious to variations in experimental set-up

(D) Predicting atomic arrangement during gas compression and expansion

Pencil and paper item: A syringe is filled with helium. Helium atoms are represented as circles.

1.The syringe plunger is pushed in.



A. Draw the helium atoms when the plunger is in.

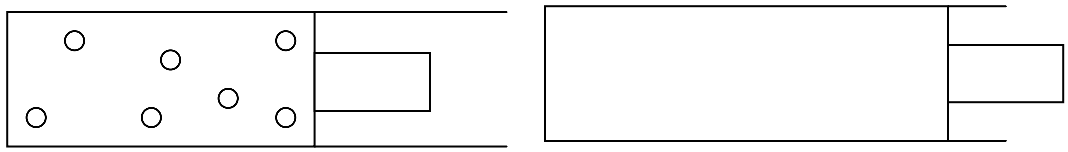
B. Are there the same number?

C. Do they change size?

D. Does the weight of the helium increase, decrease, or stays the same?

E. Explain, referring to the atomic model.

2. Another syringe is filled with helium. Helium atoms are represented as circles. The syringe plunger is drawn out.



A. Draw the helium atoms when the plunger is in.

B. Are there the same number?

C. Do they change size?

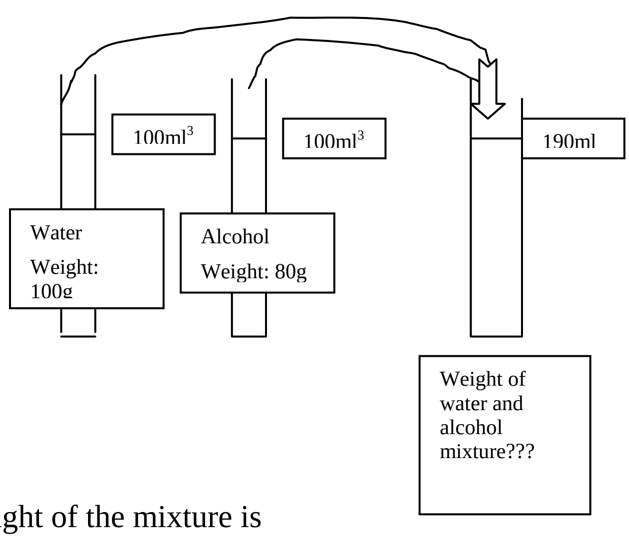
D. Does the weight of the helium increase, decrease, or stays the same?

E. Explain, referring to the atomic model.

Interpretation. This task tests students' basic understanding of the compression and expansion of gas at the atomic level. In (1) they should draw the atoms randomly distributed but closer together on the right than on the left. A common misconception is that atoms shrink when the volume of the gas decreases. Another mistake would be to pack atoms near the plunger, but leave those at the opposite end unchanged . In (2) they should again draw the atoms randomly distributed in the expanded space. A common misconception (Novick & Nussbaum, 1978) is that the atoms stay where they are. Meheut & Chomat (1990) have shown that a curriculum focusing on drawing and applying atomic-molecular models allows a large majority of students to answer this question correctly.

(E) <u>Predicting and explaining conservation of mass and weight of a mixture of water and alcohol</u>

Pencil and Paper Item: If you mix 100ml of water, weighing 100g with 100ml of alcohol weighing 80g, the volume of the mixture is 190ml, i.e., it is 10 ml less than the sum of the volume of water and alcohol you started with.



1. The weight of the mixture is

A. 200g

B. 190g

C. 180g

D. There is no way to predict

2. Water is a small molecule and alcohol a larger one. Draw a molecular model of water, alcohol, and the water-alcohol mixture that would explain why the volume of the mixture is less than sum of the volumes of water and alcohol while the weight of the mixture is the sum of the weights of alcohol and water.

Interpretation: This item tests the ability of students to apply the conservation of mass and weight across contexts. The majority of students in this grade range are able to conserve the mass and weight of solids and liquids under physical transformations such as cutting up into pieces and melting (Stavy & Satchel, 1985). Some may believe in conservation of mass as a general principle and apply it even to a surprising event. We expect that correct answers to the weight question will be correlated with molecular models that accounts for the data (Snir, Smith & Raz, 2003). However, the unexpected and unfamiliar decrease in volume of the mixture may make some students doubt that the weight of the mixture is the sum of the weights of the reactants. These students, rather than taking conservation of weight and mass as a general principle, applying to all transformations irrespective of appearances, would use volume as an indicator of mass and weight.

How do you know?

(A) <u>Using mathematical argument to obtain a measure for something indirectly</u>.

Pencil and paper item. You would like to know what the weight of a single drop of water is, but the scale that you have is only sensitive enough to weigh 5 drops of water. Is there a way to determine the weight of a single drop using that scale? Explain your reasoning.

Pencil and paper item. You would like to know the thickness of a sheet of paper, but it is too small to directly measure. You can measure, however, the dimensions of a ream of 500 sheets of paper. (Its dimensions are 8 1/2 inches x 11 inches x 2 inches). Is there a way to determine the thickness of a single sheet of paper? Explain your reasoning.

Interpretation: These tasks assess the extent to which students are willing to use mathematical argument (in combination with measurement) to make inferences about a property of something. In the case of drop of water problem, they could propose measuring out 5 drops of water, weighing that amount, and then dividing by 5 to obtain an estimate of the weight of a single drop of water. In the case of the thickness of a piece of paper, they could take the measure of the thickness of 500 sheets (2 inches) and divide by 500 to estimate the thickness of a single sheet.

(B) <u>Evaluating competing models in light of data.</u>

Pencil and paper item: Three students investigated what happened when they mixed 50 ml of water with 50 ml of alcohol. They added blue food coloring to the water and red coloring to the alcohol so that they could observe what happened during mixing more carefully. They observed the following three facts:

1. The two substances completely intermixed: that is, as they poured the red alcohol into the blue water, the red went throughout the blue, turning the mixture to a uniform purple color

2. The volume of the mixture was 95 ml, i.e., less than the sum of the volumes of the two parts (50 + 50 = 100ml)
3. The mass of the 95 ml mixture was equal to the sum of the masses of the two parts.

Later, they were arguing about how to explain their findings. Each student had a different idea. Here is what each said.

John: "I think that water and alcohol are each continuous liquids, because they look continuous--there are no spaces or gaps. But when you pour and stir then, somehow they manage to mix together. Probably, you lost some liquid when you poured, which is why the volume is less."

Ralph: "I think that water and alcohol are each composed of different kinds of molecules. Because those molecules are completely packed together, leaving no spaces or gaps, it looks continuous. When you pour and stir them, the two kinds of molecules intermingle and intermix. Probably, you lost some liquid when you poured which is why the volume is less."

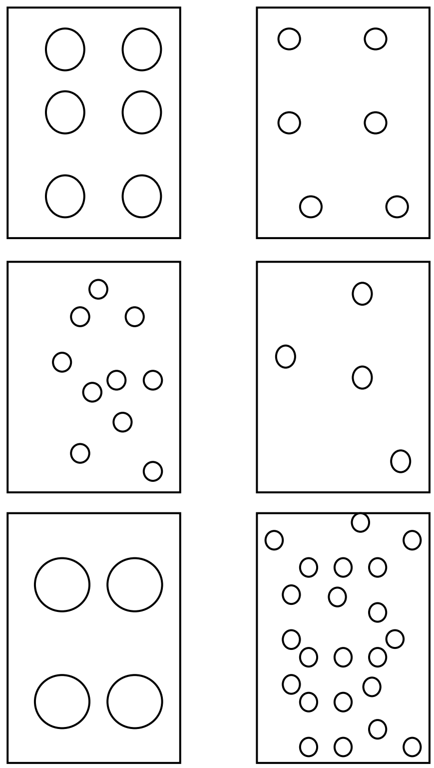
Steve: "I think that the water and alcohol are each composed of different kinds of molecules of different sizes. There are spaces between the particles; but the particles are held together by forces. When you pour the liquids together, some smaller molecules of one substance are able to slip into some of the spaces between the larger molecules, leading the volume to be a little less, even though all the alcohol and water molecules are still there.

Who do you think has the best explanation of the Water/Alcohol study? Why?

Interpretation: This item assesses the criteria students use in evaluating models and explanations: do students want proposed models to "look like" what they observed or do they want it to provide an account for *all* the data and some sense of mechanism even if it means assuming some things they cannot directly observe. If students favor "appearance matches" over systematic accounts of all the data, they may favor either John or Ralph's explanations over Steve's. In contrast, if they favor providing a sense of mechanism and an account of the data over appearance matches, then Steve's should be preferred. John's account closely sticks with surface appearance, but: (a) it provides no mechanism for mixture (if the substances were continuous it is not clear *how* they could intermix) and (b) the account is inconsistent with the fact that the mass stays the same. Ralph's account provides some mechanism for mixture, but still is inconsistent with the mass staying the same. If some liquid has been lost during the pouring, then some mass should be lost too. In contrast, Steve's account is the strongest because it accounts for three observed facts and also provides a sense of mechanism. Snir, Smith, & Raz (2003) used a similar task embedded in interactive computer software with 5-7th grade students in their teaching studies. They found that students were interested in the task and for the most part found Steve's argument more compelling than others, especially if they had strong macroscopic understandings of mass, volume, and density. Some of those with less strong understandings favored appearance matches.

(C) Reflecting on possible atomic-molecular models for density

Paper and Pencil. Substance A and Substance B have the same density (mass per volume). Could the following pairs of model represent them? Why or why not? In these models, different size circles represent different kinds of atoms with a larger atom being one with more mass.



(1) Yes No
Why or why not?

(2) Yes No
Why or why not?

(3) Yes No
Why or why not?

Interpretation. The development of the concept of density is protracted (Smith et al., 1997). Students in this age range, exposed to a model-based curriculum, do learn to differentiate density from weight, and to represent it as the ratio of weight over volume, as they acquire a theory of matter as having weight and occupying space, no matter how small the amount. However, coordinating this understanding with the atomic model is a challenging task, well suited for a classroom discussion. Students are likely to project the macroscopic feature of density—more or less packed—to the atomic model and decide that the samples in Pair A have the same density, ignoring the different masses of their atoms. They may reject C for the same reasons. This discussion will contribute to students' epistemological understanding that macroscopic properties do not simply map to atomic properties; in this case, the density of a substance depends not only on the spacing of its atoms, but on their masses.

(D) <u>Conducting an investigation of condensation to test hypotheses and make an argument about where the water came from</u>.

Performance item: Place a glass of water in the refrigerator. Take it out into a warm room and observe beads of water forming on the outside of the glass. Ask students: Where does the water come from and why does it appear on outside of the glass? Students will be encouraged to develop and test a variety of hypotheses, design and conduct experiments, and make an argument for a conclusion. For example, they can test whether the temperature of the glass is relevant (e.g., would the same thing happen if it stayed in the refrigerator for only a short time?). If they suggest the water is coming from inside the glass, they can vary what is inside the class (water, alcohol or other liquid, solid block of plastic or metal) to see if it still occurs. If they then conclude that the water is coming from water vapor in the air, they can test that hypothesis by repeating the experiment under different conditions (one in which they place the cold container in warm air, and another in which they place it in a contained filled with helium).

Interpretation. The literature shows (Johnson, 1998; Lee et al., 1993) that many students are mystified by this phenomenon but that a condensation interpretation can be scaffolded into this investigation. The most prevalent, first interpretation, is that water seeps through the wall of the glass, or evaporates from the inside and condenses on the outside. This investigation combines multiple practices: hypothetical thinking, hypothesis testing, modeling, applying conservation principles; and understanding of phase change.

Conclusion

We began this paper with a concern—that many classroom and large-scale assessments focus on school tasks that children do not connect with their life experiences. These assessments encourage teachers to focus on memorization and recitation of science facts and procedures. We asserted that research on children's learning provides valuable tools and strategies for developing different kinds of large-scale and classroom assessments that reveal students' ways of thinking about the world.

We also suggested that there are principled methods for developing standards-based assessments that use tools and strategies from research on children's learning. We suggested that those methods included two broad stages, each including several steps; these stages are *elaborating standards* and to *designing and interpreting assessments.* After describing those steps in some detail, we developed examples around an important topic in the school curriculum: matter and atomic molecular theory.

In developing our examples we have tried to be transparent about our reasoning at each step in the development process—from national standards to elaborated standards to learning performances to assessment items and interpretations—and about the contributions that research on children's learning can make at each step. We hope that this transparency will provide evidence that the sample items we have included are representative of much larger pools of items that could be developed using similar methods and a broader sampling of the research base.

We believe that classroom and large-scale assessments developed using these methods would have three important qualities missing from most current assessments:

- *Clear principles for content coverage.* Because the assessments are organized around big ideas embodied in key scientific practices, their organization and relationship to themes in the curriculum will be clearer. Rather than sampling randomly or arbitrarily from a large number of individual standards, assessments developed using these methods can predictably include items that assess students' understanding of the big ideas and scientific practices.

- *Clear relationships between standards and assessment items.* Because the reasoning and methods used at each stage of the development process is explicit, the interpretation of standards and the relationships between standards and assessment items is clearer. The relationship between standards and assessment items is made explicit and thus subject to scrutiny.
- *Providing insights into students' thinking.* The assessments and their results will help teachers to understand and respond to their students' thinking. For this purpose the interpretation of student responses is critically important, and reliable interpretations require a research base. Thus developing items that reveal students' thinking is far easier for matter and atomic molecular theory than it is for other topics with less extensive research bases.

For assessors whose primary concern is evaluation and accountability, these qualities may not seem as important as some other qualities, such as efficiency and reliability. We believe, though, that assessments with these qualities are essential for the long-term improvement of science education.

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Appendix A: Versions of Big Ideas for Secondary Students

Students at the high school level can extend their experiences to a wider range of chemical materials and reactions, and can investigate them with new techniques that reveal the specific chemical composition of many materials. They can distinguish ionic from covalent bonds, and they can distinguish the physical and chemical properties of compounds with different kinds of bonds. They can use chemical formulas to represent the composition of a variety of substances and chemical equations to represent a variety of chemical changes. This level of understanding, though far from "complete," provides students with a coherent picture of the nature of materials and the conceptual tools for understanding a wide range of systems and phenomena in the life, earth, and physical sciences.

M1. Macroscopic Properties

- There are **properties** that characterize all **matter**, **specific materials,** and **phases of matter** that can be quantified and related.
  - **Materials** have **characteristic properties** such as density, boiling points, melting points, and spectroscopic analysis, and in their combination with other materials, such as solubility, chromatographic analysis, and sensory impressions upon combination with other materials.
  - Matter exists in three general phases **solid, liquid, and gas** that vary in their properties and can be interconverted with changes in temperature, volume, and pressure.

M2. Macroscopic Conservation

- **Matter is conserved** across both chemical and physical changes.
  - **Conservation of mass** can be expressed as evidence consistent with the **conservation of particles** (atoms and molecules).
  - In a **chemical reaction**, the sum of the mass of the reactants equals the sum of the mass of the products.
  - Upon simple **mixing**, the sum of the combined masses equals the mass of the combination.
  - **Changes in state**, including phase changes, do not result in changes in mass.

AM1. Atomic-molecular theory

- **The basic tenets of the atomic/molecular model are:**
  - All matter is made up of discretely spaced particles (called **atoms**), which are far too small to see directly through a optical microscope. There are empty spaces (**vacuum**) between atoms. Atoms are comprised of sub-atomic particles.
  - Sub-atomic particles within atoms, and atoms within molecules, are held together by electromagnetic **forces**.
  - Each atom takes up space, has **mass**, and is in perpetual **motion** above absolute zero.

- There are over a hundred **different kinds** of atoms. Each kind has distinctive properties, including mass and the way it combines with other atoms or molecules.
- **Electronic configuration**, in combination with the regular and integral build-up of **protons** in the **nucleus**, accounts for **atomic identity** and the **periodic law.**
- Atoms can be joined (in different proportions) to form molecules or networks--a process that involves forming **chemical bonds** between atoms. Molecules have different characteristic properties from the atoms of which they are composed.
- **Chemical formulas** can be used to represent the specific chemical composition of compounds.

AM2: Atomic-molecular explanation of materials

- **Macroscopic properties can be explained in terms of atoms and molecules.**
  - Some substances (**elements)** are composed of just one kind of atom. Other substances (**compounds**) are composed of clusters of atoms bound together.
  - **Ionic compounds** are comprised of two or more atomic or molecular ions in a regular network known as a lattice.
  - **Covalent compounds** are discrete molecular entities comprised of two of more atoms with definable connectivity, and local and global geometries.
  - Atomic and molecular motion is expressed in terms of **translation**, **vibration**, and **rotation**.

AM3: Atomic-molecular explanation of transformations

- **Macroscopic transformations can be explained in terms of atoms and molecules**.
  - Changes in matter include **physical changes**, in which molecules change arrangement and/or motion but remain intact, and **chemical changes**, in which atoms are rearranged into new molecules but remain intact.
  - **Chemical equations** can be used to represent how atoms are rearranged into new molecules in chemical changes
  - Chemical changes are accompanied by changes in **spectroscopic**, c**hromatographic**, physical, and/or chemical properties.
  - Within a phase, adding or removing heat modifies the speed of atoms or molecules, but not their type of motion. During phase change, adding or removing heat causes a change in type of motion but not average speed.

AM4: Distinguishing data from atomic-molecular explanations

- The atomic/molecular model is based on a small set of postulates that explain a large number of macroscopic properties and transformations**. Not all macroscopic properties apply to individual atoms.** For example:
  - At the atomic-molecular level, matter is discrete although macroscopically it appears continuous.
  - Although elements, compounds, and mixtures can look equally homogeneous at the macroscopic level, they can be distinguished at the atomic-molecular level.

- Results from chromatographic, spectroscopic, and analytical experiments result from the average and/or aggregate behaviors of large numbers of atoms and molecules.
- Although atoms and molecules share the properties of having mass and weight and occupying space, other macroscopic properties, such as hardness, color and fluidity, do not apply to them but can be accounted for with the atomic-molecular model.

Appendix B: Review of Research Tables

In this Appendix, we reproduce slightly adapted Tables 1 and 2 of our Interim Report that summarize some of students' major alternative ideas about matter at atomic/molecular and macroscopic levels respectively. Each table also identifies possible reasons for each kind of alternative conception and references representative studies that support particular claims. The research in this area is vast, and our review is by no means complete. We have, however, tried to identify the major alternative conceptions that have been widely reported in the literature. These tables along with the findings of studies of innovative approaches to teaching are more fully discussed in the Research Review section of that Interim Report. The interested reader is urged to read that entire section of the Interim Report.

We believe this research allows us to understand not only why traditional instructional approaches have been largely unsuccessful but also why it is reasonable to expect that students *can* succeed in developing these understandings with more "enlightened" instructional approaches. An important message that comes from reviewing these studies is that developing macroscopic, epistemic, and atomic-molecular understandings of matter are inter-linked and that successful curricula efforts need to appreciate these linkages and work on multiple levels in order to bring about change.

Table 1. Some Major Types of Misconceptions About Atoms and Molecules

Types of Misconception	Specific Examples	Possible Reasons for Misconceptions:
Confusions about status as fundamental constituents: • Atoms and molecules are not matter itself • Atoms and molecules are not pre-existing units • Atoms and molecules are "air" or "gas"	• *Molecules-in-Matter Model* (e.g., Molecules are air-like things one finds in substances; Molecules of X are embedded in continuous X or in generic substance; Molecules go in and out of substances) (2) (22) • *Atoms as Emergent Bits, not Pre-existing Particles* (e.g., some students believe atoms are the final outcome of repeated division, not pre-existing units; so they can be square or rectangular, depending on how you cut; and there are no spaces between them (34))	• Believe that matter is fundamentally continuous (29) • Molecules are said to be invisible; air is invisible; hence molecules are like air (2) • How can matter (which is perceptible) be made of something that is not? • Told that molecules escape from liquid when heated and "see" steam escaping; this generates a perceptual/conceptual schema of molecules as things that can move in and out of substances that continue to exist (2)
Confusions about what macro properties are applied to micro level: • Inappropriately apply some macro level properties to micro level • Inappropriately fail to apply others	*Macro properties misapplied to micro level* • Atoms have color, squishiness, can melt, be liquid, solid or gaseous, hot or cold (27).(5) (38) • Atoms disappear during burning (like macro matter appears to) (1) • Molecules are unchangeable (as middle school students assume substances are) (1) • Molecules are modified (like substances): molecules of rusted iron have an iron center and rust on outside (1) *Properties not applied to micro level* • Atoms not in constant motion (30) (42) • Atoms don't have mass/weight	▪ This widespread type of misconception may be due to a lack of distinction between model and observations, and hence epistemological in origin (1) (27) • Alternatively, it may be due to a continuous view of matter; if molecules are what you get when you cut matter, it will inherit its properties • Still another possibility is that students need more knowledge of the mechanisms accounting for macro properties in terms of the model (e.g., how color can emerge from non color, hotness from non hotness) (55) • Failure to attribute weight to atoms probably reflects alternative concepts of weight as felt weight (46)

Table 1

Misconceptions about Atoms and Molecules

Types of Misconception	**Specific Examples**	**Possible Reasons for Misconceptions:**
Confusions about size and scale of atoms/molecules: • Atoms can be seen with microscope (26) • Resist acknowledging spaces between atoms	• The "molecell" concept: confuse atoms/molecules and cells (16) • May think of atoms as stacked next to each other in all states, with no spaces (1) (34) • Alternatively they may believe gaps between atoms in liquid are larger than in solid (1) (42)	• Language used during instruction: both cells and atoms have "nucleus" and both are described as fundamental building blocks; use of the word "microscopic" may imply can see with microscope • General difficulties with scale: needs for anchors (42) • Metaphysical difficulties (idea of vacuum difficult) • Continuous view of matter: no spaces is a way to assimilate "atoms" to continuous view of matter • Lack of relevant knowledge about the behavior of gases (30) • Failure to differentiate density and viscosity or runniness; lack of relevant knowledge of the comparative densities of solids and liquids • Misplaced need for order: change from solid, liquid, to gas, corresponds to larger and larger distances between molecules
Confusions about the relation between atoms and molecules	• Molecules keep their identity during chemical change (1) • Molecules of water become atoms of hydrogen when water boils	• Lack of differentiation between chemical and physical changes • "Hyperconservation" of substance

Table 2. Summary of Some Major Alternative Macroscopic Understandings

Macroscopic Aspect	Alternative Conceptions	Possible Reasons for Alternative Conceptions
Nature of matter	• Classification is based on sensory or irrelevant properties (e.g., something that you can see or feel rather than something that takes up space and has mass). [6, 22, 44, 46, 52] • Instances are incorrectly classified. (e.g., may exclude gases, dust particles, or tiny invisible pieces; may include forms of energy such as heat or electricity) [6, 22, 44, 46, 52] • Non conservation: Matter can disappear with repeated division, dissolving, evaporation, or chemical change [1, 3-4, 17, 22, 43-46, 52]	• Primacy of sense experiences and alternative conceptions of taking up space and having weight based on sensory perceptions [6, 44, 46] • Lack of knowledge of measurement procedures for physical quantities [44] • Lack of knowledge of the behavior and properties of gases [30, 31] • Lack of knowledge of atoms and molecules as underlying constituents • Alternative epistemological commitments: no clear distinction between theory and evidence; focus on observables
Nature of material kinds	• May confuse objects and materials [20, 53] • Identified by large-scale perceptual properties (e.g., color, texture, shininess, taste) [11, 45, 53] • Identity of materials is transformed during physical change (e.g., wax melts and becomes water; water evaporates and becomes air)[1, 3, 22] • Tend to think of everyday materials as single substances (rather than mixtures); does not distinguish elements (nondecomposable materials) and compounds (decomposable materials) [56]	• Primacy of sense experiences and use of these properties to distinguish materials • Lack of knowledge of other distinguishing properties of materials (e.g., melting points, boiling points, density, solubility) • Lack of knowledge of how to explain change in physical properties without assuming disappearance of substance (e.g., in terms of limits of sensory systems) • Lack of knowledge of atoms and molecules as entities that can be conserved across physical transformations and that participate in chemical reactions

Macroscopic Aspect	Alternative Conceptions	Possible Reasons for Alternative Conceptions

Nature of gases	• Gases are not clearly conceptualized either as matter or as a state of matter; instead:
	  • Gases are "fumes"/ethereal, noncorporal [22,52]
	  • Conflates air/nothingness [29, 30]
	• Do not assume that gases are homogeneously distributed in a space (i.e., gases move from one place to another and are not evenly distributed) [29,30]
		• Alternative conceptions of matter, space, and weight and fact that they can't see, touch, or feel gases and that can move through them [44]
		• Lack of knowledge of atoms and molecules
		• Lack of understanding of sensory systems: how something could exist but not be detectable by senses
		• Epistemological issues: Invisibility of gases means that one must determine their properties indirectly rather than directly

Nature of Weight[8]	• Weight is not conceptualized as a fundamental property of matter: [43-46]
	  • some objects can weigh nothing at all;
	  • weight is an emergent property: the weight of the whole is not a function of the weight of the parts
	• Felt weight is a reliable measure of weight [43-46]
	• Conflates intensive and extensive aspects of weight (i.e., heavy and heavy for size) and considers the weight of objects and substances (i.e., steel is heavy stuff) [18, 36, 45, 46]
	• Weight can change with phase change [50]
		• Alternative conceptions of matter and space
		• Epistemological and metaphysical commitments: reliance on senses rather than mathematics and use of idealization
		• Lack of knowledge of weight measurement [44]
		• Limitations in concept of number as counting number and lack of differentiation of division from repeated subtraction restricts their understanding of fractional measurements and very small numbers [43]
		• Lack of knowledge of how senses work: that would explain why not a reliable measure
		• Lack of knowledge of atoms and molecules as small constituents that have weight

[8] We use the word "weight" in this table, not mass, because that is the word students first use and the one that has typically been used in interviewing students in grades K-8. When the word "mass" is introduced in middle school, it is typically defined as a measure of "the amount of matter" in an object. Students are often initially confused by this term, not knowing whether the "amount of matter" relates to their idea of volume, weight, or some combination of the two. They often end up, however, mapping it onto their concept of weight that combines elements from the physicist's notion of mass and weight. Students come to differentiate their concepts of weight and mass as they develop an understanding of gravitational attraction.

Table 2

Alternative Macroscopic Understandings

Macroscopic Aspect	Alternative Conceptions	Possible Reasons for Alternative Conceptions
Nature of Space	• Space is occupied space (not abstracted from matter; assumed to be best measure of amount of matter); can't conceive of empty space [30] • Space is judged as global bigness, different dimensions (i.e., length, width, depth) not distinguished; different measures of spatial extent (length, area, surface area, volume) are also not distinguished [24, 44] • Water displacement is a function of weight (not volume) [36, 39]	• Alternative sensory based conceptions of matter and weight [44] • Limitations in conceptions of number (numbers are discrete; does not differentiate division from repeated subtraction) and understanding of measurement [43] • Epistemological and metaphysical commitments: reliance on senses rather than mathematics and use of idealization • Lack of understanding of atoms & molecules
Thermal Expansion	• Substances (especially solids) "shrivel up" when heated [22] • Expansion of gases is explained in terms of movement of air (hot air rises) [22]	• Lack of understanding of atoms and molecules as in constant motion [30] • Alternative conceptions of matter and gases
Dissolving	• The solute "disappears", "melts", or "evaporates" [1, 22]	• Alternative conceptions of matter in terms of perceptual properties [22] • Lack of understanding of entities (e.g., atoms) conserved across physical transformations [22]
Phase Change	• No recognition of water vapor in air ; Liquid water changes into air; wax becomes water [3, 22] • Condensation is reaction between heat and coldness [22, 32]	• Alternative conceptions of matter, gases, and substances • Lack of knowledge of atoms and molecules • "Water" may be synonym for liquid
Chemical Change	• Conflates chemical and physical change (i.e., ice melting is chemical change; burning is like evaporation but faster) [1, 53] • Identifies based on unusual or dramatic event (e.g., fizzing, explosion, change in color or mass); involves nonconservation of mass [13, 17] • Does not involve change in material kind [1, 17]	• Alternative concepts of matter and weight • Epistemic ideals: prefers explanations in terms of everyday analogies (rusting is like decay) to unseen events or changes [17] • Lack of knowledge of atoms and molecules • Overgeneralization once develops idea of conservation of substance in phase change[17]

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