9

INTEGRATING THE THREE DIMENSIONS

This framework is designed to help realize a vision of science education in which students' experiences over multiple years foster progressively deeper understanding of science. Students actively engage in scientific and engineering practices in order to deepen their understanding of crosscutting concepts and disciplinary core ideas. In the preceding chapters, we detailed separately the components of the three dimensions: scientific and engineering practices, crosscutting concepts, and disciplinary core ideas. In order to achieve the vision embodied in the framework and to best support students' learning, all three dimensions need to be integrated into the system of standards, curriculum, instruction, and assessment.

WHAT INTEGRATION INVOLVES

The committee recognizes that integrating the three dimensions in a coherent way is challenging and that examples of how it can be achieved are needed. We also acknowledge that there is no single approach that defines how to integrate the three dimensions into standards, curriculum, instruction, and assessment. One can in fact envision many different ways to achieve such integration, with the main components of the framework being conveyed with a high degree of fidelity, but with different choices as to when to stress a particular practice or crosscutting idea. For these reasons, in this chapter we offer only preliminary examples of the type of integration we envision, noting that the development of standards, curriculum, instruction, and assessment that successfully integrates the three dimensions is an area ripe for research and innovation.

Because standards guide and shape curriculum, instruction, and assessment, the task of integrating the three dimensions of the framework for K-12 science education begins with the development of standards. A major task for developers will be to create standards that integrate the three dimensions. The committee suggests that this integration should occur in the standards statements themselves and in performance expectations that link to the standards.

Standards and performance expectations that are aligned to the framework must take into account that students cannot fully understand scientific and engineering ideas without engaging in the practices of inquiry and the discourses by which such ideas are developed and refined [1-3]. At the same time, they cannot learn or show competence in practices except in the context of specific content. For example, students ask questions or design investigations about particular phenomena, such as the growth of plants, the motion of objects, and the phases of the moon. Furthermore, crosscutting concepts have value because they provide students with connections and intellectual tools that are related across the differing areas of disciplinary content and can enrich their application of practices and their understanding of core ideas. For example, being aware that it is useful to analyze diverse things—such as the human body or a watershed—as systems can help students generate productive questions for further study. Thus standards and performance expectations must be designed to gather evidence of students' ability to apply the practices and their understanding of the crosscutting concepts in the contexts of specific applications in multiple disciplinary areas.

In the committee's judgment, specification of "performance expectations" is an essential component of standards. This term refers to statements that describe activities and outcomes that students are expected to achieve in order to demonstrate their ability to understand and apply the knowledge described in the disciplinary core ideas. Following the model of the College Board's *Science Standards for College Success*, we agree that "performance expectations specify what students should know, understand, and be able to do. . . . They also illustrate how students engage in science practices to develop a better understanding of the essential knowledge. These expectations support targeted instruction and assessment by providing tasks that are measurable and observable" [4].

In this chapter we provide two examples of how the three dimensions might be brought together in performance expectations. The first example is based on a component of one of the core ideas in the life sciences (see Table 9-1), the other on a component of a core idea in the physical sciences (see Table 9-2).

The three dimensions will also need to be integrated into curriculum and instruction. A detailed discussion of all the ways in which practices, crosscutting concepts, and disciplinary core ideas can be integrated into curriculum and instruction is beyond the scope of the framework. However, in addition to the examples of performance expectations presented in Tables 9-1 and 9-2, we provide a single example that shows first steps toward this kind of integration. This example, which draws on the first component of the first physical science core idea—PS1.A: Structure and Properties of Matter—shows how a disciplinary core idea can be developed using particular practices and linked to particular crosscutting concepts for each grade band. It also describes some of the ways in which students might be asked to use specific practices to demonstrate their understanding of core ideas. Finally, the example incorporates boundary statements that make explicit what is *not* expected of students at a given level. The committee recommends that boundary statements be incorporated into standards so as to provide guidance for curriculum developers and designers of instruction. Such boundaries serve two purposes: (1) to delimit what level of detail is appropriate and (2) to indicate what knowledge related to a core idea may be too challenging for all students to master by the end of the grade band. However, any boundaries introduced here or in the specification of performance expectations will need to be subjected to further research and revisited over time, as more is learned about what level of expectation is appropriate in the context of curricula and instruction of the type envisaged in this framework.

It is important to note that this example is not intended as a complete description of instruction but only as a sketch of some experiences that can support learning of the core idea component. It illustrates how the practices both help students learn and provide a means by which they can demonstrate their understanding.

TWO ILLUSTRATIONS OF PERFORMANCE EXPECTATIONS

Two examples in this section illustrate how the three dimensions can be integrated into performance expectations. Table 9-1 presents the first example, which is based on a component—Organization for Matter and Energy Flow in Organisms (LS1.C)—of the first core idea in the life sciences. Table 9-2 presents the second example, which is based on a component—Structure and Properties of Matter (PS1.A)—of the first core idea in the physical sciences.

TABLE 9-1 Sample Performance Expectations in the Life Sciences

LS1. C: ORGANIZATION FOR MATTER AND ENERGY FLOW IN ORGANISMS			
	By the End of Grade 2	**By the End of Grade 5**	
Tasks	Classify animals into two groups based on what they eat, and give three or more different examples of animals in each group.	Explain how animals use food and provide examples and evidence that support each type of use.	
Criteria	Students should identify at least two of the three groups of animals (plant eaters, those that eat other animals, and those that eat both plants and other animals). The animals offered as examples should be correctly grouped. Students should be asked to offer evidence that supports the claim that these animals belong in the groups they have placed them in and asked to also consider and include animals from classes they have neglected (e.g., birds or fish, if they interpret animal to mean mammal).	A full explanation should be supported by diagrams and argument from evidence. It should include and support the claims that food provides materials for building body tissue and that it is the fuel used to produce energy for driving life processes. An example of building materials should include reference to growth and repair. Evidence for growth and repair should include use of some of food's weight in the process of adding body weight or tissue. An example of use of energy should include internal motion (e.g., heartbeat), external motion (self-propulsion, breathing), or maintenance of body temperature. Evidence for energy use should refer to the need for energy transfer in performing the activity. (At this level, detail is not expected on how food is actually used to provide energy.)	

	By the End of Grade 8	By the End of Grade 12
	Construct an explanation for why the air a human breathes out contains a lower proportion of oxygen than the air he or she breathed in. The explanation should address where in the body the oxygen was used, how it was used, and how it was transported there.	Construct a model that describes the aerobic chemical processes that enable human cells to obtain and transfer energy to meet their needs.
	A full explanation should contain a claim that oxygen's use in all cells of the body is part of the chemical reaction that releases energy from food. The claim should be supported with reasoning about (1) the role of oxygen in chemical reactions' release of energy and (2) how the oxygen and food are transported to the cells through the body's respiratory and circulatory systems.	The model should include diagrams and text to indicate that various compounds derived from food—including sugars and fats—react with oxygen and release energy either for the cells' immediate needs or to drive other chemical changes. It should include the example of producing adenosine triphosphate (ATP) from adenosine diphosphate (ADP) and indicate that this process increases stored energy. It should show that subsequent conversions between ATP and ADP release stored energy, for example, to cause contraction of muscles.

TABLE 9-1 Continued

LS1. C: ORGANIZATION FOR MATTER AND ENERGY FLOW IN ORGANISMS		
	By the End of Grade 2	**By the End of Grade 5**
Disciplinary Ideas	All animals need food in order to live and grow. They can get their food from plants or from other animals.	All living organisms require energy. Animals and plants alike generally need to take in air and water, animals must take in food, and plants need light and minerals; anaerobic life, such as bacteria in the gut, functions without air. Food provides animals with the materials they need for body repair and growth and is digested to release the energy they need to maintain body warmth and for motion.
Practices	Presenting information (e.g., orally, visually by sorting pictures of animals into groups, or by writing labels or simple sentences that describe why animals are in different groups). Argument from evidence: supporting placement of animals in group.	Argumentation: Supporting claims with evidence.
Crosscutting Concepts	Patterns: Grouping of animals by similarity of what they eat.	Patterns, similarity, and diversity: Living organisms have similar needs but diverse ways of obtaining food. Matter conservation.

	By the End of Grade 8	By the End of Grade 12
	Through the process of photosynthesis, plants, algae (including phytoplankton), and many microorganisms use the energy from light to make sugars (food) from carbon dioxide from the atmosphere and water. This process also releases oxygen gas. These sugars can be used immediately or stored for growth or later use. Animals obtain food from eating plants or eating other animals. Within individual organisms, food moves through a series of chemical reactions in which it is broken down and rearranged to form new molecules, to support growth or to release energy. In animals and plants oxygen reacts with carbon-containing molecules (sugars) to provide energy and produce waste carbon dioxide; anaerobic bacteria achieve their energy needs in other chemical processes that do not need oxygen.	The process of photosynthesis converts light energy to stored chemical energy by converting carbon dioxide and water into sugars plus released oxygen. The sugar molecules thus formed contain carbon, hydrogen, and oxygen, and they are used to make amino acids and other carbon-based molecules that can be assembled into the larger molecules (such as proteins or DNA) needed to form new cells. As matter and energy flow through different organizational levels of living systems, chemical elements are recombined in different ways to form different products. As a result of these chemical reactions, energy is transferred from one system of interacting molecules to another. For example, aerobic cellular respiration is a chemical process whereby the bonds of food molecules and oxygen molecules are broken and new compounds are formed that can transport energy to muscles. Anaerobic cellular respiration follows a different and less efficient chemical pathway to provide energy in cells. Cellular respiration also releases the energy needed to maintain body temperature despite ongoing energy loss to the surrounding environment. Matter and energy are conserved in each change. This is true of all biological systems, from individuals to ecosystems.
	Constructing explanations. Argument (supporting proposed explanation with arguments from evidence).	Modeling Presenting information (using labeled diagrams and text to present and explicate a model that describes and elucidates the process in question).
	Cause and effect: Oxygen is needed for the chemical reaction that releases energy from food. Matter cycles and conservation; energy flows and conservation. Systems: Roles of respiratory and circulatory systems.	Systems: Organisms have systems for processes at the cellular level that are used to carry out the functions needed for life. Matter cycles and conservation; energy flows and conservation.

TABLE 9-2 Sample Performance Expectations in the Physical Sciences

PS1.A: STRUCTURE AND PROPERTIES OF MATTER			
	By the End of Grade 2	**By the End of Grade 5**	
Tasks	Students support claims as to whether something is a solid or a liquid by providing descriptive evidence. Note: It is inappropriate at this grade level to use a material, such as sand, that is made of visible scale particles but flows as the test material for this question. Test examples should be readily classifiable.	Students provide strategies for collecting evidence as to whether matter still exists when it is not visible.	
Criteria	Descriptive evidence that a material is a solid would include the object's definite shape; for a liquid it would be that the material takes the shape of the container or that the material flows to the lowest part of the container.	Design includes ways to measure weight with and without an invisible material (gas or solute) present. For example, weighing the same container with different amounts of air, such as an inflated and deflated balloon or basketball; or weighing pure water and sugar before and after the sugar is dissolved in the water. (At this level, detail is not expected on how food is actually used to provide energy.)	

	By the End of Grade 8	By the End of Grade 12
	Students create atomic and molecular models to explain the differences between the solid, liquid, and gaseous states of a substance.	Students first develop models that describe a neutral atom and a negative or positive ion. They then use these models to describe the similarities and differences between the atoms of neighboring elements in the periodic table (side by side or one above the other).
	The model should show that atoms/molecules in a solid (1) are close together, (2) are limited in motion but vibrate in place, and (3) cannot move past or around each other and thus are fixed in relative position. The model should also show that atoms/molecules in a liquid (1) are about as close together as in a solid, (2) are always disordered, (3) have greater freedom to move than in a solid, and (4) can slide past one another and move with a range of speeds. Finally, the model should show that atoms/molecules in a gas (1) are much farther away from each other than in solid or liquid form, (2) are always disordered, (3) move freely with a range of speeds, and (4) sometimes collide with each other or the container's walls and bounce off.	The models should show that the atom consists of an inner core called the nucleus, which consists of protons and neutrons; that the number of protons in the nucleus is the atomic number and determines the element; that the nucleus is much smaller in size than the atom; that the outer part of the atom contains electrons; that in a neutral atom, the number of electrons matches the number of protons (because protons and electrons have an opposite electric charge); and that ions have an additional or a "missing" electron. Different isotopes of a given element have different numbers of neutrons, but in all stable cases the number of neutrons is not very different from the number of protons.

TABLE 9-2 Continued

PS1.A: STRUCTURE AND PROPERTIES OF MATTER			
	By the End of Grade 2	**By the End of Grade 5**	
Criteria continued			
Disciplinary Ideas	Different kinds of matter exist (e.g., wood, metal, water). Solids and liquids have different properties, which can be used to sort them. Some substances can be either solid or liquid, depending on the temperature. Substances can be observed, weighed, and measured in other ways.	Matter of any type can be subdivided into particles (tiny pieces) that are too small to see, but even then the matter still exists and can be detected by other means (such as through its effects on other objects). Gases are matter in which the gas particles are moving freely around in space and can be detected by their impacts on surfaces (e.g., of a balloon) or on larger and visible objects (wind blowing leaves, dust suspended in air). The amount (weight) of matter is conserved when it changes form, even in transitions in which it seems to vanish (e.g., sugar in solution).	

	By the End of Grade 8	By the End of Grade 12
		The electrons occupy a set of "layered" states, with a given number allowed in each of the first few layers. (Details of orbitals and reasons behind the counting of states are not expected.) The "outermost" position of the electrons corresponds to the least strongly bound electrons. The filling level of the outermost layer can be used to explain chemical properties and the types of ions most readily formed. Atoms side by side in the periodic table are close to each other in mass and differ by one in their numbers of protons. They have different chemical properties. Atoms above or below the other in the periodic table have similar chemical properties but differ significantly in mass and atomic number.
	Gases and liquids are made of molecules or inert atoms that are moving about relative to each other. In a liquid, the molecules are constantly in contact with others; in a gas they are widely spaced except when they happen to collide. In a solid, atoms are closely spaced and may vibrate in position but do not change relative locations. Solids may be formed from molecules or may be extended structures with repeating subunits (e.g., crystals, metals). The changes of state that occur with changes of temperature or pressure can be described and predicted using these three models (solid, liquid, or gas) of matter. (Predictions here are qualitative, not quantitative.)	Each atom has a charged substructure consisting of a nucleus (made from protons and neutrons) surrounded by electrons. The periodic table orders elements by the number of protons in the atom's nucleus and places those with similar chemical properties in columns. The repeating patterns of this table reflect patterns of outer electron states.

TABLE 9-2 Continued

PS1.A: STRUCTURE AND PROPERTIES OF MATTER			
	By the End of Grade 2	By the End of Grade 5	
Practices	Argumentation (e.g., using criteria for solids and liquids to make the case that a substance is one or the other).	Designing investigations.	
Crosscutting Concepts	Patterns (a great diversity of solid and liquid materials exist, but certain features are similar for all solids and all liquids).	Matter cycles and conservation.	

The performance expectations shown in these tables describe what students are expected to know and how they should be able to use these two scientific ideas. In each table, the first two rows describe the tasks that students are expected to perform and the criteria by which their performance will be evaluated. The last three rows in the tables show the disciplinary ideas, practices, and crosscutting concepts that are to be brought together in performing the tasks. Examples are shown for four grade levels (2, 5, 8, and 12) to illustrate how the performance expectations should increase in sophistication during 12+ years of instruction. Across such a span, with appropriate learning experiences, students' conceptual knowledge increases in depth and sophistication, as does the nature of the practices. Thus performance expectations at the higher grades should reflect deeper understanding, more highly developed practices, and more complex reasoning.

Note that what we describe in Tables 9-1 and 9-2 is just an initial illustration of the performance expectations for each grade band. When standards are developed that are based on the framework, they will need to include performance expectations that cover all of the disciplinary core ideas, integrate practices, and link to crosscutting concepts when appropriate. For any given aspect of content knowledge, multiple practices and crosscutting concepts could be matched to that content to yield additional appropriate performance expectations. Assessments

	By the End of Grade 8	By the End of Grade 12
	Modeling Developing evidence-based explanations.	Modeling
	Cause and effect: Changing the temperature causes changes in the motion of particles of matter. Systems and system models: Students model substances as systems composed of particles.	Structure and function: Atoms have structures that determine the chemical behavior of the element and the properties of substances. Patterns, similarity, and diversity: The periodic table can be used to see the patterns of chemical behavior based on patterns of atomic structure.

should thus use a broad set of performance expectations across the multiple items. In addition, the criteria used to judge the quality of a given performance outcome need to specify the features of the practice (e.g., a description, model, evidence-based explanation) that are relevant for the specific content and grade band.

As discussed in Chapter 4, the expectations regarding how the practices develop over the grade bands reflect an increasing competence in the use of information and the assembly of models, descriptions, explanations, and arguments. For some further examples of performance expectations that link content and practice similarly and that are appropriate for formulating both classroom-based and large-scale assessments of whether students have mastered particular standards, we refer the reader to the College Board's *Science Standards for College Success*. That volume provides numerous examples in the life sciences, physical sciences, and earth sciences [4].

ONE ILLUSTRATION OF INTEGRATING THE DIMENSIONS INTO CURRICULUM AND INSTRUCTION

This section describes through example how the three dimensions might be brought together in designing curriculum and instruction. The particular example involves the development of the Structure and Properties of Matter (PS1.A)—a component of the physical sciences core idea Matter and Its Interactions—through the integration of practices and crosscutting concepts (see Box S-1). The example illustrates, however, only one of many paths that integrate the practices and crosscutting concepts in developing this component idea, and thus it is not intended to be prescriptive. Rather, the committee emphasizes that there are many different ways to explore the disciplinary core ideas through the practices and crosscutting concepts but that such exploration is critical to aid student's development and support the deep conceptual change needed to move their understanding of the world closer to that of well-established scientific understandings.

The central question of PS1.A is "How do particles combine to form the variety of matter one observes?" In the design of curriculum and instruction regarding answers to this question, four of the crosscutting concepts (flagged in italics below) play important roles. First, across all grade levels, the relationship of *structure and function* is a key concept in studying how the structure of matter relates to the properties of matter. Second, the concept of *patterns* can be explored from the earliest grades as students investigate the various types of matter, discover their commonalities, and devise ways of characterizing their properties. Third, starting in grades 3-5 and continuing through grade 12, students work with the concept of *systems and system models* as they cultivate their understanding of the particle model of matter; students progress from the macroscopic idea of particles to imagine and model the effects of invisibly small particles (in grades 3-5) to the atomic scale (in grades 7-8) and finally to the subatomic scales (in grades 9-12). Fourth, as students encounter the notion that matter is conserved, critical to their understanding is the crosscutting concept of *energy and matter: flows, cycles, and conservation*.

The narrative for each grade band begins with a statement of the grade band endpoint ("By the end of . . ."), and the succeeding text elaborates on the grade band progression of learning that builds toward that endpoint; discussion shows how the progression involves both crosscutting concepts that students come to appreciate and practices in which they might engage as they develop and demonstrate their understanding. The discussion is followed by a boundary statement, which specifies things that do *not* need to be included in the grade band. Standards developers also should include such boundaries so as to delimit how far students, of whatever grade, are expected to progress.

Grades K-2: Endpoint and Progression

By the end of grade 2. Different kinds of matter exist (e.g., wood, metal, water), and many of them can be either solid or liquid, depending on temperature. Matter can be described and classified by its observable properties (e.g., visual, aural, textural), by its uses, and by whether it occurs naturally or is manufactured. Different properties are suited to different purposes. A great variety of objects can be built up from a small set of pieces. Objects or samples of a substance can be weighed and their size can be described and measured. (Boundary: Volume is introduced only for liquid measure.)

Students' investigations of matter begin with guided experiences, designed by the teacher, that introduce them to various kinds of matter (e.g., wood, metal, water, clay) in multiple contexts and engage them in discussion about the matter's observable characteristics and uses. These experiences begin to elicit students' questions about matter, which they answer by conducting their own investigations and by making observations; the path of the investigation is jointly designed by teacher and students. Observations here include not only how things look but also how they feel, how they sound when tapped, how they smell, and, in carefully structured situations such as a cooking project, how they taste (although students should be warned not to taste unknown substances).

In the course of these experiences the teacher engages and guides students in identifying multiple ways of characterizing matter—such as solid and liquid, natural and manufactured, hard and soft, edible or inedible—and that different types of materials are suited to different uses. Across grades K-2, the variety of properties of matter that students recognize and the specificity with which they can characterize materials and their uses develop through experiences with different kinds of matter.

The ability to make measurements of quantities, such as length, liquid volume, weight, and temperature, begins in kindergarten with qualitative observations of relative magnitude. An understanding both of the arbitrariness and the importance of measurement units is supported by allowing students to develop their own units for length before introducing them to standard units. After students observe and measure a variety of solids and liquids, classroom discussions help them focus on identifying and characterizing the materials that objects are made from and the reasons why particular materials are chosen for particular tasks. Students are then asked to present evidence to support their claims about different kinds of matter and their uses. Across the grade span, students progress in their ability to make and justify claims about different kinds of matter, to describe and quantify those claims, and to do so both with specificity and knowledge of the various properties of matter.

Starting in kindergarten (or before), students manipulate a variety of building toys, such as wooden blocks, interlocking objects, or other construction sets, leading them to recognize that although what one can build depends on the things one is building from, many different objects can be constructed with multiple copies of a small set of different components. Although such recognition occurs implicitly, it is supported at the higher end of the grade band by explicit discussion of this aspect of material objects. Students come to understand more deeply that most objects can be broken down into various component pieces and that any "chunk" of uniform matter (e.g., a sheet of paper, a block of wood, a wedge of cheese) can be subdivided into smaller pieces of the same material.

Students' building efforts progress from free play to solving design problems, and teachers facilitate this progression by asking appropriate questions about the objects that students build, by having them draw diagrams of what they have built, and by directing their attention to built objects outside the classroom (so as to discuss what these objects are built from or features of their design). By grade 2, a student should be able to follow a plan, preplan designs for simple projects, and recognize the common design elements of certain types of objects and the properties required—why axles are needed for wheels, for example, or why metal would be used for a frying pan and why rubber or plastic would be suitable for rain boots.

The awareness that some materials (not just water but also chocolate, wax, and ice cream, for example) can be either liquid or solid depending on the temperature and that there is a characteristic temperature for each material at which this transition occurs is another important concept about matter that should be developed in this grade band through teacher-guided student experiences and investigations. The transition from liquid to gas is not stressed in this grade band, however, because the concept of gases other than air, or even the fact that air is matter, cannot readily be developed on the basis of students' observations and experiences.

Boundary Statements. In this grade band, crosscutting concepts are referred to when they support development of the idea under study, but they are not stressed as separate ideas. For example, students may be asked to recognize patterns in the use of particular materials, but the idea that patterns are an important phenomenon to investigate is not stressed. Similarly, classroom discussion may focus on the components of a machine (e.g., a bicycle, a toaster) and on the roles they play, but the idea of a system is not stressed. The ideas of parts too small to see, gases other than air, evaporation, and condensation are not stressed either, and the conservation of matter when burning or evaporating is not introduced. Mass and weight are not distinguished when examining matter quantity, and volume is introduced only for liquids.

Grades 3-5: Endpoint and Progression

> *By the end of grade 5.* Matter of any type can be subdivided into particles that are too small to see, but even then the matter still exists and can be detected by other means (e.g., by weighing, by its effects on other objects). For example, a model that gases are made from matter particles too small to see that are moving freely around in space can explain such observations as the impacts of gas particles on surfaces (e.g., of a balloon) and on larger particles or objects (e.g., wind, dust suspended in air) and the appearance of visible scale water droplets in condensation, fog, and, by extension, clouds or contrails of a jet. The amount (weight) of matter is conserved when it changes form, even in transitions in which it seems to vanish (e.g., sugar in solution, evaporation in a closed container). Measurements of a variety of properties (e.g., hardness, reflectivity) can be used to identify particular materials. (Boundary: At this grade level, mass and weight are not distinguished, and no attempt is made to define the unseen particles or explain the atomic-scale mechanism of evaporation and condensation.)

Exploration of matter continues in this grade band with greater emphasis on detailed measurement of objects and materials, and the idea that matter is conserved even in transitions when it changes form or seems to disappear (as in dissolving) begins to be developed. A critical step is to recognize from experience that weight is an additive property of matter—namely, that the weight of a set of objects is the sum of the weights of the component objects. Once students understand that weight is a measure of how much matter is present, their observations in that regard—such as the total weight of the water and sugar being the same before and after dissolving, or the weight of the water formed by melting ice being equal to the weight of the ice that melted—can be used to convey the idea that matter is conserved across transitions. (The distinction between mass and weight is not introduced at this grade band.)

Two important ideas—that gas is a form of matter and that it is modeled as a collection of particles (i.e., pieces of matter too small to see) moving around in space—are developed by the end of grade 5, with careful support from guided investigations and the use of simulations. Multiple learning experiences are needed for students to shift their concept of matter to include the gaseous state, and such experiences must accordingly be structured over time.

First, the idea that matter can be subdivided into ever-smaller pieces without changing the total amount of matter (regardless of how small the pieces are) is developed by carrying out a dividing and weighing activity with one or more substances. The students should engage in discussions of what would happen if one were to keep subdividing until the pieces were too small to see.

Next, the idea that matter is made of particles too small to see can be extended to encompass gases as a form of matter. Air is the first familiar-yet-invisible material that students can learn to identify as a gas made of particles. This recognition is supported by the use of an appropriately designed simulation of particles moving around in a container, as well as by observations aimed at emphasizing the properties of air as a material (e.g., one can feel it, it affects other things, a balloon blown up weighs more than an empty balloon). Students should be helped to relate the observed properties of air to the characteristics of the simulation (e.g., the impacts of particles on surfaces) and also to their own experiences with visible particles, such as the movement of dust particles in air or the impacts of blowing sand on the skin.

Also by the end of grade 5, students' understanding of gases needs to progress a step beyond recognizing air as samples of materials. It should include recognition that the water remains the same kind of matter during evaporation and condensation, just as it does during melting and freezing. The fact that the amount of material remains the same as water is frozen and then melted again can be observed by weighing, and such continuity can be reaffirmed by freezing and melting a variety of other materials (e.g., various juices). Similarly, the amount of material remains the same as water is put through sequences of evaporation and condensation in a closed system (such as a plastic container with a lid)—a fact that can be confirmed with observation and measurement. The stress here is on qualitative comparative observations, not on precision measurements.

The additivity of volumes is a subtler concept than the addition of weights, and it must be developed with care so as not to introduce misconceptions. For like materials (e.g., water plus water, sand plus sand), volume is additive, but students should also be engaged in experiences in which volumes (as measured by a graduated container) do not combine additively, as when sand is added to a container of marbles, or rocks and pebbles are mixed together. With such examples, students can shift their perception of continuous matter to one that allows for a particle-based substructure.

In this grade band, however, definition of the particles involved is not stressed; rather, the objective is for students to begin developing and using models to explain observations. For example, they can build a model to explain why, when a volume of water is added to a volume of rubbing alcohol, the volume of the combined sample is less than the sum of the volumes of the starting samples. (Note that this experience requires careful measurement with appropriate measuring equipment—an ability that also is developed across this grade band.) The evolution of students' mental models of matter is facilitated by relating this experience to similar situations with macroscopic objects, such as the mixture of sand and marbles described above, and to simulations that provide an explicit visible model of the situation. In any case, this example is just one of the many ways in which students can begin to see that observed properties of matter are explainable in terms of a particle model.

Students' understanding of the categories of matter, properties of matter, and uses of matter is refined and expanded across this grade band. Categories of matter, such as metals and crystals, and the names of particular materials, such as iron or silicon, may be introduced in conjunction with experiences or investigations that help students identify the characteristics that distinguish one material from others, thereby allowing it to be categorized. However, no stress is placed on chemical formulas or symbols for substances. Based on studies of various kinds of matter and their properties (such as heat conduction, elasticity, or reflectivity), students can present evidence that measurements of a variety of properties are useful in identifying particular materials. Similarly, based on measurements that identify solid to liquid and liquid to gas transition temperatures for more than one substance, students generalize their understanding that substances change state at specific temperatures. Students also are encouraged to apply their understanding of matter in selecting materials for design purposes.

Throughout this grade band, all of the scientific and engineering practices begin to be developed explicitly, and the crosscutting concepts (flagged in italics below) are used to begin making linkages across disciplinary core ideas—for example, to connect students' understanding of *matter conservation* (e.g., in evaporation and condensation, as described above) to their understanding of the water cycle in earth science. Students also note *patterns* in their observations, recognizing that any pattern can be a clue that needs further investigation and explanation. By the end of grade 5, students should have developed both the ability and the habit of creating models, giving model-based explanations, and relating their models to evidence and inferences drawn from observations. Furthermore, building on their more general models of the substructure of matter, they recognize that it is useful to develop an explicit *system model* to understand any given system.

Boundary Statements. In this grade band, particles are introduced as pieces of matter too small to see, but their nature is not further specified; atoms and the distinction between atoms and molecules are not introduced. If particular pure substances, such as oxygen or iron, are named, the chemical formulas are not introduced; students' learning is confined to the familiar names of these substances, their important properties, and their roles in everyday experience. Mass and weight are not distinguished, and although solid volume can be introduced, students are not expected to be able to calculate volume, except for that of a rectangular solid. Evaporation and condensation are introduced as observable phenomena, but the processes by which they take place are not treated at this grade level. Nor is the calculation of density from measured weight and volume stressed, although a qualitative sense of density as a property of matter and of relative densities of different materials can be developed.

GRADES 6-8: ENDPOINT AND PROGRESSION

By the end of grade 8. All substances are made from some 100 different types of atoms, which combine with one another in various ways. Atoms form molecules that range in size from two to thousands of atoms. Pure substances are made from a single type of atom or molecule; each pure substance has characteristic physical and chemical properties (for any bulk quantity under given conditions) that can be used to identify it.

Gases and liquids are made of molecules or inert atoms that are moving about relative to each other. In a liquid, the molecules are constantly in contact with others; in a gas, they are widely spaced except when they happen to collide. In a solid, atoms are closely spaced and may vibrate in position but do not change relative locations. Solids may be formed from molecules, or they may be extended structures with repeating subunits (e.g., crystals). The changes of state that occur with variations in temperature or pressure can be described and predicted using these models of matter. (Boundary: Predictions here are qualitative, not quantitative.)

In this grade band, investigations are designed to enhance students' ability to create explicit models and to use them for developing explanations of observations, for building their conceptions of matter, and for analyzing new situations. In particular, students develop and apply their understanding of the particle model of matter. In grade 6 the particles are still not defined, but representations of the states of matter (solid, liquid, and gas) include the concept that, although the particles are in motion in all three states, the spacing and degree of relative motion differ substantially between them. The role of forces between particles also begins to be discussed in grade 6—topics include the recognition that particles in a solid are held together by the forces of mutual attraction and repulsion (which act like springs) and that there are forces between particles in a gas that cause them to change their paths when they collide. The core idea of energy developed across this grade band must similarly be applied in the context of models of matter—for example, to understand the temperature dependence of states of matter—and to develop consistent descriptions of such phenomena as convection and conduction, that is, heat transfer with and without fluid motion, respectively.

Across grades 6-8, investigations of matter continue to become more precise, and students' understanding of the particle model of matter continues to be refined through comparisons with empirical observations and suggested models that explain them. By grade 8, students should be able to distinguish between an atom and a molecule and the roles they play in the various states of matter. Students' own investigations and their experiences in examining data from external sources should be structured to help them examine their own understanding of the particle model and help them move toward a better understanding. Students continue to draw on and cultivate their skills in mathematics and language, in recognition of the need for precision in both the measurement and interpretation of data; precision is critical to supporting evidence-derived explanations of the behavior of matter. Students should be expected to apply their understanding of matter in the context of earth and life sciences, recognizing that matter conservation, energy conservation, and matter flows are critical concepts for understanding many large-scale phenomena.

Using evidence collected and analyzed from their own investigations, evidence from outside sources (e.g., atomic images), and the results of simulations, students confirm a model that matter consists of atoms in motion—with forces between the atoms—and that the motion of the particles is temperature dependent. Students can connect this particle model of matter to observations and present arguments based on it to defend the following claims: All substances are made from approximately 100 different types of atoms, which combine with one another in various ways; atoms form molecules that range in size from two to thousands of atoms; gases and liquids are made of molecules or inert atoms, which are moving about relative to each other; and in a solid, atoms may vibrate in position but do not change relative locations.

Students can select different materials as examples to support the claim that solids may be formed from molecules or may be extended structures with repeating subunits (e.g., crystals, metals). Recognizing that pure substances are made from a single type of atom or molecule, students present evidence to support the claim that each pure substance has characteristic physical and chemical properties that can be used to identify it.

Boundary Statement. In this grade band, the forces and structures within atoms and their role in the forces *between* atoms are not introduced—nor are the periodic table and the variety of types of chemical bonds.

Grades 9-12: Endpoint and Progression

By the end of grade 12. Each atom has a charged substructure consisting of a nucleus, which is made of protons and neutrons, surrounded by electrons. The periodic table orders elements horizontally by the number of protons in the atom's nucleus and places those with similar chemical properties in columns. The repeating patterns of this table reflect patterns of outer electron states. The structure and interactions of matter at the bulk scale are determined by electrical forces within and between atoms. Stable forms of matter are those in which the electric and magnetic field energy is minimized. A stable molecule has less energy, by an amount known as the binding energy, than the same set of atoms separated; one must provide at least this energy in order to take the molecule apart.

At this grade band, the structures within atoms and their relationships to the forces *between* atoms are introduced. Students' understanding of the particle model of matter is developed and refined through investigations and analysis of data, both their own and those from experiments that cannot be undertaken in the science classroom. Increased sophistication, both of their model-based explanations and the argumentation by which evidence and explanation are linked, is developed through mathematical and language skills appropriate to the grade level.

Students' conceptual models of matter are extended, based on evidence from their own and others' investigations, to include the following: atoms have a charged substructure of a nucleus (made from protons and neutrons) surrounded by electrons; the periodic table orders elements by the number of protons and places those with similar chemical properties in the same columns; and the repeating patterns of this table reflect patterns of outer electron states. Students can cite evidence that supports this model and relate it to the properties of matter, particularly to the variety of elements, isotopes, and chemical properties.

Students use their understanding of electrical interactions to support claims that the structure and interactions of matter at the bulk scale (link to PS2.A) are determined by electrical forces within and between atoms. Students also use their understanding of stability within systems (link to PS2.B) and the relationship between forces and energy (link to PS3.C) to support claims that stable forms of matter are those that minimize the energy in electric and magnetic fields within the system. Students can then argue that this model is consistent with the propositions that a stable molecule has less energy (by an amount known as the binding energy, which is the sum of all bond energies) than the same set of atoms separated and at rest, that one must provide at least this energy to break the molecule apart, and that it likewise takes energy to break apart stable solid matter.

Boundary Statement. The following topics are not required: the structures within protons and neutrons, the existence of quarks, and the relationship between (a) the strong forces between quarks and (b) the "strong nuclear" force between protons and neutrons.

REFERENCES

1. National Research Council. (2007). *Taking Science to School: Learning and Teaching Science in Grades K-8*. Committee on Science Learning, Kindergarten Through Eighth Grade. R.A. Duschl, H.A. Schweingruber, and A.W. Shouse (Eds.). Board on Science Education, Center for Education. Division of Behavioral and Social Sciences and Education. Washington, DC: The National Academies Press.
2. Krajcik, J., McNeill, K.L., and Reiser, B.J. (2008). Learning-goals-driven design model: Curriculum materials that align with national standards and incorporate project-based pedagogy. *Science Education, 92*(1), 1-32.
3. Berland, L.K., and McNeill, K.L. (2010). A learning progression for scientific argumentation: Understanding student work and designing supportive instructional contexts. *Science Education, 94*(1), 765-793.
4. College Board. (2009). *Science College Board Standards for College Success*. Available: http://professionals.collegeboard.com/profdownload/cbscs-science-standards-2009.pdf [March 2011].