NAEP Pilot Learning Progression Framework

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Using a tentative learning progression for "Tracing Matter", we have developed a set of 19 unique items for inclusion in the pilot for the 2009 NAEP science assessment. Because this learning progression describes the way in which student understanding might develop across the three grade levels assessed in NAEP, we have proposed that many of those items be included at more than one grade level. Thus, we are proposing 9 items for inclusion in the pilot assessment at Grade 4, 12 items for inclusion at Grade 8, and 12 items for inclusion at Grade 12. This is our response to the call for items based on learning progressions in the *Science Framework for the 2009 National Assessment of Educational Progress*. We quote from the framework (page 86):

> A learning progression is a sequence of successively more complex ways of reasoning about a set of ideas. For any important set of ideas in science, understanding increases over time as students learn more and more, moving from initially naïve knowledge of the natural world to increasingly more sophisticated knowledge and conceptual understanding; and this typically occurs in conjunction with educational experiences in and out of school (NRC, 2001). In other words, the progression from novice learner to competent learner to expert begins with the acquisition of relevant experiences, principles, concepts, facts, and skills and moves to the accumulation and organization of knowledge in a specific domain and finally to expertise after extensive experience and practice (e.g., Ericsson, 2002). The attention paid to growth of understanding may yield rich information about student progress.
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> Research has been conducted on students' learning progressions in some areas of science and at some levels of students' development. It is expected that this research will directly inform the development of assessment items at grades 4, 8, and 12. For example, the National Research Council (NRC) has commissioned papers on learning progressions in evolution (Catley, Lehrer, & Reiser, 2005) and in atomic molecular theory (Smith, Wiser, Anderson, Krajcik, & Coppola, 2004). Learning progressions provide opportunities for assessing specific content in greater depth.

A working committee[1] was convened to discuss how we could respond to this call for the 2009 Science Assessment. In order to fulfill the potential suggested in the *Framework,* we felt that we needed to find a domain that met two criteria. First, there needed to be content statements in the Framework that included key concepts from the domain at the fourth, eighth, and twelfth grade levels. Second, there needed to be a body of empirical work in place that provided solid evidence for the development of a definitive learning progression and sufficient resources for assessment development.

In the course of three teleconferences, we decided that there was no domain that met both of these criteria sufficiently well to warrant inclusion of items representing a fully developed learning progression in the 2009 assessment. In particular, research on learning progressions is still in its early stages, with presently available learning progressions being limited in scope, fragmented, insufficiently detailed, and/or incomplete. No learning progression currently has sufficient empirical validation and assessment resources for NAEP's needs (Briggs, Alonzo, Schwab, & Wilson, 2006; National Research Council, 2007; Smith, Wiser, Anderson, & Krajcik, 2006).

Instead, we proposed that we should focus our efforts on a partially developed (although still tentative learning progression) to explore the use of learning progressions in NAEP assessments in 2009 and beyond, recognizing that – given time constraints – this learning progression would not be as fully validated as would be recommended for later NAEP administrations. Based upon this learning progression, we would develop a set of pilot items for inclusion in the 2008 pilot for the 2009 assessment that would help us to gain valuable experience with item development for assessing learning progressions, to explore the difficulties in

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[1] In addition to the authors listed above, this working committee included Marilyn Binkley, Terre Neidorf, Deb Brockway, Amy Drescher, and Cary Sneider. Terre Neidorf, Deb Brockway and Amy Drescher also participated in item development.

reconciling learning progressions with current models for scaling item difficulty, and to develop an empirical base for validation of stages in the proposed learning progression. This framework and the items we developed are the result of that effort. In this framework we (a) describe the domain for the proposed items, (b) identify content statements from the NAEP framework that apply to these items, (c) propose a learning progression, including developmental trends and levels based on currently available research, and (d) suggest issues and challenges that we faced in developing these items and will continue to face during continuing development of learning progression items for NAEP.

Domain for Proposed items

The domain that we have chosen focuses on students' abilities to trace matter (to account for where matter goes and how it changes) in selected physical and chemical changes. The phenomena in this domain include physical changes such as changes of state; chemical changes associated with global climate change and the biogeochemical carbon cycle (combustion of wood and fossil fuels); and chemical changes associated with plant and animal metabolism and the biological carbon cycle (photosynthesis, cellular respiration, digestion, growth of plants and animals, weight loss in animals, and decay). These processes have macroscopic manifestations (e.g., plant growth) that can be explained using atomic-molecular models (e.g., photosynthesis). The physical and chemical changes included at different grade levels are summarized in Table 1 below.

Table 1: Phenomena in the Domain

Grade	Macroscopic phenomena to be explained and predicted	Atomic-molecular processes that explain these phenomena
4	• Physical changes in solids and liquids, such a pouring liquids from one container to another or breaking solids into pieces • Changes of state • Growth of plants and animals	----
8	• Changes of state • Plant growth and plants' dependence on sunlight • Breathing, eating, digestion, growth, and weight loss in animals • Decay of organic materials • Combustion of wood and fossil fuels	• Atomic-molecular explanations of changes of state • Photosynthesis explained as transformation of materials • Digestion and animal growth explained as transformation of materials • Cellular respiration explained as transformation of materials • Combustion explained as transformation of materials
12	• Changes of state • Plant growth and plants' dependence on sunlight, including quantitative measurements of mass • Breathing, eating, digestion, growth, and weight loss in animals, including quantitative measurements of mass • Decay, including quantitative measurements of mass • Combustion of wood and fossil fuels, including quantitative measurements of mass	• Atomic-molecular explanations of changes of state • Digestion and growth explained as atomic-molecular processes within cells • Photosynthesis explained as rearrangement of atoms into new molecules • Cellular respiration explained as rearrangement of atoms into new molecules • Combustion explained as rearrangement of atoms into new molecules

We have three reasons for feeling that Tracing Matter is a good target domain for initial piloting of learning progression items.

1. *Foundations in research on student learning.* The research on student learning in this domain is extensive, though not without gaps. It is a focus of the review by Smith, et al. (2006). Anderson and Wilson are also working on a project that includes the development of a learning progression for the biogeochemical carbon cycle and global climate change (http://edr1.educ.msu.edu/EnvironmentalLit/index.htm). This background work provided both ideas about important developmental trends (see below) and an initial item pool.

2. *Coverage in the NAEP Framework.* The NAEP Framework includes specific and detailed content statements at all three levels that include the key aspects of student understanding in this domain (see Table 2 below). Biogeochemical cycles in general, and the carbon cycle in particular, are identified as important crosscutting content that unites the life, earth, and physical sciences (NAEP Framework, pages 65-6).
3. *Scientific and environmental importance.* The detailed coverage in the NAEP Framework reflects the judgment of the Steering Committee that understanding of the phenomena or processes in Table 1 above is especially important. The general domain of physical and chemical change plays an important role in all three content areas. Furthermore, these particular processes are central to understanding plant and animal metabolism and the ecological carbon cycle. Global climate change will be a central issue throughout the lives of the students taking the NAEP during the next 12 years. The course of global climate change will be determined largely by the balance between processes that produce atmospheric carbon dioxide (combustion and cellular respiration in producers, consumers, and decomposers) and the primary process that absorbs atmospheric carbon dioxide (photosynthesis).

For all of these reasons we judged that a set of items tracing the development of students' abilities to explain and predict where matter goes and how it changes during the processes listed in Table 1 would be timely and important.

Content Statements in the NAEP Framework

Content Statements related to the phenomena in this domain are found in the Life, Earth, and Physical Science sections of the NAEP Framework. The Earth Science content statements focus on the biogeochemical carbon cycle in large Earth systems (see NAEP Framework, pages 65-6 and 72). In order to limit the size of the domain, we decided to focus on processes at smaller scales (macroscopic, cellular, and atomic-molecular). The Content Statements (from Physical and Life Science) addressing these phenomena are reproduced in Table 2.

Table 2: NAEP Framework Content Statements for Learning Progression Items

Grade	Physical Science	Life Science
4	**P4.3:** Matter exists in several different states; the most commonly encountered are solid, liquid, and gas. Each state of matter has unique properties. For instance, gases are easily compressed while solids and liquids are not. The shape of a solid is independent of its container; liquids and gases take the shape of their containers. **P4.6:** One way to change matter from one state to another and back again is by heating and cooling.	**L4.2:** Organisms have basic needs. Animals require air, water, and a source of energy and building material for growth and repair. Plants also require light.
8	**P8.6:** Changes of state are explained by a model of matter composed of tiny particles that are in motion. When substances undergo changes of state, neither atoms nor molecules themselves are changed in structure. Mass is conserved when substances undergo changes of state. **P8.7:** Chemical changes can occur when two substances, elements, or compounds react and produce one or more different substances, whose physical and chemical properties are different from the reacting substances. When substances undergo chemical change, the number and kinds of atoms in the reactants are the same as the number and kinds of atoms in the products. Mass is conserved when substances undergo chemical change. The mass of the reactants is the same as the mass of the products.	**L8.3:** Cells carry out the many functions needed to sustain life. They grow and divide, thereby producing more cells. Food is used to provide energy for the work that cells do and is a source of the molecular building blocks from which needed materials are assembled. **L8.4:** Plants are producers—they use the energy from light to make sugar molecules from the atoms of carbon dioxide and water.[2] Plants use these sugars along with minerals from the soil to form fats, proteins, and carbohydrates. These products can be used immediately, incorporated into the plant's cells as the plant grows, or stored for later use. **L8.5:** All animals, including humans, are consumers that meet their energy needs by eating other organisms or their products. Consumers break down the structures of the organisms they eat to make the materials they need

[2] The statement "they use the energy from light" does not imply that energy is converted into matter or that energy is lost.

		to grow and function. Decomposers, including bacteria and fungi, use dead organisms or their products to meet their energy needs.
12	**P12.5:** Changes of state require a transfer of energy. Water has a very high specific heat, meaning it can absorb a large amount of energy while producing only small changes in temperature. **P12.7:** A large number of important reactions involve the transfer of either electrons (oxidation/reduction reactions) or hydrogen ions (acid/base reactions) between reacting ions, molecules, or atoms. In other chemical reactions, atoms interact with one another by sharing electrons to create a bond. An important example is carbon atoms, which can bond to one another in chains, rings, and branching networks to form, along with other kinds of atoms—hydrogen, oxygen, nitrogen, and sulfur—a variety of structures, including synthetic polymers, oils, and the large molecules essential to life.	**L12.4:** Plants have the capability (through photosynthesis) to take energy from light to form higher energy sugar molecules containing carbon, hydrogen, and oxygen from lower energy molecules. These sugar molecules can be used to make amino acids and other carbon-containing (organic) molecules and assembled into larger molecules with biological activity (including proteins, DNA, carbohydrates, and fats). **L12.5:** The chemical elements that make up the molecules of living things pass through food webs and are combined and recombined in different ways. At each link in an ecosystem, some energy is stored in newly made structures, but much is dissipated into the environment as heat. Continual input of energy from sunlight keeps the process going. **L12.6:** As matter cycles and energy flows through different levels of organization of living systems—cells, organs, organisms, communities—and between living systems and the physical environment, chemical elements are recombined in different ways. Each recombination results in storage and dissipation of energy into the environment as heat. Matter and energy are conserved in each change.

Developmental Trends and Levels

This section includes two parts. In the first part we describe general trends that we expect to see in student learning from elementary through high school level, based on current and previous research, including that reviewed by Smith, et al. (2007). In the second part we describe four levels of achievement that can be used to track students' progress in the domain.

In describing trends and levels, we focus primarily on describing student performances, particularly the language they use to explain and predict the phenomena in Table 1. This contrasts with more traditional science education descriptions of misconceptions—strongly held beliefs that are in opposition to scientific knowledge. Our focus on performance arises in part from a desire to describe student learning in terms that can readily generate assessment items and in part because misconceptions are not the primary form of misunderstanding in this domain. Instead we see students piecing together gradually more coherent, model-based ways of understanding systems and processes—and building their model-based explanations and predictions on earlier narrative understandings.

General Trends in the Learning Progression

As students move through the learning progression, their accounts of phenomena in this domain grow more sophisticated in several ways. Moving through the learning progression means that learners' horizons expand in part because they gain access to personal knowledge, but even more as they gain the ability to access and use critically the many information resources that are available to them. Three general trends are summarized below.

Awareness of Systems and Processes: From Invisible to Visible

Parts or aspects of the phenomena in Table 1 that are invisible to younger children enter the awareness of more advanced learners. This general trend has multiple dimensions, including increasing awareness of microscopic and atomic-molecular scale parts of systems, invisible mechanisms, and the roles of gases in physical and chemical change.

- *Microscopic and atomic-molecular scale systems:* Younger children sometimes learn to recite facts about cells or about atoms and molecules, but they are unlikely to use those facts when they try to explain the phenomena in Table 1. Their perceptions of those phenomena are limited to what they can see at a macroscopic scale. More sophisticated learners are increasingly aware of smaller parts of systems, first at a barely visible or microscopic scale (bits of sawdust, cells), then at an atomic-molecular scale.[3] In general their narrative performances—their ability to tell stories about smaller systems—precedes their model-based performances—their ability to use these systems to explain macroscopic scale phenomena (see the section on Nature of Accounts below).
- *Invisible mechanisms:* Younger children are aware of cause-effect relationships, but they rarely are able to suggest mechanisms by which one event causes another. These mechanisms often involve parts of systems that are hidden or too small to see—body organs, cells, bacteria in the soil, movement of molecules, etc. Older learners are increasingly aware of hidden mechanisms and able to use those mechanisms in their predictions and explanations.
- *Gases:* Younger children often exclude gases entirely from their explanations of events, taking "evaporate" as a synonym for "disappear," for example. Older learners' awareness of gases often begins with accounts that treat gases as conditions (e.g., fires need oxygen but don't necessarily use it) or as bystanders to other processes (e.g., the "oxygen-carbon dioxide cycle" is not connected with plant growth or animal metabolism). The most mature learners recognize gases as forms of matter that are reactants or products in chemical and physical changes.

Precision in Measurement and Description: From Impressions to Data

Younger children rely primarily on their senses and on informal or metaphorical descriptions of phenomena. More mature learners master practices and learn to use tools that enable them to (a) describe systems and phenomena with greater precision and accuracy, (b) find patterns in data, and (c) understand and communicate with others. These practices and tools include increasing use of instruments to extend the reach and accuracy of our senses, precision in measurement and data representation, and use of scientific terms and classification systems.

- *Trust in instruments and procedures rather than personal experience and "seeing is believing:"* Younger children must rely primarily on their senses for information about the world around them. Older learners gain skill in using instruments to measure more precisely and perceive systems or phenomena that would otherwise be invisible. Furthermore, they recognize that appropriate instruments and standardized procedures can be superior to sense impressions for many purposes, and that data collected by others can extend our access to phenomena that we do not witness ourselves.
- *Precision in description, measurement, and data representation.* Younger children rely extensively on metaphorical or analogical description and on sense-based perceptions of "amount of matter." At higher levels students move toward attribute-value description, with the attributes (variables) increasingly differentiated and precise (e.g., shifting from "amount" to "weight and volume" at to "mass, volume, and density"). Accompanying this increasing sophistication in description are practices that represent data in ways that communicate with other people and make patterns visible, such as graphs and tables.
- *Use of scientific descriptive terms and categories:* We focus here especially of classifications of materials and forms of matter. Younger children may have trouble distinguishing objects from the materials of which they are made or distinguishing matter from non-matter (e.g., they classify gases with other "ephemera" or conditions such as heat, light, and temperature; they may also have trouble tracing matter into and out of living organisms). Older learners increasingly recognize a variety of material kinds, some of which are mixtures of other materials. Only

[3] A similar trend is evident in children's awareness of large-scale systems such as ecosystem and Earth systems. These systems, however, are not included in this learning progression.

students who have mastered atomic-molecular models can reliably distinguish between substances and mixtures and trace matter through chemical changes.

Nature of Accounts: From Stories and Procedures to Models Constrained by Principles

The final trend is the most complex and perhaps the most important. As students grow in awareness of hidden systems and processes and master instruments and procedures for describing and finding patterns in phenomena, they also need to undergo a shift in their fundamental approach to explaining and making predictions about the phenomena in Table 1, from *narrative* to *model-based* reasoning. These are two different approaches[4] to understanding and explaining the world (Bruner, 1985; Myers, 1991).

Model-based reasoning[5] is what we normally think of as scientific reasoning. Model-based reasoning uses patterns in observations of phenomena (i.e., laws) and models or theories to explain and make predictions. Model-based reasoning puts widely applicable principles (including laws, models, and theories) in the foreground and seeks to understand the details of particular phenomena through the application of those principles. Three of the four NAEP practice categories—Using Science Principles, Using Scientific Inquiry, and Using Technological Design—assume model-based reasoning as a starting point. For this learning progression we are particularly interested in *tracing matter* as a form of model-based reasoning.

Narrative reasoning plays a minor role in the NAEP framework but a major role in how most people make sense of the world. Narrative reasoning explains and predicts phenomena by constructing stories that make intuitive sense. Stories are often connected to other stories by metaphors and analogies (e.g., growth of trees is sort of like growth of people). The meaning and sense of the stories does not rely on the application of general principles.

Thus narratives and model-based reasoning are alternative approaches to making sense of the world. Narratives put events in order; models function as flexible intellectual tools that can be systematically applied within their domains. As learners mature, they are able to use model-based reasoning more widely, they learn to use principles such as conservation of matter to constrain and connect models, and they learn to make distinctions among types of knowledge claims that are essential to model-based reasoning.

- *Changing balance between narrative and model-based reasoning.* Most children in elementary school are able to trace matter under some circumstances, such as understanding that a ball of clay flattened into a pancake is still the same amount clay with the same physical properties. They explain most changes in matter, though, as events with causes and outcomes through which they do not trace matter. (Their explanations of a fire, for example, focus on the origins of the flame and what the flame does to the wood rather than how the material of the wood is combining with oxygen.) As learners mature, the domains in which they are able to engage in model-based reasoning constitute growing "islands" in a narrative "sea;" they use models more widely, but still rely on narratives as a default sense-making strategy. Some learners, currently a small minority, eventually shift to model-based reasoning as a primary sense-making strategy; they use models to generate narratives rather than locating models within narratives.
- *Using principles to constrain and connect models.* In this learning progression we focus on *conservation of matter* as a fundamental principle that constrains and connects the models we use to explain many different processes, including all the processes in Table 1. Learners who master this principle and its applications have important constraints on processes that enable them to assess their understanding. ("I must not really understand this process because I haven't accounted for all the carbon atoms.") They can also see deep connections among processes that

[4] These notes omit another important aspect of students' reasoning about the material world: practical or craft reasoning based on direct experience with phenomena. It is difficult to construct verbal assessment items that assess students' practical reasoning.

[5] Modeling or model-based reasoning can have different meanings in different fields. In particular, developmental psychologists tend to use "modeling" or "model-based reasoning" much more broadly than we are using the term here, including a wide variety of ways in which children construct and use representations or models of the material world. Specialists in information technology commonly use "modeling" more narrowly, referring primarily to computer models of systems and processes.

narratives connect weakly and metaphorically. (Consider the difference between showing that the reactants and products of combustion and cellular respiration are chemically similar—a model based connection—and saying that exercise "burns off" fat—a metaphorical connection between narratives.)

- *Distinguishing models from observations and patterns.* Narratives put facts in order, without distinguishing among different kinds of facts. In contrast, model-based reasoning requires learners to distinguish between things that we can observe and measure (for example, the masses of reactants and products in a chemical reaction) and models or theories that we use to explain our observations (for example, atomic molecular theory). The science practices of Using Science Principles and Using Scientific Inquiry depend on this distinction. Using Science Principles requires applying models[6] to observations; Scientific Inquiry requires finding patterns in observations and/or developing models to explain those patterns.

Proposed Levels in the Learning Progression

The general trends described in the previous section are reasonably well empirically validated through prior research (e.g., Smith, et al., 2007) and continuing research and development. Reporting students' progress, however, requires demarcation of specific levels or benchmarks along the trend lines. This is where the currently available research falls short. Thus the levels suggested in this section are in part speculative—a reasonable foundation for further development.

We also note other limitations to the descriptions of levels in this section. These levels represent a simplification of a complex and changing reality. In order to create levels, we had to put boundaries within a generally continuous developmental process. These levels represent what we see in data from current American students, not a developmental trajectory that all learners will inevitably follow.[7]

The levels in this section focus on students' abilities to trace matter (i.e., apply the principle of conservation of matter) to the processes of physical and chemical change listed in Table 1. Those processes differ greatly, though, in the demands they make on students' intellectual resources. For simple physical changes such as changing the shape of a ball of clay, students can trace matter without knowledge of the chemical composition of the clay or how mass and volume are related to density. In contrast, tracing matter through biological processes such as cellular respiration requires a detailed understanding of how atoms are recombined into new molecules in complex biological systems. Thus the alignment of performances with levels represents empirically based guesses about the difficulty of tracing matter in different types of changes; students' ability to use conservation of matter as a general principle emerges only after they have learned to conserve matter in a variety of more limited domains.

Thus Table 3 below describes five general levels[8] of students' performance on questions that involve tracing matter through the processes in Table 1. There are three columns in recognition of the different challenges posed by physical changes, combustion, and metabolic processes in living systems. These levels, in descending order, are as follows:

- *Level 5: Successful qualitative model-based reasoning about physical and chemical changes.* Students at Level 5 can use atomic-molecular theory to trace atoms, molecules, or chemical substances through all of the processes in Table 1. They know the general structures of key biomolecules in living systems and in common foods and fuels (see Content Statements P12.4 and L12.7 in Table 2 above), and they can understand new information about chemical

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[6] The NAEP Framework uses "principles" as a general term that encompasses principles (like conservation of matter), models (like a billiard-ball model of a gas), and theories (like atomic-molecular theory).

[7] The NAEP Framework (page 86) points out that "learning progressions are not developmentally inevitable but depend upon instruction interacting with the student's prior knowledge and construction of new knowledge. Thus, learning progressions will need to invoke assumptions about instruction."

[8] Although we describe five levels, the lowest level (Level 1) is characteristic mostly of students in preschool and primary grades, so the items developed for NAEP piloting target Levels 2 through 5.

composition of organisms and materials. In general, performances based on NAEP Grade 12 content statements, as well as some Grade 8 content statements such as P8.7, require Level 5 reasoning.

- *Level 4: "School science" narratives of physical and chemical changes.* Students at Level 4 are generally successful in using ideas about the motion and arrangement of molecules to explain changes of state. They can make correct predictions about mass conservation for melting and freezing, though not for changes involving gases. They know some facts about atoms and molecules and names of some chemical substances, but they generally cannot use atomic-molecular models to reason about observable processes such as burning, growth, weight loss, or decay. They can describe the functions of organs and organ systems in plants and animals, but not the role of subcellular processes such as biosynthesis and cellular respiration. In general, performances based on NAEP Grade 8 content statements require either Level 4 or Level 5 reasoning.
- *Level 3: Events driven by hidden mechanisms.* Students at Level 3 generally explain the phenomena in Table 1 with stories about events rather than treating the phenomena as processes involving changes in matter. They do trace matter through melting and freezing (though they may not conserve mass because of confusions about the distinction between weight and density). They describe some materials as mixtures of other materials, though they cannot use chemical reasoning systematically to distinguish substances from mixtures. They can explain that plants and animals take in materials when they grow and have organs that carry out body processes, though they fail to trace materials such as food or oxygen through body systems. In general, performances based on NAEP Grade 4 content statements require either Level 3 or Level 4 reasoning.
- *Level 2: Events with little attention to tracing matter or hidden mechanisms.* Students at Level 2 successfully trace matter only through the simplest changes such as changing the shape of a ball of clay or pouring liquids from one container to another. They recognize that plants and animals have needs, but they do not generally distinguish among conditions (such as warmth), forms of energy (such as sunlight), and materials (such as food and water). They explain combustion as an event; they are likely to focus on the observable flame and heat rather than how matter is changing. Some questions based on Grade 4 content statements can be successfully answered with Level 2 reasoning.
- *Level 1: Egocentric reasoning about events.* Students at Level 1 focus mostly on events in which they are personally involved and on how people make them happen (as opposed to independent causation). Plants and animals are generally both viewed as alive, though there may be some confusion about plants. There is no evidence of understanding of what goes on inside plants and animals, and they are described and classified with words that emphasize their relationships with humans (pets, flowers, weeds, wild animals). Descriptions of needs may also include human-centered conditions (e.g., "care"). The NAEP framework does not include performances requiring only Level 1 reasoning.

Table 3: Levels of Accomplishment in Tracing Matter through Physical and Chemical Changes

Levels	**Physical Change (Changes of Shape and Size, Changes of State)**	**Chemical Changes (Combustion)**	**Metabolic Processes in Living Systems (Photosynthesis, Cellular Respiration, Digestion, Biosynthesis, Growth, Weight Loss)**
Level 5: Successful qualitative model-based reasoning about physical and chemical changes	• Students at Level 5 are successful at using atomic-molecular models to predict and explain physical and chemical changes even when questions are posed at the macroscopic scale • They successfully trace substances and conserve mass in all changes of state. • They characterize materials as composed of chemically identifiable substances.	• They have a variety of strategies for identifying the substances of which familiar materials are made. They know that the molecules of fossil fuels contain carbon and hydrogen. They are able to interpret written explanations or chemical formulas describing the composition of common materials. • They recognize that atoms are recombined into new molecules in chemical changes, and they trace atoms of fuels and gases through combustion. • They consistently distinguish matter from conditions and forms of energy in describing chemical changes such as combustion.	• They successfully explain macroscopic processes in living systems such as growth, breathing, weight loss, and decay, in terms of metabolic processes occurring in cells. • They explain cellular metabolic processes such photosynthesis, biosynthesis, and cellular respiration in chemical terms. • They recognize proteins, lipids, and carbohydrates as key molecules in plants and animals, and they know that these organic molecules are made primarily of atoms of carbon, hydrogen, and oxygen. They are able to interpret written explanations or chemical formulas describing the composition of these materials. • They consistently distinguish matter from conditions and forms of energy in describing metabolic processes.
Level 4: Successful "school science" narratives of physical and chemical changes; substances and mass are still not clearly traced through macroscopic changes	• Students at Level 4 recognize that materials are made of pure substances, that substances are made of molecules, and that molecules are made of atoms. However, they can assign chemical identities only to a few common substances, such as water and carbon dioxide. • They explain changes of state as changes in motion and arrangement of molecules. • They conserve mass for all physical changes except boiling, evaporation, and condensation. COMMON ERROR: Describing substances as gaining or losing mass when they evaporate or condense because they think of gases as "lighter" than solids or liquids. COMMON ERROR: Mistakes suggesting that substances change chemical identity when they change state (e.g., air is in the bubbles of boiling water). In contrast to Level 3, where students are likely to believe that substances are really changed by evaporation, Level 4 students' errors generally arise from an incomplete understanding of	• They have learned some facts about atoms and molecules and perhaps procedures for balancing chemical equations, but they fail to use those facts and procedures to explain visible phenomena such as combustion. • They are generally successful in distinguishing matter from conditions and forms of energy in chemical changes involving solids and liquids, and they generally conserve mass in those changes. • They recognize that gases can react with solids or liquids to be reactants or products in combustion, but they do not trace C or H atoms from fuels to gaseous products (CO_2 and H_2O) • They recognize the need to conserve matter and mass in chemical changes. However, since they generally think of gases as "lighter" than solid or liquid fuels, they resort to mechanisms such as matter-energy conversion or minor products (e.g., ashes, smoke)	• They recognize the role of plant and animal circulatory systems in moving materials through bodies. However, they cannot provide cellular or chemical accounts of what happens to those materials when they reach their destinations. • They recognize cells as living units in bodies, but fail to explain the role of cells in carrying out organismal metabolic processes such as growth or respiration or to explain cellular processes in chemical terms. • They recognize the chemical names of some foods and biomolecules, but fail to use chemical knowledge to explain metabolic processes. • They attribute decay to decomposers such as bacteria and fungi, but cannot explain what the decomposers do in chemical terms. • They recognize that animals incorporate food into their bodies as they grow, though they cannot explain the processes of digestion and biosynthesis in biochemical terms. • They recognize that gases are

Levels	Physical Change (Changes of Shape and Size, Changes of State)	Chemical Changes (Combustion)	Metabolic Processes in Living Systems (Photosynthesis, Cellular Respiration, Digestion, Biosynthesis, Growth, Weight Loss)
	chemical identity (e.g, not being clear about how water is different from hydrogen and oxygen or how air is a specific mixture of gases rather than a synonym for "gas" in general).	to explain what happens to mass. COMMON ERROR: Explaining what happens to the mass of burning substances with matter-energy conversions or minor products such as ashes and smoke. COMMON ERROR: Failing to use available information about chemical identity (e.g., molecular formulas) when explaining events involving chemical changes. COMMON ERROR: Accounting for combustion in ways that fail to account for all atoms or to include relevant reactants or products (e.g., asserting that oxygen is needed for combustion but not describing fuel molecules as reacting with oxygen molecules).	reactants and products (not just conditions or bystanders) in photosynthesis and cellular respiration, but they do not trace C, H, or O atoms between food and body materials and gaseous products or reactants (O_2, CO_2, and H_2O) • They recognize the need to conserve matter and mass in chemical changes involving gases as reactants or products such as plant growth, animal growth or weight loss, and decay. However, since they generally think of gases as "lighter" than solid or liquid fuels, they resort to mechanisms such as matter-energy conversion or minor products (e.g., urine, sweat or feces) to explain what happens to mass COMMON ERROR: Failing to use information about cellular processes (e.g., photosynthesis, cellular respiration) when accounting for macroscopic processes such as growth, weight loss, or breathing. COMMON ERROR: Describing cellular metabolic processes in ways that fail to account systematically for atoms (e.g., saying that photosynthesis converts O_2 to CO_2 or that cellular respiration converts glucose to ATP). COMMON ERROR: Accounting for mass in plant growth and animal weight loss with matter-energy conversions or minor contributors such as water and soil minerals (for plant growth) or feces and urine (for animal weight loss).
Level 3: Measured quantities of materials and events driven by hidden mechanisms; materials not clearly distinguished from conditions or forms of energy	• Students reasoning at Level 3 recognize the importance of measured weight (as opposed to felt weight) as a reliable measure of amount • They conserve weight in physical changes where shape changes but not volume (e.g., pouring water, breaking glass).. • They recognize the need to account for matter in evaporation and condensation, but generally will not successfully trace materials between liquid and gas states. For example, they may, say	• They recognize chemical changes such as combustion as involving changes in matter, but they do not clearly distinguish between materials (solids, liquids, and gases), conditions (e.g., temperature), and forms of energy (e.g., heat, light) when they explain chemical changes. Thus they are rarely able to trace mass or materials through chemical changes. • They recognize that air (or oxygen) is needed for	• They know the names of important body organs and can name their functions. However, they tend to locate systemic functions in particular organs (e.g., stomachs digest food so we can grow). Thus their explanations of systemic functions generally do NOT involve tracing materials through body systems. • They can generally distinguish between substances that are foods and substances that are not, with some confusion about liquids such as water, juice, and soda.

Levels	**Physical Change (Changes of Shape and Size, Changes of State)**	**Chemical Changes (Combustion)**	**Metabolic Processes in Living Systems (Photosynthesis, Cellular Respiration, Digestion, Biosynthesis, Growth, Weight Loss)**
	that water turns into air, etc. • They recognize that macroscopic objects and materials can be broken down into smaller, even microscopic parts that retain some of their properties. • They recognize that little bits of materials still have mass, and that many materials can be separated into other, simpler materials. • They may know some facts about atoms and molecules (e.g., water is H_2O; atoms are made of protons, neutrons, and electrons), but they do not use them successfully to explain macroscopic events (e.g., water freezes because the molecules freeze). COMMON ERROR: Attributing macroscopic properties (e.g., color, hardness) to atoms or molecules. COMMON ERROR: Saying that substances change into other substances during evaporation and condensation. COMMON ERROR: Saying that weight changes a little bit when materials melt or freeze.	combustion, but are likely to treat it as a condition rather than as the source of oxygen that reacts with the fuel. • They can generally distinguish between substances that will burn (fuels) and substances that will not, but the distinction is based on experience rather than an ability to describe chemical properties that all fuels share. COMMON ERROR: Describing materials as "burned up" by combustion without suggesting where they go OR suggest conversion ONLY to visible solid products like ashes. COMMON ERROR: Recognizing that combustion requires oxygen without being able to explain any role for oxygen in combustion. COMMON ERROR: Recognizing that combustion produces carbon dioxide without being able to explain where it came from.	However, their distinctions are based on experience rather than an ability to describe chemical properties that all foods share. • They may describe plants and animals as made of living cells, but the concept has little explanatory power. They do not, for example, attribute growth of plants and animals to cell growth or cell division. • They do not recognize the role of microorganisms in decay, so they do not distinguish between decay and chemical processes such as rusting. • They are likely to be familiar with the "oxygen-carbon-dioxide cycle (animals breathe in O_2 and breathe out CO_2; plants breathe in CO_2 and breathe out O_2). However, they treat this cycle as independent of metabolic processes in plants and animals. COMMON ERROR: Explaining growth or weight loss in terms of processes that are localized in particular organs (e.g., digestive system) without tracing materials through body systems. COMMON ERROR: Explaining breathing in terms of processes that are localized in the lungs (e.g., our lungs breathe in oxygen and breathe out carbon dioxide) COMMON ERROR: Focusing on things that are taken in as being "like" what they become. No notion of transformation of materials inside bodies. So for example, they focus on plants taking in food or water in through their roots in explaining plant growth and do not refer to the process of production of sugars in leaves (photosynthesis).
Level 2: Viewing chemical and physical changes as events with little attention to tracing matter or hidden mechanisms	• Students at Level 2 recognize that the amount of a material does not change in simple physical changes such as rolling ball of clay into a snake, breaking an object into pieces, or pouring a liquid from one container to another. However, they rely on perceptual judgments of amount (felt weight, apparent volume), so they do not distinguish clearly among weight (mass), volume,	• They describe chemical changes as events rather than changes in matter (e. g., the flame consumes the wood). • They recognize materials and conditions necessary for combustion, but they do not suggest different roles for materials (fuel, air), conditions (heat), and triggering events (spark). • Causes of events may be related to essential	• They recognize materials such as food, air, water, and soil as fulfilling needs of plants and animals. However, they do not distinguish between materials that organisms need and conditions or forms of energy. Thus we need to eat in order to grow, but they do not describe how food is incorporated into our bodies. • They do not explain phenomena such as digestion, growth, or movement in plants and animals

Levels	**Physical Change (Changes of Shape and Size, Changes of State)**	**Chemical Changes (Combustion)**	**Metabolic Processes in Living Systems (Photosynthesis, Cellular Respiration, Digestion, Biosynthesis, Growth, Weight Loss)**
	and density. They are likely to think that weight changes substantially in melting and freezing and that liquids disappear when they evaporate. • They do not extend their reasoning about macroscopic materials to barely visible or microscopic scales. For example, they say that a block of wood or a bag of sand has weight, but not a bit of sawdust or a grain of sand. COMMON ERRROR: Saying that the weight changes when a substance melts or freezes. COMMON ERROR: Saying that small bits of matter do not have weight. COMMON ERROR: Using "evaporate" as a synonym for "disappear," saying that substances no longer exist after they evaporate.	characteristics of materials (e.g., the match burns because wood is flammable.) COMMON ERROR: Responding to questions about what happens to matter in chemical changes with descriptions of the event focusing on conditions or properties of materials.	in terms of functioning of organs or cells. • They may use vitalistic causality—idea of vital powers; we need air and water because they are good to maintain energy and health. COMMON ERROR: Responding to questions about internal mechanisms in plants and animals statements about needs of plants and animals or properties of substances (e.g., food helps us grow because we need it).
Level 1: Egocentric or anthropocentric reasoning (not included in learning progression for NAEP, but we probably will get some responses like this to open-response questions)	• Objects are not clearly distinguished from the materials that they are made of and are classified according to how people use them (e.g., students will describe a wooden spoon and group it with other "things that you eat with" rather than focusing on the material that it is made of. • Objects broken into parts may not be recognized as being made of the same material as the original objects	• Chemical changes are described as events rather than changes in matter. • Causes and effects center on human intentions and effects on humans (e.g., the match burns because someone struck the match).	• Plants and animals are characterized according to their relationships with humans—food, pets, flowers, etc.—or are understood in human terms (e.g., cartoon movies about animals with human traits and emotions.)

Issues and Challenges for Assessment[9]

The general picture developed above is that misconceptions—strongly held beliefs that are in opposition to scientific knowledge—are not the primary form of misunderstanding in this domain. Instead students piece together gradually more coherent, model-based ways of understanding systems and processes—and build their model-based explanations and predictions on earlier narrative understandings. So indications of what levels students are at are likely to take forms like these.

- Responses that rely on narrative rather than model-based reasoning or incomplete explanations that leave out important model-based components. (This is especially common if the model-based reasoning requires students to shift scales between macroscopic and smaller scales. For example, Level 3 students may explain that a person loses weight by "burning up" fat when exercising.). This is then an issue because (a) It is difficult to write open-ended items which prompt students to provide complete explanations without telling them what should be included, and (b) It is difficult

[9] The issues described in this section are likely to apply to many – but not all – learning progressions.

to write multiple-choice items for which the highest level distractor is not just the most "science-y" one

- Responses that fail to address the purpose of the question. (For example, Level 2 students will generally respond to questions asking them to trace matter through chemical and physical changes with accounts of events or information about conditions, causes, or properties of materials.[10]) This is an issue for writing multiple choice items, since a student who might provide a Level 2 response in a more open-ended format could eliminate a distractor which does not answer the question in favor of one which does (even though this does not represent his/her "true" level. It is also generally not good item –writing practice to have non-parallel distractors, particularly if one or more simply don't answer the question.
- Inability to use relevant information. (For example, providing information about the chemical identities of substances will be valuable to Level 5 students, but mostly not to students at lower levels.) Thus some items may supply important chemical details in order to assess whether students are able to use that information appropriately.

What all of these indications of levels share is that they are difficult to translate into large scale assessment items where there are clear distinctions between correct and incorrect answers. This is particularly problematic since people with higher-level understandings may choose to give lower-level explanations. For example, consider the following (hypothetical) explanations of a burning match:

Level 2: The flame is burning up the match.

Level 3: The flame uses air to burn up the match.

Level 4: Oxygen in the air is combining with the wood to produce smoke and heat.

Level 5: Cellulose and other organic compounds in the wood are combining with oxygen to produce (primarily) carbon dioxide and water.

None of these descriptions is really "wrong," and a person with Level 5 understanding might choose in some circumstances to describe a burning match in Level 2 language. Thus assessment items should prompt students to give the highest-level description that they are capable of while allowing all students to choose the level that makes the most sense to them, without signaling which choices are the most "scientific" through vocabulary or sentence structure.

The 2008 NAEP pilot will provide an invaluable opportunity to assess how items with these qualities can be written and scored. The pilot will also provide an empirical data to align learning progression levels with NAEP content statements and to judge appropriate expectations for grade levels.

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[10] Phrases such as "burned up" or "eaten up" can be indicators of this type of thinking. A Level 2 student using those phrases may be indicating that s/he simply has not considered what happens to fuels after they are burned or foods after they are eaten. This is different from saying that fuels and foods disappear or become nothing.

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