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# Characterizing Curriculum Coherence

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## INTRODUCTION

THE CENTER for Curriculum Materials in Science (CCMS) and the Technology Enhanced Learning in Science (TELS) Center promote the design of curriculum materials and technology tools that help students develop an understanding of important connections among science ideas and the inclination and ability to use those ideas to make sense of the world. Researchers at both centers analyze the fragmented ideas that students bring to class, identify important connections to be made, and design new materials that enable students to use ideas in a variety of contexts and to regularly improve the connections among their ideas. Both centers distinguish the following:

- *Integrated understanding,* the desired set of connections among scientific ideas that students need as they progress through school. Goals for integrated understanding emerge from careful analysis of science topics and content standards.
- *Knowledge integration,* a lifelong process that involves continuously seeking additional, more valid, and more concise connections among scientific ideas. Identifying knowledge integration processes depends on understanding how students link and connect ideas (where "link" refers to recognition of a relationship between ideas and "connect" indicates the requirement of evidence for the relationship between the ideas). Curriculum materials and technology tools can promote knowledge integration by actively engaging students in making important connections among ideas and applying them to new contexts.

- *Curricular coherence,* a desired quality of science curriculum materials that involves presenting a complete set of interrelated ideas and making connections among them explicit. Coherent curriculum materials illustrate and model integrated understanding.

This chapter describes how CCMS and TELS have approached the design of coherent curriculum materials to help middle school and high school students move toward an integrated understanding of science. By combining coherent materials and support for knowledge integration processes, instruction can help all students achieve the integrated understanding that is the goal of learning.

## Research Context

Both CCMS and TELS build on research on student learning that highlights the importance of helping students make connections among ideas. Bruner (1960, 1995), for example, argues that knowledge of the relationships among ideas and of the fundamental principles that connect the particulars enables learners to integrate new ideas into what they already know. According to Bruner, "the only possible way in which individual knowledge can keep proportional pace with the surge of available knowledge is through a grasp of the relatedness of knowledge" (1995, p. 333). Studies comparing the knowledge and abilities of experts and novices in a discipline describe the advantages of a richly connected understanding (Chi, Feltovich, & Glaser, 1981; Larkin & Reif, 1979; Markham, Mintzes, & Jones, 1994). The integrated knowledge that experts have enables them to use their knowledge in many contexts, including recognizing patterns in observations and explaining them, whereas the fragmented knowledge that students typically bring to science class can stand in the way of even knowing that science is useful for making sense of the world (Grigg, Lauko, & Brockway, 2006; O'Sullivan, Reese, & Mazzeo, 1997; Schmidt, McKnight, & Raizen, 1997). Studies also document the challenge of creating instructional materials with the right degree of coherence for a particular audience; materials representing the richly interconnected understanding of experts may not be the most successful materials for novice learners (Ainsworth & Burcham, 2007; Britton & Gulgoz, 1991; McKeown, Beck, Sinatra, & Loxterman, 1992; McNamara, Kintsch, Songer, & Kintsch, 1996).

CCMS works with the interconnected set of ideas, or learning goals, that both *Benchmarks for Science Literacy* (AAAS, 1993) and the *National Science Education Standards* (*NSES*) (NRC, 1996) have identified as central to science literacy. CCMS designers have articulated an approach to focusing the content of curriculum materials on this set of interrelated ideas, identifying important connections among the ideas in the set, and helping students to make connections among the ideas and use them to explain phenomena (Krajcik et al., 2008). In so doing, they seek to meet the criteria that served as the basis for the science

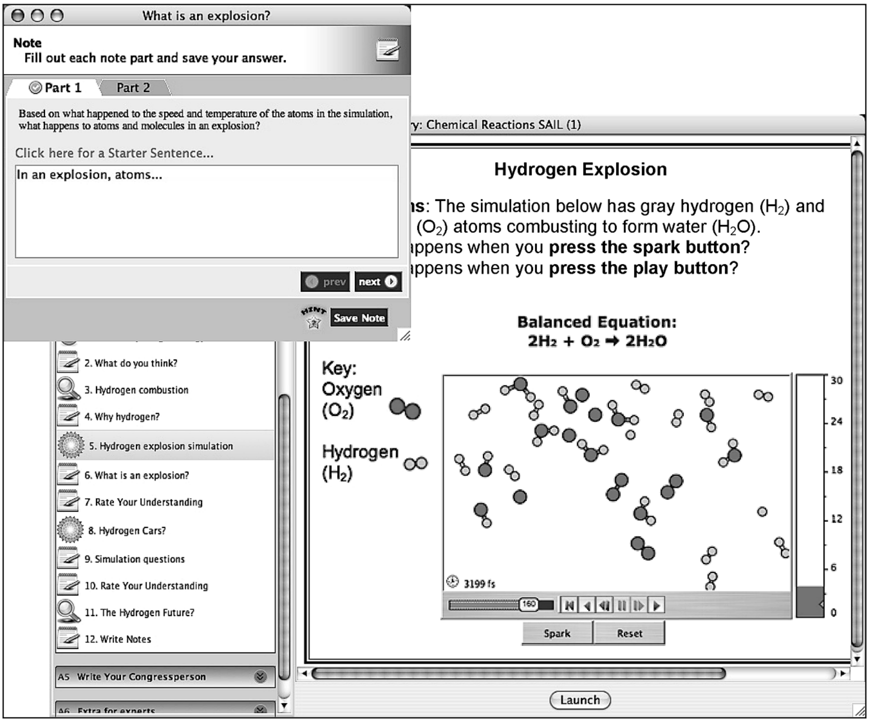


**FIGURE 2.1 TELS inquiry learning environment, illustrating dynamic visualization of a hydrogen explosion and a note tool.**

textbook evaluation studies of AAAS Project 2061 (Kesidou & Roseman, 2002; Stern & Roseman, 2004). As CCMS designers investigate the impact of their materials on students and teachers, the focus on learning goals guides those efforts as well (Chapter 3, Krajcik, Slotta, McNeill, & Reiser; Chapter 7, DeBoer, Lee, & Husic).

TELS builds on design principles that grew out of longitudinal research (Linn & Hsi, 2000), design studies (Linn, Davis, & Bell, 2004), and a series of workshops and conferences leading to a database of features, research evidence, and principles (the Design Principles Database, http://www.edu-design-principles.org; Kali, 2006). These principles are reflected in the knowledge integration framework (Linn, 1995, 2006; Linn, Lee, et al., 2006). TELS researchers take advantage of the Web-Based Inquiry Science Environment (WISE) and technological innovations from the Concord Consortium (see Figure 2.1) to create and study how curricular materials can promote knowledge integration. The curricular materials developed by TELS address science topics that teachers identify as (a) difficult for students, (b) required by standards, and (c) likely to benefit from technology enhancement. TELS has refined and tested the modules in classroom studies and shown that they improve knowledge integration (Linn, Lee, et al., 2006; Linn & Slotta, 2006).

### Design Context

In attempting to design coherent materials that promote knowledge integration, both CCMS and TELS have developed and applied specific principles and criteria. CCMS design draws on criteria used in Project 2061's evaluations of science textbooks and on findings of those studies, which shed light on the coherence of available textbooks and the quality of their instructional design (Kesidou & Roseman, 2002; Roseman, Stern, & Koppal, 2008; Stern & Roseman, 2004). TELS design draws on its own principles for knowledge integration (Kali, 2006; Linn, Davis, & Bell, 2004). To synthesize their work, the centers identified a single set of research-based guiding principles that provide the basis for both research programs. The guiding principles include

- Focusing materials on science learning goals
- Building pedagogical supports into materials
- Incorporating learning technologies into materials
- Promoting the use of student investigations as learning activities
- Serving the needs of diverse science learners
- Supporting teacher learning
- Taking account of policy contexts

This chapter and Chapter 3 describe how the two centers address the first three guiding principles. The remaining principles are the focus of other chapters in this volume.

## THE CCMS APPROACH TO CURRICULUM COHERENCE

This section speaks to the role of curriculum materials in illustrating and modeling an integrated understanding and in promoting knowledge integration. It highlights Project 2061's study of the coherence of high school textbooks and describes criteria for analyzing their coherence and the quality of their support for teaching and learning.

### Analyzing Textbook Coherence

CCMS argues that the content of curriculum materials is coherent when it focuses on an important set of interrelated ideas and makes various kinds of connections explicit. CCMS researchers have used these characteristics of coherent content to evaluate the content of existing curriculum materials and to design new ones.

***Alignment with a Coherent Set of Ideas.*** The starting point in any discussion of coherence is the relationships among the specific ideas that students are expected to learn. CCMS focuses its work on science learning goals that are derived from *Science for All Americans* (AAAS, 1989), which recommends a set of knowledge and skills in science, mathematics, and technology that characterizes science literacy for high school graduates. Instead of presenting a list of topic headings and terms, *Science for All Americans* provides a scientific account of the world that includes some of the most important ideas and connections among them. For example, in characterizing knowledge about matter and energy transformations in ecosystems, *Science for All Americans* articulates connections between life science and physical science that all high school graduates should know:

> However complex the workings of living organisms, they share with all other natural systems the same physical principles of the conservation and transformation of matter and energy. Over long spans of time, matter and energy are transformed among living things, and between them and the physical environment. In these grand-scale cycles, the total amount of matter and energy remains constant, even though their form and location undergo continual change. (p. 66)

The authors of *Science for All Americans* then present examples of matter and energy transformations to illustrate relationships between living systems and physical systems at several levels of biological organization—molecule, organism, ecosystem.

To allow time for students to develop a deep understanding of these ideas and their interconnections, *Science for All Americans* limits the total number of ideas to be learned to a central core of the most important ideas. Hence, in life science (as in physical science, social science, mathematics, and technology), the authors left out several topics that are typically included in textbooks. For example, details of plant anatomy and the metabolic steps of photosynthesis and respiration were not considered essential for making sense of everyday phenomena or for making social and personal decisions about matters involving science, mathematics, and technology. Decisions about what to include and what to exclude from the science curriculum carry through to *Benchmarks for Science Literacy* (AAAS, 1993), a companion volume to *Science for All Americans,* which specifies what students should know and be able to do at the end of Grades 2, 5, 8, and 12. To achieve the vision of science literacy described in *Science for All Americans,* the learning goals in *Benchmarks* convey key concepts while including selected supporting details, are specific enough to be informative but avoid fragmentation, and are comprehensible by students at each grade and developmental level. To emphasize the interconnectedness of this core knowledge, the two-volume *Atlas of Science Literacy* (AAAS, 2001, 2007) displays K–12 connections among ideas for nearly 100 topics.

Figure 2.2 shows a progression of ideas (included in both *Benchmarks* and *NSES*) from primary school through middle school that contributes to an understanding of matter and energy transformations in ecosystems. The progression has been adapted from several related *Atlas* maps and can be used to serve the needs of both curriculum and assessment design. The map shows that by the end of Grades K–2, students should be able to view food as a *need* of organisms, which requires students to connect observations of particular plants and animals around them to that general principle. By the end of elementary school, students are expected to have a more functional definition of food—food provides material for body repair and growth—and to associate growth with an increase in body weight (mass). In middle school, students are expected to link the growth of organisms to the synthesis of new molecules in chemical reactions. With these foundational ideas in place, students in high school are then able to connect the synthesis and breakdown of molecules in organisms to the cycling of atoms in ecosystems and to recognize that the workings of all living organisms are governed by physical principles of transformation and conservation. Thus, at each grade level students are expected to relate their new knowledge to what they already know and to make more sophisticated links among ideas.

In thinking through what would constitute an appropriate story about matter and energy transformations in middle school, the developers of *Benchmarks* considered the benefits and costs of helping students understand the underlying molecular mechanisms for each. Students who understood the underlying mechanisms would benefit by being able to tie together seemingly unrelated phenomena. By learning about matter transformation and the rearrangement of atoms during chemical reactions in physical systems (where matter transformations are more directly observable), students are better able to understand the same mechanism at work in biological systems (where changes in matter are not easily observed). Costs would arise from the need to first help students understand that the properties of substances and mixtures of substances are determined by the molecules they are made of, that changing the molecules changes the properties, and that changes in molecules in chemical reactions involve changing the arrangements of atoms making up the molecules (but not the atoms themselves). Given the documented difficulties students have with these ideas and the experiences of other curriculum developers on this and related topics, the CCMS researchers working on the middle school science curriculum "Investigating and Questioning Our World Through Science and Technology" (IQWST), a 3-year

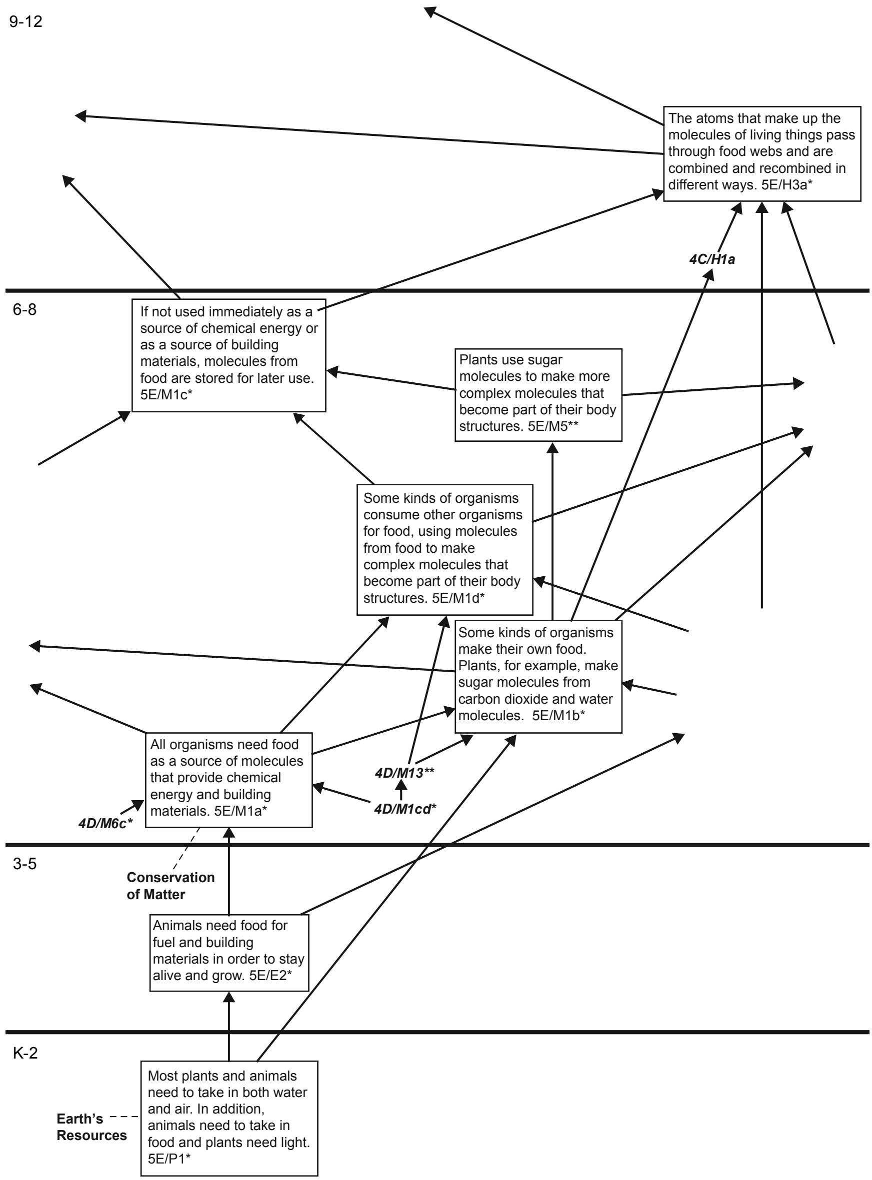


**FIGURE 2.2** Map developed by AAAS Project 2061 showing a sequence of ideas from kindergarten through 12th grade that contribute to students' integrated understanding of the flow of matter and energy in living systems.

middle school science curriculum, estimated that it would take between 8 and 16 weeks to provide students with the chemical foundation they would need. Despite this significant investment of instructional time, the researchers decided that the potential benefits for students' understanding justified the costs of targeting these ideas in their middle school curriculum.

In contrast, the IQWST developers decided that including a molecular level mechanism for energy transformation in middle school could not be justified. Including a mechanism for energy transformations in chemical reactions such as photosynthesis and cellular respiration would require knowledge of the link between molecular structures and chemical energy, why changes in molecular structure are accompanied by changes in chemical energy, and how energy from the sun is transformed into chemical energy. Providing the necessary foundation for this learning in the available time would overburden students struggling to understand and apply the mechanism of matter transformation. In the end, IQWST researchers concurred with the decisions reflected in *Benchmarks for Science Literacy* (AAAS, 1993, p. 85) and the *Atlas of Science Literacy* (AAAS, 2007, p. 25) to limit the energy story at the middle school level to patterns in observable energy transformations.

***Connections Between the Ideas of Science and Phenomena in the Natural World.*** For students to appreciate the explanatory power of science ideas, they need to have a sense of the range of phenomena that the ideas can explain. Appropriate phenomena help students to view scientific concepts as plausible and enhance students' sense of the usefulness of scientific concepts (Anderson & Smith, 1987; Champagne, Gunstone, & Klopfer, 1985; Strike & Posner, 1985). To understand how matter is transformed within ecosystems, it is important that students appreciate various transformations at the molecular level not only within organisms but also between organisms in ecosystems and the abiotic environment. Curriculum materials need to provide a range of observable phenomena involving matter transformations within organisms and relate the phenomena to underlying molecular explanations. For example, materials could show students that as the egg yolk and egg white decrease in mass during the development of a chick embryo, the body of the chick increases in mass; that as a weight-lifter "bulks up," the increase in muscle mass looks quite different from the milk, eggs, and cheese consumed; or that plants grown in air enriched in carbon dioxide produce more sugar and starch and grow faster than plants grown in normal air.

***Connections to Prerequisite and Other Related Ideas.*** Coherence also includes making connections between new ideas and prior knowledge explicit (Bishop & Anderson, 1990; Eaton, Anderson, & Smith, 1984; Lee et al., 1993; McDermott, 1984).

As shown in Figure 2.3, the idea that "carbon and hydrogen are common elements of living matter" provides necessary, though not sufficient, information to understand a few simple transformations of matter in organisms, starting with the idea that "plants make sugar molecules from carbon dioxide (in the air) and water" (Idea $a_1$ in Figure 2.3). Curriculum materials could make a connection between these two ideas by explaining that carbon dioxide and water molecules contain atoms of the elements carbon and hydrogen (and also oxygen) and that photosynthesis by plants begins the process of incorporating these atoms into larger molecules, which can then lead to their incorporation into the much larger molecules that make up body structures (parts of Ideas $b_1$ and $c_1$ in Figure 2.3).

Connections are particularly important when new ideas and their prerequisite ideas are presented in different chapters of a text. For example, a textbook's chapter on cells should make a link between the elements that make up cells (particularly carbon), the ability of carbon atoms to form large and complex molecules (which might be presented in an introductory chemistry chapter), and chemical reactions in cells that link carbon atoms to form sugars (Idea $a_1$ in Figure 2.3) and then use those sugars to make more complex molecules of body structures (Ideas $b_1$ and $c_1$ in Figure 2.3). A connection could be made by reminding students that living things don't violate basic chemical principles:

> *Carbon atoms can easily bond to several other carbon atoms in chains and rings to form large and complex molecules. And in fact they do. Plants take simple molecules of carbon dioxide and water and put them together to form rings and put the rings together to form more complex structures. All of this is possible because carbon can bond to other carbon atoms in rings or chains.*

Similarly, the idea that "within cells are specialized parts for the capture and release of energy" (typically presented in a chapter on cells) should be linked to key ideas about the release of that energy by plants and animals (Ideas $b_2$ and $c_2$ in Figure 2.4). Curriculum materials might make such a connection by pointing out that cells with high energy needs tend to have more of the specialized parts for releasing energy than do cells with lower energy needs. Curriculum materials can connect these ideas to relevant phenomena, such as by pointing out that cells located on the upper surface of leaves—where there is more direct access to light energy—have more of the parts used to capture the sun's energy than do cells located on the undersurface of leaves.

There are also opportunities for curriculum materials to make connections between ideas taught in life science and underlying principles typically taught in chemistry. As noted earlier in this chapter, *Science for All Americans* suggests that students learn that "However complex the workings of living organisms, they

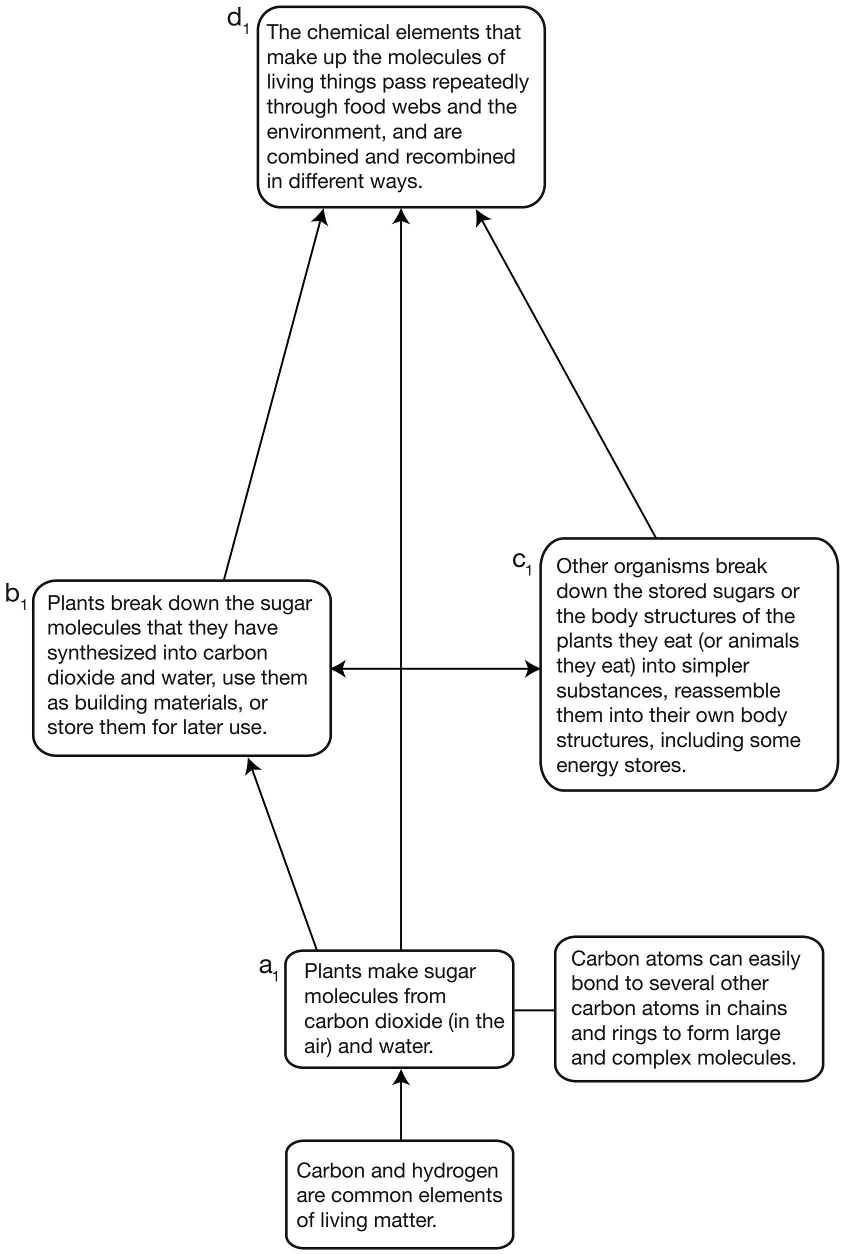


**FIGURE 2.3 Detail from a map showing relationships among ideas about matter transformations that were the focus of AAAS Project 2061's review of biology textbooks (AAAS, 2005).**

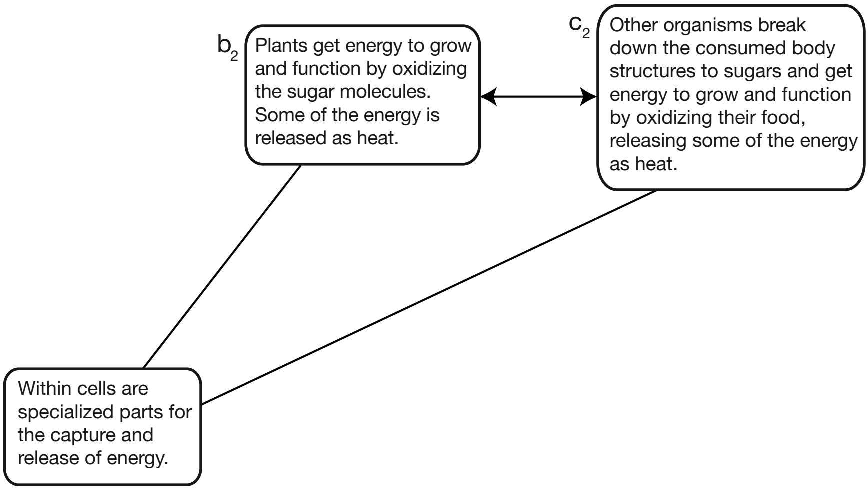


**FIGURE 2.4 Detail from a map showing relationships among ideas about matter and energy transformations that were the focus of AAAS Project 2061's review of biology textbooks (AAAS, 2005).**

share with all other natural systems the same physical principles of the conservation and transformation of matter and energy" (AAAS, 1989, p. 66). Textbooks often present individual ideas in separate chapters—photosynthesis and cellular respiration in a chapter on cells, food breakdown in a chapter on the human digestive system, nutrient cycles and energy pyramids in a chapter on ecosystems—and never convey the idea that these processes are instances of matter and energy conservation and transformation (which students typically encounter in physical science courses). To support the interconnectedness of ideas from the life sciences and the physical sciences, matter transformations in living systems can be described in terms of atoms combining and recombining in cells, organisms, and ecosystems.

***Connections to Evidence Supporting the Ideas.*** Coherence also comes from connections between scientific ideas and the enterprise that produced them. Curriculum materials can help students appreciate ideas about the nature of science by providing evidence-based arguments for the scientific ideas presented. Using logical arguments to link evidence to conclusions can also give students a sense of why particular ideas are believable and why scientists believe them. In attempting to build a case for science ideas, it is important that materials present a case that is valid (e.g., by making legitimate inferences from observations and presenting sufficient evidence to support arguments). It is also important that the case be comprehensible to students (e.g., by presenting evidence at an appropriate level of sophistication and presenting the argument and links to evidence in manageable steps). Textbooks typically assert ideas without evidence. When they do provide evidence, it is not adequately linked to the idea it supports. For example, on the topic "Matter and Energy Transformations" biology textbooks rarely present Priestley's experiment (which showed that plants produce oxygen) or Ingenhousz's experiment (which showed that oxygen is only produced in the presence of light). When textbooks do present these experiments, they fail to link them to the equation for photosynthesis or to students' own observations that plants grown in the presence of light produce sugars, whereas plants kept away from light do not.

***Avoidance of Nonessential Information.*** It is also important that curriculum materials pay attention to the relevance and comprehensibility of what is included. Curriculum materials can reduce coherence by including distracting technical detail that goes beyond what is needed to understand the essential ideas and their connections. For example, on the topic "Matter and Energy Transformations" textbooks often include details of metabolism, such as the reactions of Photosystems I and II and the Calvin cycle, which make it difficult for students to extract the main story about photosynthesis. Or materials may include abbreviated diagrams of the Krebs cycle and formulas for molecules such as NADH, $NAD^+$, ATP, and ADP, which have no meaning for students who do not yet have an understanding of organic chemistry.

Subtle forms of content inaccuracy can also detract from coherence. One form consists of the juxtaposition of statements that may lead students astray even though neither is factually wrong. Diagrams, rather than clarifying ideas, may reinforce common student misconceptions (Tversky et al., 2002). For example, diagrams of nutrient cycles in biological systems, such as the carbon–oxygen cycle or the nitrogen cycle, often misrepresent the transformation of matter by showing atoms of carbon for one organism represented in the diagram but not for others. By failing to show atoms of a particular element throughout the cycle, a text can reinforce the misconception that matter can disappear in one place and reappear in another, as opposed to simply changing forms (by combining with different atoms to make new molecules). Similarly, diagrams of energy pyramids that indicate decreases in energy (without indicating that energy is given off as heat) can reinforce students' misconception that energy is not conserved.

To summarize, for students to understand how matter is transformed within living systems, it is important that they appreciate various transformations at the molecular level not only within organisms but also between organisms in ecosystems. It is particularly important that curriculum materials make it clear that matter transformations in an ecosystem are a consequence of transformations of matter in the organisms that make up the ecosystem, and that the recycling of elements in an ecosystem results from repeated cycles of synthesis, storage, and breakdown in the organisms and involves movement of matter between organisms and the abiotic environment. When textbooks treat only part of the story or fail to make important connections among different parts of the story, students are likely to be left with fragmented knowledge. They are also less likely to appreciate what they are taught when the ideas are not linked to practical applications such as explaining the growth of organisms or considering claims about the effects of global climate change on ecosystems.

## Designing Coherent Materials That Promote Knowledge Integration

Both the criteria used to evaluate the coherence of textbooks' presentation of content and the criteria used to evaluate the quality of their instructional support for knowledge integration have been adapted for use by materials designers. Chapter 3 describes the role of these criteria in the design of IQWST materials, and Project 2061 uses them as a basis for formative feedback provided to IQWST and other development teams (Heller, 2001; Krajcik et al., 2008).

***Learning-Goals-Driven Design.*** CCMS researchers believe that the detailed content analysis illustrated above is a crucial part of the design process and must be done for virtually every topic; only general design guidelines are applicable across topics. Such careful thinking about ideas, connections, and sequences has been part of the development process being used by CCMS researchers working on IQWST. Describing their approach as a "learning-goals-driven design model," the IQWST developers begin their work by first identifying in *Benchmarks* and *NSES* the content to be targeted in their curriculum units. To ensure a close alignment of the ideas addressed in the curriculum with those specified in the standards, the IQWST developers then "unpack" each standard to consider "the science concepts articulated … in depth and how they link to other science ideas" (Krajcik et al., 2008, p. 7). The science content is then "mapped" beginning first with the relevant maps from the *Atlas of Science Literacy* followed by construction of more detailed maps for each sequence of ideas. According to the developers, mapping has enabled them to "identify clusters of standards that interrelate, determine what are the big ideas … and build an instructional sequence to foster more complex understandings over time" (Krajcik et al., 2008, p. 6).

As a result of this learning-goals-driven design approach, the IQWST developers have designed a coherent sequence of units that contrasts sharply with the model that is typical of most middle school science curricula. Sequencing is especially critical for the IQWST curriculum because it relates ideas across life, earth, and physical sciences. For example, IQWST developers have sequenced their units to ensure that students understand chemical reactions in physical systems (where the inputs and outputs of these reactions are observable) *before* the students encounter chemical reactions in living systems (where the inputs and outputs are more difficult to observe). For similar reasons, IQWST first targets ideas about conservation of energy in physical systems, using examples that involve readily detectable forms of energy. This gives students a sense that, like matter, energy does not disappear or appear from nowhere. IQWST then builds on students' emerging ideas about energy conservation to introduce the idea of chemical energy as a new type to account for changes in the energy types they are already familiar with. Once students accept the existence of chemical energy, they are then able to use it to explain phenomena in which energy seems to have disappeared. Ideas about both matter and energy transformation are tied together in IQWST's eighth-grade unit on the synthesis of sugars by plants and its subsequent oxidation to extract energy. Chapter 3 describes in more detail the IQWST design process and its contribution to students' integrated understanding.

***Pedagogical Supports.*** Focusing on learning goals and thinking through the kinds of connections that must be made explicit and sensible to students are essential first steps. However, these are not sufficient to help students achieve the knowledge integration needed for lifelong science learning. Curriculum materials should do more than present content to students; they should also support the teaching and learning process. For that reason, CCMS contends that science curriculum materials should include goals-specific pedagogical supports for students and teachers that are based on empirically tested theories of learning. For its evaluation of biology textbooks, AAAS Project 2061 developed a set of criteria to consider the extent to which textbooks incorporated these pedagogical supports (AAAS, 2005).

By pedagogical supports we mean the text, activities, and assessments used by curriculum materials to motivate and help students to learn, along with the background information, suggestions, diagnostic questions, and remedial strategies used to help teachers monitor and promote that learning. Pedagogical supports can be incorporated directly into students' materials as well as materials intended specifically for the teacher, such as teacher editions of textbooks. To help all students gain important and lasting science knowledge and skills, curriculum materials must provide a wide array of supports that enable students and teachers to meet the following challenges:

- Taking account of prerequisite knowledge and student misconceptions to enable students to construct new understanding that builds on their prior understanding
- Helping students appreciate the purpose of classroom activities and the content they are learning to provide an adequate level of motivation to learn
- Using phenomena and representations to clarify the meaning of abstract ideas and to make the ideas plausible to students
- Helping students interpret phenomena and representations in light of the ideas

- Promoting student reflection and application of their developing understanding
- Using continuous assessment and student feedback to inform instruction
- Enhancing the learning environment to enable students with different abilities and levels of preparation to experience success

The demands of teaching for understanding are significant, especially in today's classrooms that serve students with widely diverse backgrounds, abilities, and interests. Teachers certainly cannot be expected to design their own research-based pedagogical supports for an entire curriculum. Therefore, CCMS researchers have incorporated these supports as an integral part of their IQWST student and teacher materials. The supports are based on empirically tested theories of learning that have been described by Edelson (2001) and Kesidou and Roseman (2002).

Through attention to the research-based content and pedagogical criteria used in Project 2061's textbook evaluations, CCMS developers are mindful of the kinds of difficulties many students are likely to have and of the kinds of supports that are likely to help. Chapter 3 and Chapter 8 (Kali, Fortus, & Ronen-Fuhrmann) describe and illustrate the application of these criteria to the design of IQWST student materials, and Chapter 5 (Davis & Varma) describes their application to the design of educative materials for teachers.

## THE TELS APPROACH

The goal of TELS is to spur design of technology-enhanced materials that lead to knowledge integration and support a lifelong tendency to seek connections among ideas. TELS approaches this by designing and testing inquiry learning environments that incorporate educational software and simulations of scientific phenomena to promote an integrated understanding of science in students. To help future designers, TELS incorporates guiding principles and contributes to the Design Principles Database (http://www.edu-design-principles.org; Kali, 2006; Kali & Linn, 2007; see also Chapter 8). TELS extracts design processes and patterns from successful instructional materials to highlight ways to stimulate knowledge integration (Linn, 2006; Linn & Eylon, 2006). Research from TELS also strengthens the WISE learning environment (see Figure 2.1), creates effective professional development (Chapter 5), builds a community of school leaders (Chapter 6, Bowyer, Gerard, & Marx), and stimulates an open source community of developers (see Chapter 3).

### Knowledge Integration Processes and Patterns

TELS has identified four reasoning processes that, taken together, are used to construct pedagogical patterns (sequences of activities) that can promote knowledge integration (Linn & Eylon, 2006). The pedagogical patterns incorporate prior research on technology-enhanced learning (Bell, Davis, & Linn, 1995; Buckley et al., 2004; Horwitz & Christie, 1999; Linn, Lee, et al., 2006; Slotta & Linn, 2000; Songer & Linn, 1992). The pedagogical patterns feature four interrelated processes of knowledge integration in combinations that contribute to integrated understanding. These processes are (a) elicit current ideas, (b) add new ideas, (c) develop criteria for evaluating ideas, and (d) sort out ideas. Materials can interleave the four processes, revisiting some and visiting others only once. In TELS research, the patterns are combined to form curriculum materials tailored to specific disciplinary characteristics. This section describes the four knowledge integration processes and illustrates them with examples from research on the successful Japanese Ikatura method for science inquiry learning (Hatano & Inagaki, 1991). The next section ("The TELS Design Process") discusses how the patterns inform design of the TELS modules.

***Elicit Current Ideas.*** As documented in research on student reasoning, students develop a repertoire of ideas about any phenomenon (Clark & Linn, 2003; diSessa, 1988). TELS research suggests that students need to articulate their varied ideas as part of the process of building a more integrated view of a topic. When instructional materials present a single view without encouraging students to consider their own views, the new view is typically added to the repertoire rather than integrated (Bransford, Brown, & Cocking, 1999). Eliciting ideas in multiple contexts ensures that they are considered in forming a view of a scientific topic. Studies of contextualized learning show that when students study science in abstract contexts, for example, they fail to connect the instruction to their everyday ideas, often even claiming that science in school differs from science in everyday life (e.g., Bell & Linn, 2002; Gilbert & Boulter, 2000). For example, students often remark that cold flows on a snowy day but only heat flows in the classroom. Chapters 3 and 8 describe how instruction can support contextualization.

Eliciting ideas is the first step in the Ikatura method. When using this method, Japanese instructors first pose a dilemma and elicit student ideas. They list all of the student ideas on a whiteboard. They then ask students to select one perspective or another, in essence making predictions about the outcome of the demonstration. In one example, students explore adding either a wood or a metal object of similar mass to a beaker filled with water. They predict whether the mass of the beaker with the wood object floating on the water or with the metal object sinking in the water will be the same. That is, students compare the mass of the water plus the floating object with the mass of the water plus the sinking object. By eliciting predictions, teachers engage their students in the experiment and also learn about the ideas held by their students.

***Add New Ideas.*** As shown in the analysis of CCMS curriculum materials, adding new, normative ideas is an essential part of science instruction. Historically, science instruction has introduced new ideas in lectures or text accounts of a phenomenon, in a manner that is often consistent with a model of the learner as an absorber of information (Thorndike, 1963). Recently, however, research has demonstrated the benefit of careful design of the ideas that are added to the mix held by students. Researchers have studied bridging analogies (Clement, 1993), benchmark lessons (diSessa & Minstrell, 1998), didactic objects (Thompson, 2002), prototypes (Songer & Linn, 1992), and pivotal cases (Linn, 2005). For example, Clement (1993) describes bridging analogies, such as comparing the behavior of a book on a spring, pillow, and table to help students understand the forces between the book and the table.

Adding these types of ideas motivates learners to examine their own repertoire of ideas. For example, the phenomenon of thermal equilibrium can be illustrated through two pivotal cases. In one case, to help explain why objects feel different even though they are the same temperature, students use an interactive animation to explore the rate of heat flow in different materials, such as metal and wood, learning that heat flows faster in metal than in wood. Students use this pivotal case to make sense of their sensory observations that metals feel colder than wood, even when both are the same temperature. In another case, to help disentangle ideas about materials and their temperature, students recall personal experiences to compare the feel of wood and metal at room temperature with the feel of these materials at the beach on a sunny day. Students use this pivotal case to sort out ideas about insulation and conduction. Both cases stimulate learners to reconsider their existing ideas (Linn & Hsi, 2000). Research suggests criteria for successful pivotal cases, including (a) make a compelling, scientifically valid comparison between two situations; (b) draw on accessible, culturally relevant contexts, such as everyday experiences; (c) provide feedback that supports students' efforts to develop criteria and monitor their progress; and (d) encourage students to create narrative accounts of their ideas using precise vocabulary so they can discuss them with others (Linn, 2005; Linn & Hsi, 2000).

To further its goal of designing and testing powerful interactive, dynamic visualizations as pivotal cases for central topics in middle school and high school science, TELS takes advantage of the visualization software designed by the Concord Consortium (http://www.concord.org) and also creates new visualizations using NetLogo and other resources (see Figure 2.1). Although TELS has found that most students claim that they are visual learners, many research studies suggest that visualizations either lack value or interfere with learning, which is consistent with CCMS findings about textbook diagrams (e.g., Stern & Roseman, 2004; Tversky et al., 2002). TELS has identified design principles to help designers find effective ways to use interactive visualizations. TELS has evidence that the interactive visualizations are key to the success of the TELS modules (Casperson & Linn, 2006; Liu, Lee, Hofstetter, & Linn, 2008).

In the Ikatura method, after eliciting ideas teachers use experiments or demonstrations to add new ideas. In the study of mass mentioned above, students conduct a valid comparison of the mass of the beaker with a floating object (wood) or a submerged object (metal), analyze the feedback from the experiment, connect the experiment to their own ideas about things like the floating and sinking of boats, and create narratives to summarize their work.

***Develop Criteria for Evaluating Ideas.*** To help them develop coherent ways to evaluate the scientific ideas they encounter, students need to have criteria for selecting among views. Students often accept questionable scientific information, such as advertisements for new drugs, persuasive accounts of research findings, and compelling personal anecdotes. They rarely explore the controversies that led to scientific advances or learn that research methods have limitations (Bell & Linn, 2000; Roseman et al., 2008). Often, the scientific method is exalted rather than explained as a social construct open to negotiation (Keller, 1983; Longino, 1994). Students may accept bogus results—encountered on the Internet or in quasi-scientific publications—because they are cloaked in scientific jargon. Alternatively, students may discredit all of science when they learn that new advances discredit previously established ideas about medical treatments or nutritional practices. Successful instruction helps students develop sound ideas about criteria for evaluating scientific information. Ultimately, students need to understand the fallibility of experimental investigations, the epistemology of methods in varied disciplines (such as earthquake prediction, cloning, design of new drugs, and environmental conservation), and the nature of scientific advancement. Although science standards help determine the level of sophistication appropriate for specific grade levels, empirical research is needed to be sure that the recommendations in the standards are feasible and that they enable students to reason effectively about practical problems.

To help students develop criteria for distinguishing among ideas, teachers in the Ikatura method ask students to align evidence from their experiments with their ideas, to revise their ideas based on the experiments, and to use the evidence to convince peers who have alternative ideas. Students discuss the validity of the evidence, make further predictions, and conduct more experiments to resolve differences of opinion.

***Sort Out Ideas.*** To help them sort out new and current ideas, students need opportunities to apply their criteria to the ideas in their repertoire, distinguish ideas, and weigh evidence. Students benefit from applying their criteria to evidence, sorting out potential contradictions, and identifying situations where more information is needed (Bagno, Eylon, & Ganiel, 2000; Bransford et al., 1999; Collins, Brown, & Holum, 1988; Linn & Hsi, 2000; Scardamalia & Bereiter, 1999). To succeed, students need to allocate their limited energy to the most central confusions, to evaluate their progress, and to seek clarification when necessary (Bielaczyc, Pirolli, & Brown, 1995; Lin & Schwartz, 2003). Instead, many students respond to the barrage of information in science courses by memorizing information they expect on tests (Songer & Linn, 1992) and then forgetting what they memorized (Bjork, 1994).

In the Ikatura method, teachers help students sort out ideas by encouraging small groups to discuss their ideas and reach joint conclusions. When groups of four cannot reconcile their views, the whole class listens to the alternative ideas and contributes criteria as well as evidence. This approach to helping students develop coherent understanding has proven successful in many studies of Japanese instruction (e.g., Lewis, 1995; Lewis & Tsuchida, 1998) and in studies inspired by the method (e.g., Clark & Sampson, 2007).

**TELS CREATES** pedagogical patterns by using the four processes described above. An instructional *pattern* is a sequence of activities followed by teachers and students in a classroom that features all four processes: elicit current ideas, add new ideas, develop criteria for evaluating ideas, and sort out ideas. Activities such as experimentation often fail to promote knowledge integration when used in isolation. As the Ikatura method illustrates, experimentation can succeed when implemented as part of a pattern where learners articulate their ideas before experimenting and sort out alternative interpretations afterward. Similarly, pedagogical patterns can improve collaborative learning by ensuring that students contribute their own ideas before they hear the ideas of others, adding multimedia examples that serve participants as pivotal cases, guiding learners to agree on criteria for critiquing evidence, and motivating learners to reconcile alternatives (Brown & Campione, 1994; Linn & Hsi, 2000; Scardamalia & Bereiter, 1999). Linn and Eylon (2006) identified 10 instructional patterns that incorporate all four of the knowledge integration processes and apply to common classroom activities such as experimentation, collaboration, and critique.

## The TELS Design Process

To create curriculum modules, TELS forms partnerships that include individuals with expertise in classroom teaching, the science discipline, technology, student learning, curriculum, and professional development. The partnerships use the WISE learning environment to design instruction (see Figure 2.1) and the partnership process to develop the design (Linn & Holmes, 2006). TELS design partnerships use guiding principles, design principles, and pedagogical patterns to create the modules. Modules feature pivotal cases of scientific phenomena often designed by the Concord Consortium (http://www.concord.org). For example, one module on natural selection implements a series of patterns including explore a visualization, debate, reflect, discuss, and reflect again. In this module, students generate ideas about natural selection in the context of plants, fish, and dinosaurs (Teruel, 2006). They then explore a visualization that uses a pivotal case in the form of an interactive Flash animation to compare learning within a generation versus survival across generations. Next they reflect on the difference between natural selection and developing expertise. They compare fish that learn when to swim fast with fish that survive because they are faster swimmers. Using a debate pattern, students research alternative accounts of the impact of habitat change on fish populations, develop arguments, formulate criteria, and participate in a class debate in which they need to use their criteria to evaluate the ideas of their peers. A discussion pattern allows students to articulate their ideas more accurately. Finally, students use the reflection pattern to develop a report summarizing their ideas.

Kali and Linn (in press) illustrate how design principles can help materials developers create effective modules. Whereas patterns assist designers in determining sequences of activities, design principles guide the design of each activity. For example, in implementing the discussion pattern, designers draw on two design principles: "Scaffold the process of generating explanations" and "Enable multiple ways to participate in online discussions."

The WISE environment supports extensive student guidance (Linn, Clark, & Slotta, 2003). Recently, the TELS technology team has created a new Java-based infrastructure for designing, developing, and delivering computer-based curricula that extends the capabilities of WISE. The Scalable Architecture for Interactive Learning (SAIL) manages persistence in a network environment (allowing student work and software versions to be stored and retrievable over time). The technology offers powerful authoring, logging, and experimentation capabilities that enable rapid design and refinement of instruction.

## TELS Classroom Research

TELS has conducted longitudinal studies and comparison studies to identify effective ways to teach science. For example, to study how best to design a molecular workbench visualization, the learning environment can deliver alternative treatments within the same class (when alternatives are similar) or in different classes taught by the same teacher.

In the first year, TELS created and tested 10 modules and assessments aligned with those modules to measure knowledge integration (Chapter 7). In addition, TELS designed a principal network to support teachers (Chapter 6) and professional development to rapidly prepare users (Chapter 5).

In a cohort comparison study involving 50 teachers (Linn, Lee, et al., 2006), TELS found that studying with the module instead of the regular lesson resulted in student gains of about one third of a standard deviation in integrated understanding. TELS is now in the process of sorting out the factors that jointly result in the success of the modules, including guided inquiry; pivotal cases based on interactive visualizations, models, and probeware; eliciting ideas in relevant contexts that interest students; ample time for reflection; a focus on integrating prior experiences with new observations; and support for student collaboration.

The modules were extensively revised based on classroom trials, and modules showing positive impact on student learning were placed in the TELS Library (see http://www.wise.berkeley.edu). These modules are free for use by researchers and teachers. By spring 2007, over 100 TELS teachers had used the modules with over 14,000 students in more than 30 schools in five states.

Studies of the modules, teachers, professional developers, and science students have improved instruction. Results have led to revision of design principles and pedagogical patterns (Ronen-Fuhrmann, Kali, & Hoadley, 2008). Results of this research resonate with the findings from CCMS and suggest next steps for increasing the emphasis on coherence in science courses.

## SUMMARY AND CONCLUSIONS

The work of both CCMS and TELS points to the importance of careful planning, analysis, and iterative refinement in the early stages of curriculum development to ensure that (a) materials present a coherent and explicitly related set of important and useful ideas and (b) students have the pedagogical support necessary to help them integrate their knowledge in the classroom and beyond. It also makes clear the need for policies throughout the education system that can promote the development of high-quality curriculum materials and sustain their effective implementation in schools. Taken together, these research programs offer some proven guiding principles, design principles, and pedagogical criteria that can be applied by those who evaluate and design science curriculum materials and by those who articulate and carry out policies to guide science education.

### Implications for Research and Curriculum Design

The idea maps from the *Atlas of Science Literacy* (AAAS, 2001, 2007) offer researchers a starting point for considering the coherence of a topic both within and across grade bands. *Atlas* maps also provide a rationale for the design and sequencing of phenomena-based activities that can be tested by empirical studies of student learning. Project 2061's textbook evaluation criteria can guide the design and testing of student experiences with phenomena and representations, and the TELS instructional design patterns and principles can provide similar guidance in the design and assessment of technology-based instructional materials. By taking advantage of these analytical tools and resources in the early stages of development, curriculum designers will have a more thoughtfully designed draft and a more informed set of questions to investigate in the classroom. To benefit from this work, designers should (a) consider the learning trajectories depicted in the *Atlas* maps, (b) ensure that materials have face validity according to Project 2061's textbook coherence criteria, (c) adhere to the instructional design criteria used by CCMS, (d) employ the TELS design principles and patterns, and (e) engage in iterative rounds of evidence-based refinements *before* investing in large-scale empirical studies.

Studies on learning are only just beginning to examine what it would take to develop students' understanding of a well-defined set of interrelated ideas in key topics and across several grades. At CCMS, for example, researchers are drawing on the K–12 progressions of understanding suggested in Project 2061's *Atlas* maps to develop, refine, and test more detailed instructional sequences for the topics addressed in their IQWST curriculum. At TELS, researchers are exploring the impact of using the same visualizations for common topics in middle school and high school science. More study is needed to extend the work of both centers to additional topics, different learners, varied instructional contexts (e.g., self-guided technology-based modules as well as print-based units), and the design process itself.

Future research should investigate the processes by which students develop an integrated understanding of science, their motivations for continuing to link ideas together, and the factors that support this process across the lifespan. (See, for example, CCMS's draft national research agenda available at http://www.sciencematerialscenter.org/research_agenda.htm.) In addition, research on more targeted questions—such as identifying features of curriculum materials that make a difference in students' learning—deserve attention.

## Implications for Policy

CCMS and TELS both acknowledge that well-aligned and coherent curriculum and assessment materials are insufficient on their own to accomplish the kinds of changes that are needed in science teaching and learning. The goals targeted must be feasible for learners. Teachers need the knowledge and skills to make effective use of materials, which requires changes in how teachers are prepared and in the environments in which they work. School leaders need knowledge and opportunity to guide teachers and students. The curricular issues raised in this chapter point to a few modest recommendations for federal and state education policies that can make a difference.

***National Science Benchmarks and Standards.*** Ideally, all science curriculum materials would be based on high-quality learning goals, and there would be adequate instructional time available for students to achieve those goals. In reality, however, the materials being used in most of the nation's classrooms are based on 50 different sets of state science standards, and most of these materials have been judged to be lacking in coherence as well as accuracy and specificity (Roseman et al., 2008). Time allotted for science instruction continues to shrink in response to the emphasis on reading and mathematics in the current era of No Child Left Behind. Both the *Benchmarks for Science Literacy* (AAAS, 1993) and the *National Science Education Standards* (NRC, 1996), while imperfect, offer educators and curriculum developers and publishers a starting point for addressing the incoherence resulting from state standards. Some debate has focused on the idea of national standards and their benefit if carefully designed (Olson & Hoff, 2006). The framework for the 2009 National Assessment of Educational Progress (NAEP) in science, which draws extensively on *Benchmarks* and *NSES,* offers one possibility for building national consensus on science learning goals. How many topics and ideas can be targeted in ways that foster students' integrated understanding of science depends on the nature of the learner (including prior experiences), the time available, and the quality of the curriculum materials themselves. Ultimately, what is needed are well-designed science standards that are both coherent and feasible for students to achieve in the time available. Empirical tests to identify more precisely what, how, and when students are able to learn important science ideas are crucial.

***Textbook and Technology Adoption.*** States and school districts need to offer more flexibility in textbook and technology adoption policies and in assessment practices so that schools can take advantage of the innovative, research-based curriculum materials now being developed. Allowing schools to adopt textbooks and technologies that are aligned with national standards and benchmarks, as well as with the relevant state standards, would be a good first step.

***Investment in Curriculum Research and Development.*** Little improvement in science learning can be accomplished without better and more uniform data on what works, why, and with whom. Those involved in designing and carrying out research on the effectiveness of curriculum know the enormous complexities involved in conducting the kinds of research that are needed and in interpreting the results, yet it is essential to have high-quality data to inform the many decisions in which curriculum plays a role.

Whatever approach is taken, it is important that all involved be realistic about the time and resources needed to produce high-quality materials and to evaluate their effectiveness. It will require significant and more consistent funding over the long term from federal government agencies such as the National Science Foundation and the Department of Education, from private foundations and professional organizations, and from state agencies. Research on the effectiveness of curriculum materials should be viewed as an essential step in the development of standards, assessments, and curriculum. Budgets and timelines for development projects should reflect this reality.

Research programs need to include more studies that have a broader focus. Many learning studies provide insight into what can be accomplished under carefully defined conditions, using precisely focused instruction, working with a small number of students, and dealing with a small number of ideas and skills. Broader contexts must now be studied to fully understand the role that powerful curriculum materials could play as more and more users participate. Funding for TELS, for example, has enabled study of the effects of scaling up its interventions to over 150 teachers in entire school districts in six states. At the same time, studies are needed to guide customization of instruction for specific learners and teachers.