2

Characterizing Curriculum Coherence

Jo Ellen Roseman, Marcia C. Linn, and Mary Koppal

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

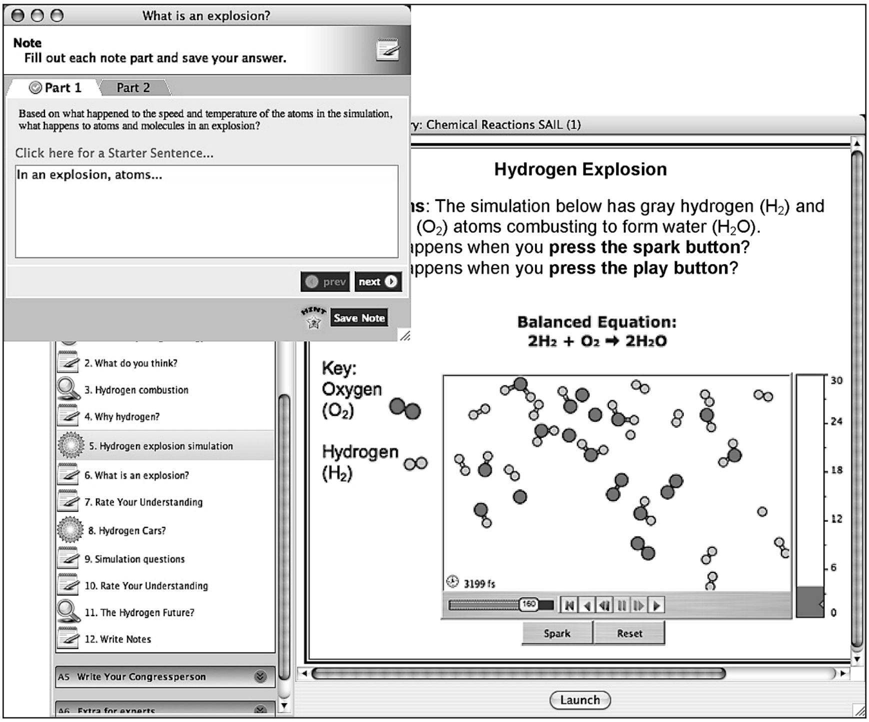

FIGURE 2.1 TELS inquiry learning environment, illustrating dynamic visualization of a hydrogen explosion and a note tool.

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

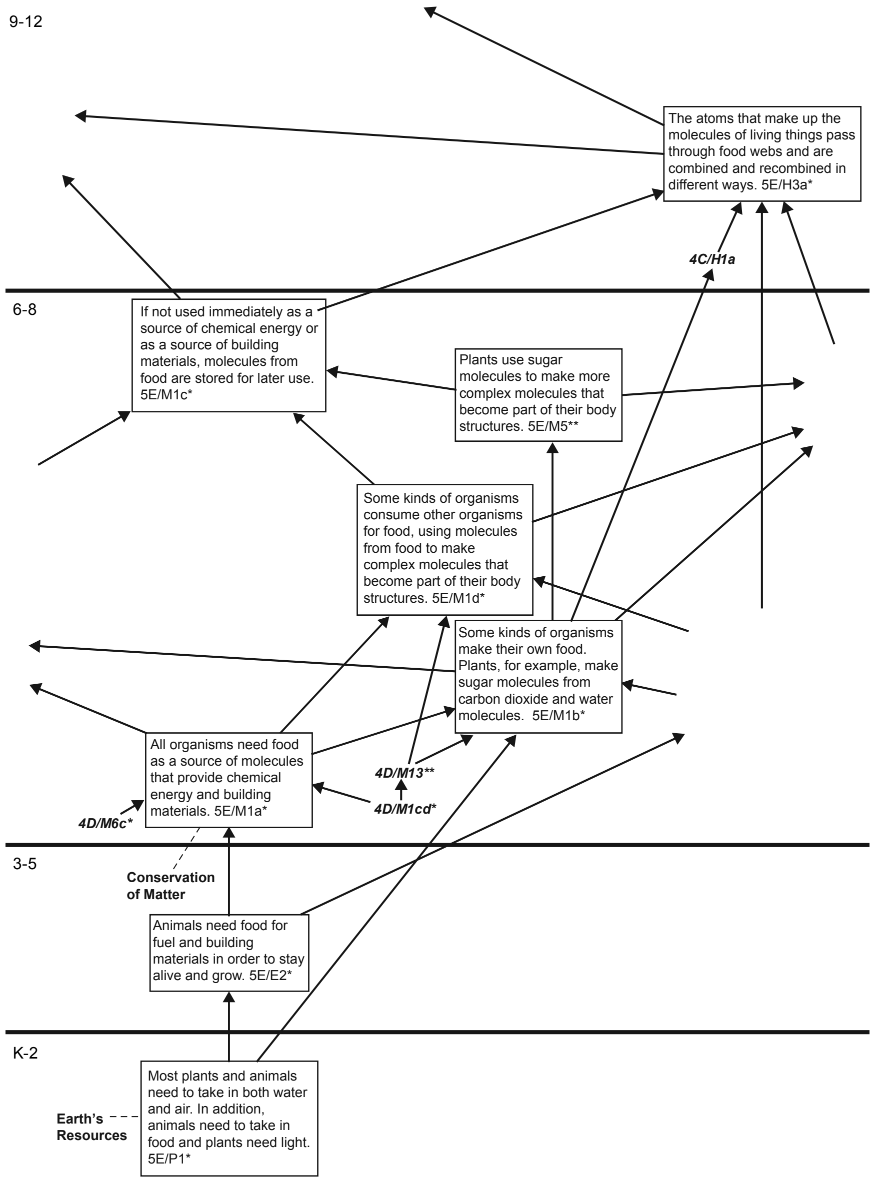

FIGURE 2.2 Map developed by AAAS Project 2061 showing a sequence of ideas from kindergarten through 12th grade that contribute to students' integrated understanding of the flow of matter and energy in living systems.

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

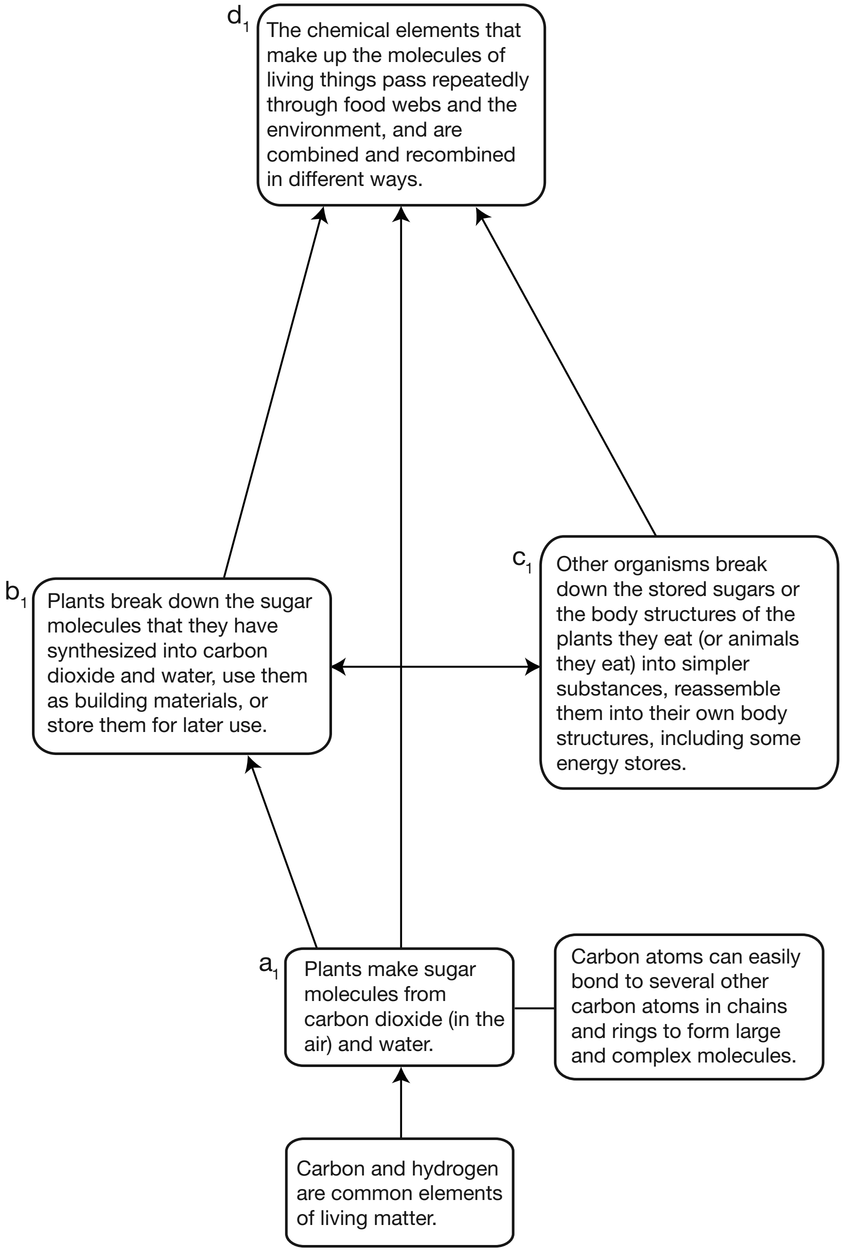

FIGURE 2.3 Detail from a map showing relationships among ideas about matter transformations that were the focus of AAAS Project 2061's review of biology textbooks (AAAS, 2005).

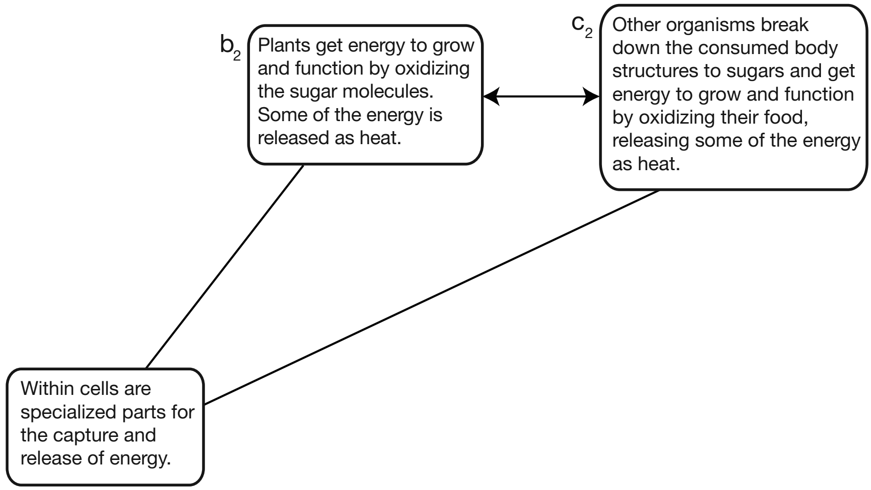

FIGURE 2.4 Detail from a map showing relationships among ideas about matter and energy transformations that were the focus of AAAS Project 2061's review of biology textbooks (AAAS, 2005).

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 organ-