CHAPTER 32

Ensuring That College Graduates Are Science Literate:

Implications of K–12 Benchmarks and Standards

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Are college and university students getting what they need from their science courses? According to a study by Seymour and Hewitt of undergraduate science and engineering education, many students expressed general dissatisfaction with the quality of their course work and instruction. Seniors who were going to graduate with degrees in science or engineering fields reported that their "first two years had given them a shaky foundation for higher level work" and nonmajors felt that their need for basic understanding of science and mathematics had not been met (as cited in Advisory Committee to the National Science Foundation Directorate for Education and Human Resources 1996, p. 38). Findings from this study, along with similar statements from colleges and universities, public and private funding agencies, and scientific societies call attention to the need for reform of undergraduate science courses, particularly those at the introductory level and those intended for nonscience majors. In a 2002 synthesis of 17 years of reports from a range of organizations, Project Kaleidoscope emphasized their shared vision for reform of undergraduate science education:

> *The vision is of an environment in which all American undergraduates have access to learning experiences that motivate them to persist in their studies and consider careers in these fields; it is of an environment that brings undergraduates to an understanding of science and technology in their world. It is a vision that calls for attention to practices and policies that affect shaping the curriculum and building human and physical infrastructure to sustain strong programs. It is a vision that calls for collective action.* (p. 1)

To make this vision a reality requires, among other things, a closer collaboration between higher-education institutions and the K–12 education system. Most educators and policy makers agree that there is a growing recognition of their interdependence. It is also clear that educators at both levels have knowledge and expertise that can be of benefit to the other. In recent years, this has led to the concept of a seamless K–16 continuum in which K–12 and higher-education institutions share common goals and accountability. At least half of all states have initiated some level of K–16 cooperation, particularly in the area of teacher education (Kirst and Usdan 2004).

This chapter draws on some fundamental lessons learned about science teaching and learning at the K–12 level that are likely to be applicable to a higher-education context. Recommendations are made in three areas that seem especially important to improving undergraduate science programs: (1) identifying the goals for learning, (2) designing a curriculum or sequence of learning activities that will enable students to achieve the goals, and (3) fostering a climate that will support continued monitoring, evaluation, and improvement over the long term. The chapter will highlight relevant K–12 tools and strategies that are consistent with a goals-based and learner-based approach to science teaching and learning. Working on their own or collectively, college and university faculty can use these strategies and tools to make progress in improving the content, teaching, and outcomes of undergraduate science education.

Since the mid-1980s, the reform of pre-college science education has focused in large part on science literacy: establishing it as a goal for all citizens, defining what constitutes science literacy for high school graduates and progress toward it for K–12 students, and developing teaching methods and materials that can help all students achieve it. At the same time, a small but growing body of research has enabled K–12 educators to base their reforms on credible findings about how learners develop and apply science knowledge and what that implies for the organization of content and selection of instructional strategies and materials. The American Association for the Advancement of Science (AAAS) with its Project 2061, the National Research Council (NRC), and the National Science Teachers Association (NSTA) have been among the organizations guiding these K–12 reforms. Their efforts have resulted in tools and strategies for specifying the science knowledge and skills that all students need and for promoting a standards-based approach to science teaching and learning. As these reform efforts continue to play out at the K–12 level, they also contribute to an ongoing reevaluation of the nature, purpose, and quality of science education at the undergraduate level.

Developing Goals for Undergraduate Science Learning

The idea of starting out with an end in mind is common in many endeavors, particularly in the design professions such as architecture, engineering, and the graphic arts (AAAS 2001b; Wiggins and McTighe 1998). In education, however, the content of the curriculum and how it is taught are more likely to have their origins in "textbooks, favored lessons, and time-honored activities rather than ... from targeted goals or standards" (Wiggins and McTighe 1998, p. 8). What is needed, say reformers, is precisely the reverse approach. By first establishing the purposes of a curriculum—whether for K–12 or university students—the task of identifying more specific goals for learning can take place within a framework where constraints and trade-offs can be considered carefully.

A K–12 Example

An example of this approach is the process used by AAAS's Project 2061 in its long-term effort to help reform K–12 science education. In the late 1980s, Project 2061 staff convened panels of scientists from across the disciplines to help define the end points—that is, what students should know and be able to do in science, mathematics, and technology after 13 years of schooling. As a first step, the scientific panels formulated a rationale for selecting a credible set of learning goals in the natural and social sciences, mathematics, and technology for all high school graduates (i.e., What would a science-literate adult need to know and be able to do in order to thrive in a world shaped by science and technology?). Next, they considered the degree of specificity that would be required (i.e., How much detail is needed to describe what students are intended to learn?). Finally, they addressed the feasibility of each goal (i.e., What will students actually be able to learn, given the real-world constraints of the classroom?). As will be described below (and in more detail in the works referenced in this section), this process took three years to complete, required substantial funding, and involved hundreds of scientists and educators and multiple levels of review (AAAS 2001b). The product of that effort—one that few college science departments would be willing or able to replicate—was Project 2061's report *Science for All Americans* (AAAS 1990b), which describes the knowledge and skills that science literacy would entail and ends with an agenda for action throughout the education system.

Among the report's recommendations is a call for colleges and universities to establish science literacy as a top priority and to "reshape undergraduate requirements as necessary to ensure that all graduates (from whom, after all, tomorrow's teachers will be drawn) leave with an understanding of science, mathematics, and technology that surpasses" what *Science for All Americans* recommends for high school graduates (1990b, p. 226). Although the goals in *Science for All Americans* are meant to be achieved by high school graduation, few first- or second-year college students are likely to have built this kind of conceptual foundation. As a result, the recommendations in *Science for All Americans* can also serve as a logical starting place for identifying learning goals for college courses, especially for introductory courses and for students who are not science majors.

Science for All Americans describes a coherent body of knowledge that characterizes adult science literacy. It is based on the belief that the science-literate person is one who is aware that science, mathematics, and technology are interdependent human enterprises with strengths and limitations; understands key laws and theories of science; is familiar with the natural world and recognizes both its diversity and unity; and uses scientific knowledge and scientific ways of thinking for individual and social purposes. The recommendations fall into four major categories:

- Chapters 1–3 deal with the nature of science, mathematics, and technology as human enterprises, and Chapter 10 illustrates the evolution and impact of scientific knowledge with examples of some of the great episodes in the history of the scientific endeavor.
- Chapters 4–9 cover basic knowledge about the world as currently seen from the perspective of science and mathematics and as shaped by technology.
- Chapter 11 presents some crosscutting themes that can serve as tools for thinking about how the world works.
- Chapter 12 lays out the habits of mind that are essential for science literacy.

Figure 32.1

Criteria for Selecting Goals for *Science for All Americans*

Utility: Will the proposed content—knowledge or skills—significantly enhance the graduate's long-term employment prospects? Will it be useful in making personal decisions?

Social Responsibility: Is the proposed content likely to help citizens participate intelligently in making social and political decisions on matters involving science and technology?

The Intrinsic Value of Knowledge: Does the proposed content present aspects of science, mathematics, and technology that are so important in human history or so pervasive in our culture that a general education would be incomplete without them?

Philosophical Value: Does the proposed content contribute to the ability of people to ponder the enduring questions of human meaning such as life and death, perception and reality, the individual good versus the collective welfare, certainty and doubt?

Childhood Enrichment: Will the proposed content enhance childhood (a time of life that is important in its own right and not solely for what it may lead to in later life)?

Source: Reprinted from American Association for the Advancement of Science. 1990. *Science for all Americans* (pp. xix–xx.). New York: Oxford University Press. © 1989, 1990 by the American Association for the Advancement of Science.

The recommendations in *Science for All Americans* are intended to apply to everyone, regardless of socioeconomic status or career choice. Selected by disciplinary experts, these science literacy goals represent a consensus of what the scientific community thought was important for all citizens to know. The panels were charged with making recommendations on what content in five domains—biological and health sciences, mathematics, physical and information sciences and engineering, social and behavioral sciences, and technology—is most worth learning by everyone. Panel members proposed the particular knowledge or skills that they believed to be especially important for all students to acquire by the time they graduated from high school. Such arguments as "It's in all the popular textbooks," "I remember learning it when I was in school," or "A Nobel laureate at my university agrees with me" were not adequate endorsements.

Proposals from panel members also had to be clear and unambiguous. For example, "Everyone should understand momentum" would not do; the proponent had to specify what it is about momentum that students would be expected to learn. Is it the general idea of momentum? Its calculation? Its conservation? Its applications? A proposed learning goal was added to the list of possibilities if, in the ensuing discussion, a persuasive case was made for it. Moreover, the case had to take into account the selection criteria that had been agreed to ahead of time (Figure 32.1). The criteria stipulated that learning goals must be important for individuals and important for society, that they must matter in the long run, and that they should define the knowledge and skills students will need for living interesting, socially responsible, and productive lives after leaving school.

In addition to their individual importance, the ideas described in *Science for All Americans* were chosen for their coherence as a set. Ideas that contributed to understanding other ideas were given high priority. But even after applying all of these criteria, the panelists found that there was much more worth knowing than students could be expected to learn in the K–12 years. Having a pre-established set of criteria helped, but that alone did not sufficiently narrow the range of possible content and skills. Curriculum designers at all levels face the same problem: It is simply not feasible to teach everything. Choices must be made and priorities set. How does one decide? Answering that question means choosing the best among many potentially valuable learning goals.

To create an integrated and coherent set of goals from all five of the scientific and technical domains, the panels presented their recommendations to each other and, based on the feedback they received, goals were revised, added, or eliminated. Subsequent drafts were reviewed extensively in an attempt to reduce the goals to a reasonable number. In this phase of the process, panelists asked: What is the relative importance of each idea to be learned in comparison with the other recommended learning goals? Eventually, the five panels issued their reports and then drew on them to create a single unified presentation of the recommendations for science literacy. The question of priority continued to surface both within and across the domains of science, mathematics, and technology. After individuals, scientific societies, educational associations, the National Council for Science and Technology Education, and the board of directors of AAAS had evaluated successive drafts, *Science for All Americans* emerged.

This intensive three-year process led to the formulation of a particular set of learning goals in science, mathematics, and technology, but it is not the only possible formulation. Other groups and other individuals using a similar process would be likely to produce different, but equally valid, sets of learning goals. The point is that the goals derive their validity from a process that generates a broad consensus of expert opinion, provides adequate time for debate and review, and focuses that debate on predefined criteria for selecting appropriate goals.

In 1993, the recommendations for adult science literacy in *Science for All Americans* were elaborated by Project 2061 into a set of specific statements of the ideas and skills that students should learn by the end of grades 2, 5, 8, and 12. Published as *Benchmarks for Science Literacy* (AAAS 1993), these goals provide guidance to educators as they plan and deliver instruction to students, to curriculum developers as they create new instructional materials, and to assessment specialists as they devise ways to evaluate what students know and are able to do. In 1996 the NRC completed a similar multiyear process and published its learning goals as content standards in *National Science Education Standards* (*NSES*; NRC 1996). With considerable overlap between the learning goals in *Benchmarks for Science Literacy* and *NSES*, these two documents represent a strong national consensus on the science that is most important for all students to learn (NRC 2003). From this point on, when we speak of learning goals, we will be referring to the kinds of statements that are found in *Benchmarks for Science Literacy* and *NSES*.

Coherence Is Key

Helping students to develop an interconnected, coherent understanding of science is a central premise of the reform efforts of Project 2061, the NRC, NSTA, and others. To move students toward this level of understanding requires, at the very least, a set of learning goals that are themselves coherent in their logic and structure. Bruner's view on this is apt: "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).

Organizing content to emphasize connections both within and across subject areas and grade levels can contribute to the coherence of an entire curriculum and, ultimately, to students' ability to make sense of new ideas and to fit them into their own developing conceptual frameworks. Consider, for example, a central lesson that researchers are drawing from their analyses of data collected for the Third International Mathematics and Science Study (TIMSS). As part of this massive study of K–12 science and mathematics achievement worldwide, researchers considered the coherence of content standards in the top-ranked countries and concluded that coherence in standards is critical:

> *Understanding implies, at least at some level, that the structure of the discipline has become visible to the learner so she or he can move beyond its particulars. We suggest that one way to facilitate such learning is by making the inherent logical structure of the discipline more visible both to teachers and students.* (Schmidt, Wang, and McKnight 2005, p. 554)

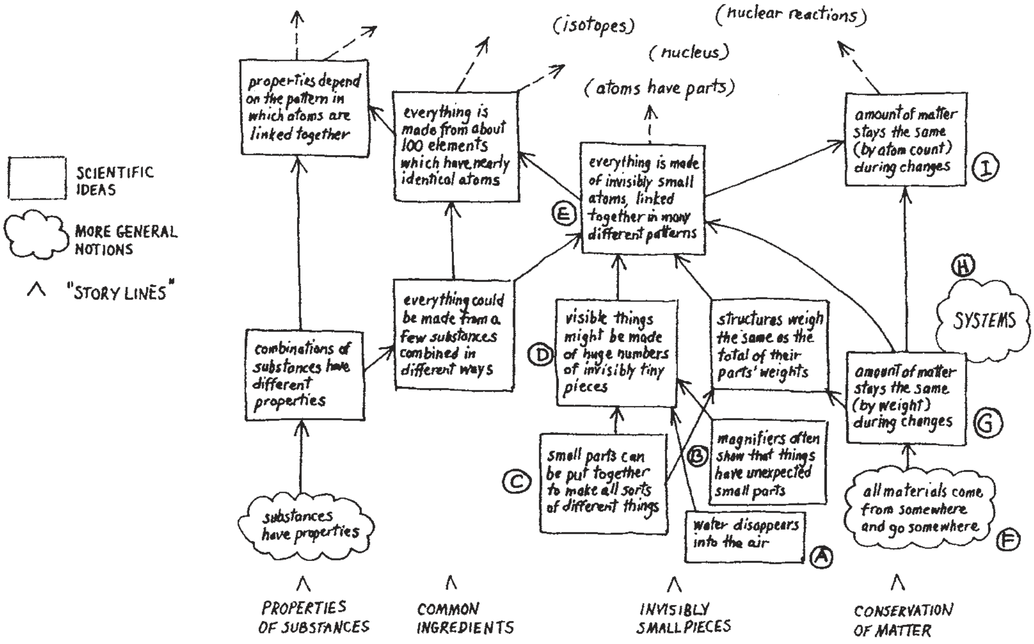
This view is also prevalent among those who develop and study K–12 science curriculum materials, and there appears to be a growing consensus that a curriculum or set of goals that attends closely to coherence—in terms of content presentation and learning progressions—is more likely to help students gain deeper and more sophisticated understandings over time (Catley, Lehrer, and Reiser 2004; Commission on Behavioral and Social Sciences and Education 2000; Smith et al. 2004).

The challenge is to make Bruner's "relatedness of knowledge" apparent to educators and to help them appreciate the elegance and simplicity of the fundamental ideas that undergird modern science. In response to this need for coherence, Project 2061 has produced a set of coordinated tools—each with a different purpose and perspective—that is focused on the same coherent set of science learning goals. In *Science for All Americans*, for example, Project 2061 presents more than 60 major topics in science, mathematics, and technology, setting out the central concepts and principles and showing how these threads are woven into the larger story of science literacy. In *Benchmarks for Science Literacy* (and in *NSES* as well), these same topics are unpacked into discrete ideas distributed into sequential K–12 grade bands to show appropriate steps toward science literacy. And in *Atlas of Science Literacy* (AAAS 2001a), these topics are further delineated in "strand maps" that emphasize conceptual developmental connections.

Used during the drafting of B*enchmarks for Science Literacy*, early versions of the strand maps (such as the one in Figure 32.2) helped the development teams think about how students make progress toward the adult literacy goals in *Science for All Americans* and how that progression might take place over the course of grades K–12. These early maps displayed connections among ideas both within a grade band and over time and were intended to facilitate the work of the teachers, researchers, and scientists who were working on *Benchmarks for Science Literacy*. It soon became apparent that the maps were also useful tools for curriculum and textbook adoption committees and for developers of instructional and assessment materials. Project 2061 has now completed a collection of nearly 50 maps and published them in *Atlas of Science Literacy* (AAAS 2001a). Each map focuses on a topic important for science literacy and shows the benchmarks—from primary school to high school—that students need to achieve as they build their understanding of the topic. Maps also depict relationships among benchmarks, us-

Figure 32.2

Example of How Concepts in *Science for All Americans* Related to a Particular Topic (in This Case, the Structure of Matter) Were Backmapped to Develop a Coherent Set of Grade Range Benchmarks


SCIENTIFIC IDEAS
MORE GENERAL NOTIONS
"STORY LINES"
(isotopes)
(nuclear reactions)
(nucleus)
(atoms have parts)
properties depend on the pattern in which atoms are linked together
everything is made from about 100 elements which have nearly identical atoms
everything is made of invisibly small atoms, linked together in many different patterns
E
amount of matter stays the same (by atom count) during changes
I
H
SYSTEMS
combinations of substances have different properties
everything could be made from a few substances combined in different ways
visible things might be made of huge numbers of invisibly tiny pieces
D
structures weigh the same as the total of their parts' weights
amount of matter stays the same (by weight) during changes
G
small parts can be put together to make all sorts of different things
C
B
magnifiers often show that things have unexpected small parts
substances have properties
water disappears into the air
A
all materials come from somewhere and go somewhere
F
PROPERTIES OF SUBSTANCES
COMMON INGREDIENTS
INVISIBLY SMALL PIECES
CONSERVATION OF MATTER

Reprinted from American Association for the Advancement of Science. 1993. *Benchmarks for science literacy* (p. 306). New York: Oxford University Press. © 1993 by the American Association for the Advancement of Science.

ing arrows to suggest how benchmarks in the earlier grades support those that come later (see Figure 32.3 for an example of an *Atlas* strand map).

To illustrate how Project 2061's tools are related and designed to present science concepts as part of a coherent story rather than as isolated bits of information, consider how they deal with the topic of conservation. *Science for All Americans* explicitly introduces this topic in the context of the flow of matter and energy in living systems:

> *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.* (AAAS 1990b, p. 66)

Science for All Americans also presents the topic in a historical context, describing the work of Lavoisier and the law of conservation of mass:

> *He showed that when substances burn, there is no net gain or loss of weight. When wood burns, for example, the carbon and hydrogen in it combine with oxygen from the air to form water vapor and*

> *carbon dioxide, both invisible gases that escape into the air. The total weight of materials produced by burning (gases and ashes) is the same as the total weight of the reacting materials (wood and oxygen).* (AAAS 1990b, p. 154)

Other sections explain the atomic structure of matter, making it clear that high school graduates should understand chemical reactions and the recycling of matter in terms of atoms and molecules. The following sections in *Science for All Americans* address the fundamental concept of conservation:

- 4D. Structure of Matter (pp. 46–47): Matter consists of a small number of "atomic" building blocks that combine and recombine.
- 5E. Flow of Matter and Energy (p. 66): Matter is conserved in living organisms—that is, though its form and location change, elements are recycled.
- 11C. Constancy and Change (pp. 173–174): Conservation is a property of closed systems.
- 10C. Relating Matter and Energy and Time and Space (p. 151): Matter is a form of energy, so mass/energy conservation holds even in nuclear reactions.
- 10F. Understanding Fire (pp. 153–155): Lavoisier's careful measurements demonstrate mass conservation in the burning process.
- 4B. The Earth (p. 44): Some of the earth's resources are nonrenewable.
- 3C. Issues in Technology (p. 33): Nonrenewable resources can be depleted or contaminated.
- 8B. Materials and Manufacturing (p. 112): Matter doesn't "disappear," so waste disposal can be a problem.

The information in these sections reflects Project 2061's vision of the *lasting* knowledge that students should acquire by the time they become adults and can serve as a guide for identifying college-level learning goals related to the concept of conservation.

In *Benchmarks for Science Literacy* and in *NSES*, the idea of mass conservation is listed explicitly as a learning goal for middle school students. *Benchmarks* also expects middle school students to understand conservation in terms of atoms and molecules:

> **Benchmarks:** *No matter how substances within a closed system interact with one another, or how they combine or break apart, the total mass of the system remains the same. The idea of atoms explains the conservation of matter: If the number of atoms stays the same no matter how they are rearranged, then their total mass stays the same.* (AAAS 1993, p. 78)

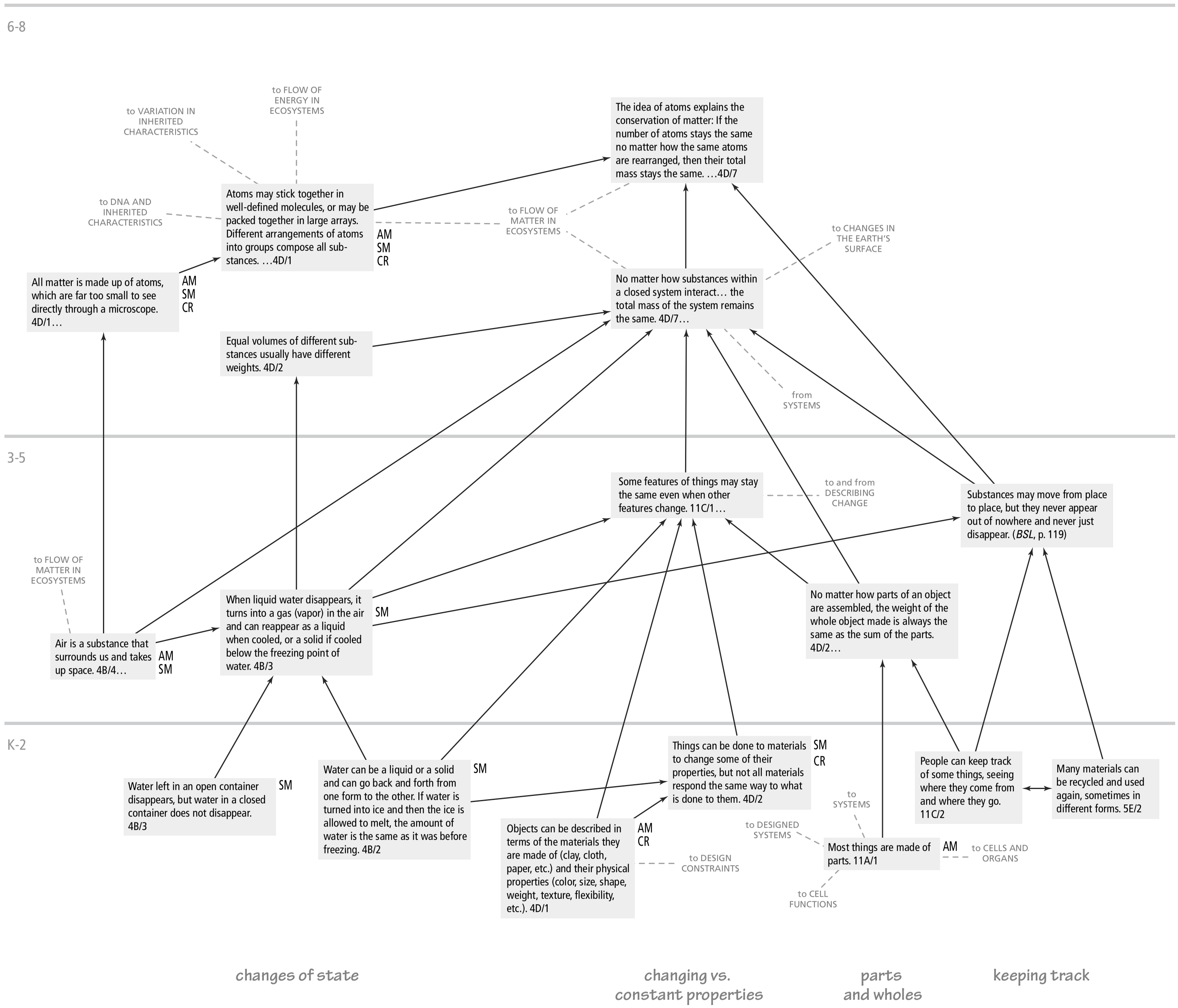
> ***NSES:*** *Substances react chemically in characteristic ways with other substances to form new substances (compounds) with different characteristic properties. In chemical reactions, the total mass is conserved.* (NRC 1996, p. 154)

Both the *Benchmarks* and *NSES* versions of the learning goal assume that middle school students will already understand that materials can exist in different states and that water can go back and forth between states (AAAS 1993, pp. 67–68; NRC 1996, p. 127).

Figure 32.3 shows the conservation of matter strand map from *Atlas of Science Literacy*. It

Figure 32.3

Structure of Matter: Conservation of Matter Strand Map



The idea of atoms explains the conservation of matter: If the number of atoms stays the same no matter how the same atoms are rearranged, then their total mass stays the same. …4D/7

Atoms may stick together in well-defined molecules, or may be packed together in large arrays. Different arrangements of atoms into groups compose all substances. …4D/1

All matter is made up of atoms, which are far too small to see directly through a microscope. 4D/1…

No matter how substances within a closed system interact… the total mass of the system remains the same. 4D/7…

Equal volumes of different substances usually have different weights. 4D/2

Some features of things may stay the same even when other features change. 11C/1…

Substances may move from place to place, but they never appear out of nowhere and never just disappear. (*BSL*, p. 119)

When liquid water disappears, it turns into a gas (vapor) in the air and can reappear as a liquid when cooled, or a solid if cooled below the freezing point of water. 4B/3

Air is a substance that surrounds us and takes up space. 4B/4…

No matter how parts of an object are assembled, the weight of the whole object made is always the same as the sum of the parts. 4D/2…

Water left in an open container disappears, but water in a closed container does not disappear. 4B/3

Water can be a liquid or a solid and can go back and forth from one form to the other. If water is turned into ice and then the ice is allowed to melt, the amount of water is the same as it was before freezing. 4B/2

Objects can be described in terms of the materials they are made of (clay, cloth, paper, etc.) and their physical properties (color, size, shape, weight, texture, flexibility, etc.). 4D/1

Things can be done to materials to change some of their properties, but not all materials respond the same way to what is done to them. 4D/2

Most things are made of parts. 11A/1

People can keep track of some things, seeing where they come from and where they go. 11C/2

Many materials can be recycled and used again, sometimes in different forms. 5E/2

6-8
3-5
K-2
to VARIATION IN INHERITED CHARACTERISTICS
to FLOW OF ENERGY IN ECOSYSTEMS
to DNA AND INHERITED CHARACTERISTICS
to FLOW OF MATTER IN ECOSYSTEMS
to CHANGES IN THE EARTH'S SURFACE
from SYSTEMS
to and from DESCRIBING CHANGE
to FLOW OF MATTER IN ECOSYSTEMS
to SYSTEMS
to DESIGNED SYSTEMS
to DESIGN CONSTRAINTS
to CELLS AND ORGANS
to CELL FUNCTIONS
AM SM CR
AM SM CR
AM SM
SM
SM
SM
AM CR
SM CR
AM
changes of state
changing vs. constant properties
parts and wholes
keeping track

culminates in middle school with the benchmark shown above. The two ideas in the benchmark (mass conservation of substances and its explanation in terms of atoms) are displayed in two separate boxes to distinguish their precursors. This map is unusual because it does not include high school benchmarks. In other *Atlas* maps, however, this middle school benchmark dealing with conservation provides a foundation for high school benchmarks related to the transformation and conservation of matter and energy in ecosystems and the interconversion of matter and energy in nuclear reactions.

With appropriate interest and funding, university faculty could undertake a similar process to articulate a coherent set of learning goals for college programs and courses. Several foundations have supported efforts to rethink and revise undergraduate courses in the past, some of which have resulted in elaborate and interesting course syllabi (e.g., the New Liberal Arts Program funded by the Alfred P. Sloan Foundation in the 1980s, the Project on Liberal Education and the Sciences funded by the Carnegie Corporation of New York [AAAS 1990a], and the National Science Foundation's Collaboratives for Excellence in Teacher Preparation [CETP] program in the 1990s). It was through such funding that Dr. Katherine Denniston of Towson University, along with other science faculty from across the University of Maryland System, developed new science courses such as the biosciences course that is described later in this chapter. The National Science Foundation's Course, Curriculum, and Laboratory Improvement (CCLI) program and the Department of Education's Fund for Improvement of Postsecondary Education (FIPSE) and its Mathematics-Science Partnerships program currently support such efforts. In addition, some universities may offer incentives and support for individuals and department teams engaged in curriculum reform and development projects.

Based on his experience working with Project 2061 to foster closer ties between science faculty and education faculty at Towson University, Laurence Boucher, who was then dean of the College of Science and Mathematics, suggested that a "mini-grant program to provide seed money" for new course development and pilot studies would be "a strong motivating factor for faculty" (Boucher, manuscript in preparation). To help engage Towson faculty in reform efforts, Boucher offered modest stipends to those who were willing to engage in specific tasks such as reviewing new curriculum materials and analyzing courses.

Faculty can work individually or as teams, but there may be more lasting effects if several members of a department are involved. For interdisciplinary courses in particular, it makes sense to involve faculty from all of the relevant departments in designing learning goals for the course. Organizations such as Project Kaleidoscope and scientific societies such as the American Institute of Biological Sciences or the American Association of Physics Teachers often promote and facilitate such collaborations among their members.

Applying a K–12 Process for Undergraduate Course Design

Good designs do not happen by accident. Designing a course, like designing a skyscraper or a highway exit or a garden, needs to be both purposeful and deliberate. Basic design principles drawn from other areas such as engineering or architecture can be helpful. The basic proposition of *Designs for Science Literacy*, Project 2061's guide to curriculum reform, is that "treating curriculum reform as a design problem will contribute significantly to the achievement of the ambitious goals of science literacy" (AAAS 2001b, p. 1). *Designs* points out that course design must be undertaken within a "context of purposes—or goals—and constraints" (AAAS 2001, p. 44). In this section, we describe and illustrate some key steps in any design process that aims to serve the needs of students and the goals of science literacy. Variations of this process are currently being used by several K–12 curriculum developers, and their research is helping to identify its most promising features and applications (Heller 2001; Reiser et al. 2003). Summarized in the following steps, the process can be readily adapted for college course design:

- Identify a coherent set of learning goals as a foundation for your design. Articulate the most important ideas you want your students to remember long after your course has ended.
- Take account of where your students are starting from by becoming familiar with the research base (if one exists) on preconceptions and misconceptions that students commonly have on the topics that your course will address.
- Develop learning activities around phenomena and representations that focus students' attention on the ideas in the learning goals and are likely to help them make progress.
- Sequence the activities carefully, deciding which need to be firsthand or vicarious, how each will be used, and the role each will play in promoting students' understanding.
- Develop meaningful questions to help students relate course activities to the scientific ideas they are expected to learn.
- Monitor students' progress carefully, using assessments that are well aligned to the learning goals of your course and effective in probing precisely what students do and do not know.
- Try out the activities and other course components, assess what students have learned and why, and determine what modifications should be made in the course design.

This basic process is repeated several times, with each round of revision based on feedback from students' assessment responses. More iterative than linear, these cycles of testing and refining all aspects of the course are integrated into the development process itself. Underlying the process is the assumption that students will learn more if their instruction is focused on a coherent set of specific ideas rather than a collection of loosely related ideas that fall into a broad topic area. Clear definition of the most important ideas allows for more precise curriculum design and assessment of student outcomes, which can then lead to more informed revisions.

Faculty can use this basic process for the design of any course—from an integrated science course for nonmajors to an advanced physics course for majors—as long as the learning goals are clearly stated. At The George Washington University, for example, science faculty are working with Project 2061 to develop a set of advanced-level courses for a new master's degree program for professional studies in middle grades science. They are using the process outlined above to design their courses around the 12th-grade learning goals for physical, life, and Earth science topics included in *Benchmarks for Science Literacy*.

Every step in the design process contributes value to the end product. We have already dealt with the first step of identifying an appropriate set of learning goals for a course. In the following subsections, we will consider in more detail three steps that are central to this course design process. We will also point out instances where faculty can take advantage of K–12 tools and resources created by Project 2061 and others to facilitate their course development work.

Take Account of Where Students Are

In an ideal world, students would arrive at colleges and universities with a solid knowledge of the ideas in *Science for All Americans*. University courses could then present students with opportunities to learn more sophisticated ideas that build on their prior knowledge. For example, with a solid understanding of matter conservation and its explanation in terms of atoms, college students could apply those ideas to writing balanced chemical equations or to explaining the role of various organisms (including humans) in the cycling of nitrogen in the biosphere. They could be expected to be able to trace various paths of nitrogen from its reservoir in the atmosphere, through its conversion to nitrates and ammonia, their incorporation into proteins and nucleic acids in cells of various living organisms, the production of nitrogen oxides in factories and its contribution to acid rain, and so forth. College students could also apply conservation ideas to understanding the role of bedrock as a reservoir of phosphate in the phosphorus cycle and be expected to be able to describe its course through processes of erosion and deposition, uptake by microorganisms and plant roots, its incorporation into the molecules that make up living things, such as DNA and adenosine triphosphate (ATP), and how it eventually becomes reincorporated into bedrock.

Unfortunately, this scenario is rare. College and university freshmen often arrive with inadequate knowledge and skills and exhibit misconceptions similar to those of middle and high school students. In her work with Project 2061 on a study of undergraduate science education funded by the John D. and Catherine T. MacArthur Foundation, Towson University professor Denniston observed that few students entering her biology classes, including biology majors, had achieved even the eighth-grade benchmarks related to heredity and evolution (Denniston, manuscript in preparation). A number of other university science faculty who have attended Project 2061 workshops have made similar comments about their students. Denniston reported another experience as she began to encounter former students in her more advanced classes:

> *My own introductory biology students came into my medical microbiology class with an appalling lack of understanding of the biological principles that I had taught them. Student evaluations notwithstanding, I had somehow failed to help these students learn.... Why weren't my students learning?* (Denniston, manuscript in preparation)

Of course, Denniston is not alone in her realization that learning is not always the result of teaching and that other factors may be getting in the way of students' understanding. Harvard physics professor Eric Mazur describes his experience in dealing with his students' learning difficulties:

> *Students enter their first physics course possessing strong beliefs and intuitions about common physical phenomena. These notions are derived from personal experiences and color students' interpretations of material presented in the introductory course. Instruction does very little to change these "common-sense" beliefs.... When asked, for instance, to compare the forces in a collision between a heavy truck and a light car, a large fraction of the class firmly believes the heavy truck exerts a larger force on the light car than vice versa. My first reaction was, "Not my students ...!" I was intrigued, however, and [tested my own students]. The results of the test were undeniably eye-opening.* (quoted in Richardson 2005, pp. 19–20)

To find out where students "are" in their understanding of particular concepts, it would make sense to ask them outright. But it is not usually as straightforward as that, particularly where abstract ideas are concerned. What is more, students are rarely expected to reflect on their own learning, so they are often ill equipped to provide useful feedback on where they are in their conceptual development. We can, however, gain helpful insights about starting points for teaching and learning from logical backmapping of learning goals and from research on students' misconceptions about specific science topics. (By "backmapping" we mean a process for working backward from the desired learning goals for high school graduates to identify conceptual steps that students would need to make in the earlier grades to achieve those goals.)

With the likelihood that incoming students may not have achieved even a high school level of science literacy, it makes sense to define appropriate outcomes for courses by first examining the relevant middle and high school benchmarks. Denniston (manuscript in preparation) describes departmental recommendations and her state's core learning goals for high school students as major influences on her choice of topics for her introductory bioscience course. Through her participation in the Project 2061 study, she became acquainted with *Science for All Americans* and *Benchmarks for Science Literacy* and was able to compare her course's content to the learning goals in those documents. She found them to be consistent and found the K–12 benchmarks helpful in elaborating a more detailed set of content objectives. In some cases, the content objectives mirror benchmarks (e.g., "know that mutations of the DNA alter the proteins that are produced; these may alter the phenotype of the organism or cell or kill it"). In other cases, she chose to hold her students to higher expectations (e.g., expecting them to know *how*—rather than just *that*—the structure of DNA encodes genetic information and *how* the genotype of an organism or cell is responsible for the phenotype of the organism or cell). Denniston points out that because college students are likely to have a stronger grasp of chemistry, they may be better able to appreciate the mechanisms of these processes than they are as 9th or 10th graders, when they typically take high school biology. Thus, through this backmapping process, Denniston was able to develop a logical learning trajectory for her students, setting goals that would build on what they were likely to have achieved by the end of high school.

After comparing college-level outcomes with middle and high school benchmarks, a next step is to determine what ideas their own students are likely to have about the topics to be covered in the course. This involves examining relevant learning research, if research has been published on the topic, and probing students' ideas with appropriate assessment tasks. For the topic of conservation of matter, for example, several research studies have shed light on some common student preconceptions and misconceptions. The available research on this topic has been summarized and accompanies the Conservation of Matter strand map in *Atlas of Science Literacy*:

> *Students cannot understand conservation of matter and weight if they do not understand what matter is, or accept weight as an intrinsic property of matter, or distinguish between weight and density (Lee et al., 1993; Stavy, 1990). By 5th grade, many students can understand qualitatively that matter is conserved in transforming from solid to liquid. They also start to understand that matter is quantitatively conserved in transforming from solid to liquid and qualitatively in transforming from solid or liquid to gas—if the gas is visible (Stavy, 1990). For chemical reactions, especially those that evolve or absorb gas, weight conservation is more difficult for students to grasp (Stavy, 1990).* (AAAS 2001a, p. 56)

Other sources of research on middle and high school students on this topic and other topics can be found in *Making Sense of Secondary Science* (Driver et al. 1994), in *Benchmarks for Science Literacy* (AAAS 1993; see Chapter 15, "The Research Base"), and in *Atlas of Science Literacy*, where summaries of the available research accompany each of the conceptual strand maps (AAAS 2001a).

Evidence from research studies indicates that for some topics, at least, many students retain their earlier misconceptions, even at the college level (Berkheimer, Anderson, and Spees 1990). Research on college students' understanding of specific science topics is available in professional journals such as *Journal of College Science Teaching, Journal of Chemical Education*, and *Journal of Research in Science Teaching*. In addition to providing research findings that shed light on students' ideas, the research articles are a potential source of assessment tasks that may be useful for probing students' initial ideas about a topic. A typical article, for example, is one from *Journal of Chemical Education* that explores the nature of misconceptions about hydrogen bonding that are common among college-level students (Henderleiter et al. 2001). Although hydrogen bonding is a basic principle with applications in all areas of chemistry, the study finds that even in their second year of college chemistry, some students

> *still possess misconceptions found in younger, less experienced students. They have not abandoned—or have even formed—faulty beliefs, such as hydrogen bonds can be induced, intermolecular forces lead to reactions, or boiling breaks covalent bonds. These misconceptions make it difficult, if not impossible, for students to apply chemical concepts to data interpretation and analysis. Reliance on rote memorization as a means to analyze and interpret data is also problematic.* (Henderleiter et al. 2001, p. 1129)

This article includes the assessment tasks and interview questions the researchers used to probe the students' understanding, along with recommendations for some specific instructional strategies and activities designed to help students overcome their misconceptions and foster their analytical and problem-solving skills.

Even if research provides insights into ideas that students often have about a topic, it is still useful to find out firsthand whether your students have those same ideas. When research is not available, it is especially important to identify appropriate assessments or use other strategies that can effectively probe students' thinking. Interviewing a subset of students on a few questions at the outset can help uncover particularly prevalent or challenging misconceptions. For example, the following questions could be used to probe students' initial ideas about conservation:

> *Question 1:* Jill is investigating the reaction between baking soda and vinegar. She places vinegar in one cup and baking soda in a second cup. Then she places both of the cups on a balance. The balance with the two cups, baking soda, and vinegar reads 120 grams. Then she pours the vinegar into the cup with the baking soda. The baking soda and vinegar react and produce a gas. She places both cups back on the balance. Do you think the balance will read 120 grams after the chemical reaction? Why?
>
> As a follow-up, ask your students how they could modify the procedure so that the reverse of what they said occurred. For those responding that the balance would still read 120 grams, ask, "Is there a way to change Jill's procedure to make the reading change? How?" For those responding that the balance would not read 120 grams, ask, "Is there a way to change Jill's procedure to make the reading stay the same? How?"

Question 2: Which of the following is a possible chemical reaction? Explain your choice(s) and why you think each of the other choices are not possible.

A. $CuSO_4 \rightarrow CuSO_4$
B. $O_2 + CO_2 \rightarrow CO_2 + O_2$
C. $NaOH + HCl \rightarrow NaCl + H_2O$
D. $O_2 \rightarrow H_2$

In designing her bioscience courses, Towson University's Denniston built in several strategies for identifying her students' misconceptions. Using questions to accompany reading assignments, classroom exercises in which student groups were asked to explain their understanding of a topic before it has been studied, periodic assignments in which students were asked to write down their current understanding of a targeted concept, and weekly e-mail journals in which students reflected on their learning, Denniston was able to uncover potential problems:

> *One misconception identified in this way is that students may understand chromosomal events of meiosis (separation of homologous chromosomes into daughter cells) and fertilization (joining new combinations of chromosomes from two parents) and yet have no concept that these random events are the basis for using probability to predict the outcome of genetic crosses.* (Denniston, n.d., p. 27)

With those insights, Denniston made changes in the structure of the course and added instructional activities that would address her students' misconceptions head-on. Each year she was able to refine her course further based on the progress her students were making in their understanding.

Develop Activities and Relevant Phenomena

Much of the point of science is explaining real-world phenomena in terms of a small number of ideas. For students to understand and appreciate the explanatory power of scientific ideas, they need to have a sense of the range of phenomena that they can explain and predict. *Benchmarks* and *NSES* present expectations for K–12 students in terms of empirical generalizations and accepted theories. However, neither document presents specific phenomena to illustrate the empirical generalizations or the explanatory power of the theories, leaving decisions about which phenomena are most appropriate to designers of curriculum and instruction. These decisions must take into account the nature of the knowledge or skill to be learned, what is known about difficulties students may have in learning them, and the resources that are likely to be available to students and teachers in the classroom. For example, to enable students to learn the ideas associated with the concept of conservation, a curriculum designer might decide that students should observe a range of phenomena, including phenomena they might encounter in the real world, and that the set of phenomena should include both changes of state and chemical reactions that have gases as reactants or products. Where possible, the reactions should involve simple molecules.

With these kinds of design constraints in mind, the developers of *Chemistry That Applies*, an instructional unit for grades 8–10 produced by the Michigan Science Education Resources Project (1993), focused on matter conservation and included phenomena to illustrate both mass conservation and how the atomic theory accounts for mass conservation. The unit presented students with a range of relevant phenomena: the distillation and decomposition of water; the reaction of calcium chloride with potassium carbonate, of Alka-Seltzer with water, and of baking soda with vinegar; the oxidation of butane; and the rusting of iron. Students first examined reactions involving only solids and liquids and observed that the mass did not change. In examining reactions involving gases, students observed that the mass did not change as long as matter was not allowed to enter or escape from the system.

Students then revisited these same reactions, representing and accounting for their observations using ball-and-stick models of the molecules involved. When considering mass conservation, the developers sequenced the phenomena to postpone consideration of gases until students had observed mass conservation with solids and liquids and to postpone consideration of gaseous reactants until students had experience with gaseous products. In contrast, when considering the atomic explanation for mass conservation, the developers sequenced phenomena to give students experience with simpler molecular recombinations before encountering more complex ones. Additional details about *Chemistry That Applies* and Project 2061's analysis of its content and instructional quality are available at *www.project2061.org/events/meetings/textbook/literacy/cdrom/CTA/CONTENT/CAcon.htm*; analyses of other middle and high school curriculum materials are available at *www.project2061.org/publications/textbook/default.htm?ql*.

Choosing appropriate phenomena and incorporating them effectively into course work can be as challenging for college faculty as it is for K–12 teachers. Considerations include not only the alignment of phenomena with the ideas that are to be learned but also the use of pedagogical strategies that can help students see the connections between the phenomena and those ideas. For its evaluations of middle and high school textbooks, Project 2061 developed criteria for judging the effectiveness of the phenomena presented in the textbooks in helping students learn specific science concepts and skills. These same criteria can be applied by faculty when making decisions about phenomena and how to use them to further their students' learning. Shaped by both research and teacher craft, the criteria offer faculty a framework for constructing science courses that

- engage students in a variety of vivid firsthand (if possible) experiences with phenomena that are relevant to the ideas that are to be learned,
- link the phenomena (along with related vocabulary and representations) explicitly to the ideas that are to be learned, and
- provide opportunitites and guidance to help students make sense of the phenomena and the ideas.

Even with these criteria as a guide, it may still be difficult to incorporate phenomena into a course design. In the case of middle and high school science textbooks, for example, Project 2061's evaluation studies found that most texts did not do a good job of presenting an adequate variety of appropriate phenomena (particularly in life science) to illustrate the ideas that students were to learn. Consider the following examples of activities designed for middle school students and their alignment (or lack thereof) to the idea that plants use the energy from light to make "energy-rich" sugars from carbon dioxide and water:

> *An activity in which students separate plant pigments through paper chromatography may fit with the general topic of photosynthesis but does not align with the substance [of this idea about matter and energy transformation].… The pigment chromatography activity could be used to explain the*

> *basis for the color change of leaves in the fall because it shows that even green leaves containing the pigments for their fall colors. However, the activity won't be useful for explaining the very important ideas ... stated above and, hence, would not be judged to align with them.... Neither [would] an activity in which plants are shown to grow toward the light nor an activity in which students read about and discuss the light-capturing step in photosynthesis address the sophistication of the idea that plants use light.... The former activity addresses the less sophisticated idea that plants need light (grades 3-5), and the latter addresses the more sophisticated idea that a chlorophyll molecule can be excited to a higher-energy configuration by sunlight (grades 9-12).* (Roseman and Stern 2003, pp. 271–272; © 2003 by Springer-Verlag, New York, Inc.)

In contrast to these poorly aligned activities, one that is well aligned with the middle school idea about matter transformation might

> *direct students to use diabetic strips to show that sugar is present in iris leaves grown in the presence of* CO_2 *but not in its absence. An experiment in which sugar (or starch) is detected on leaves grown in open jars, but is detected only in the first few hours on similar leaves grown in closed jars, would also be aligned.* (Stern and Roseman 2001, p. 55)

To help provide educators with a wider variety of resources that can be used with confidence to teach important science ideas, Project 2061 is building an online annotated database of relevant phenomena that are well aligned to national learning goals. The database includes full descriptions of phenomena for more than a dozen important topics, including the solar system, conservation of matter, laws of motion, flow of matter in ecosystems, molecular basis of heredity, and natural selection. These same topics are also central to the science framework being developed for the National Assessment of Educational Progress (NAEP), scheduled to be administered to students beginning in 2009. In some cases, the descriptions in the database include references to detailed activities related to the phenomena or to research studies that shed light on the science itself or on the utility of the phenomena as teaching resources. Although the phenomena are being selected with K–12 teachers and curriculum developers in mind, they are likely to be useful in the design of college-level introductory science courses or courses for nonscience majors. Table 32.1 presents examples of phenomena that could be used to help students in grades 6–16 understand important ideas about matter and energy transformation in living systems ("A Jump-Start" 2004).

Monitor Students' Progress

Finding out what students are learning as a result of instruction is an essential element of any effort to improve curriculum and teaching. Currently, assessment of student learning at the K–12 level plays a much more prominent role as an accountability measure than it does as a diagnostic tool. Nevertheless, research suggests that monitoring students' progress has the potential to promote learning (Stern and Ahlgren 2002) by providing teachers with data that allows them to diagnose problems their students are having and make appropriate adjustments in their instructional strategies. Assessment of student progress is also a powerful tool for curriculum designers, and this application of assessment will be discussed later in this chapter.

At the college level, most institutions focus on students' course evaluations (which may or may not ask students to report on what they have learned) as a primary measure of success for

Table 32.1

Examples of Phenomena Related to Ideas About Matter and Energy Transformations in Living Systems

Idea	Phenomena That Could Be Used to Illustrate This Idea
Plants make sugar molecules from carbon dioxide (in the air) and water, releasing oxygen as a by-product.	• Sugars can be detected in tissues of a variety of plants, such as sugar beets, onion bulbs, and corn. • Sugar levels are reduced or absent in onion bulbs that are sprouted in the absence of carbon dioxide. • Radioautographs of *Chlorella* (a unicellular green algae) grown in the presence of $^{14}CO_2$ show ^{14}carbon in various organic compounds, including sugars.
Plants break down the sugars they have synthesized back into carbon dioxide and water, use them as building materials, or store them for later use.	• Carbon dioxide can be detected in the presence of seeds germinated in the dark but not in the presence of dry seeds. • Geranium leaves kept in the dark for 24 hours have reduced levels of starch, compared with light-grown plants; and corn leaves have reduced levels of sugar. • Chlorella originally grown in the presence of $^{14}CO_2$ release $^{14}CO_2$ and show reduced amounts of ^{14}carbon in various organic compounds, including sugars. • Air, water, and minerals are the only substances given to a hydroponically grown tomato plant, yet it grows and produces structures that look different from these inputs. Furthermore, the plant weighs more than the water and minerals it uses. • If leaves of daffodil bulbs are removed in the spring, the bulbs show less increase in mass by fall than bulbs with leaves left on. The smaller bulbs usually don't produce flowers the next season.

a course or for an instructor's performance. But, as the work of McDermott and the Physics Education Group has shown, "when student learning is used as a criterion,… the outcome is often quite disappointing. Systematic investigations have demonstrated that the gap between what is taught and what is learned is often greater than many instructors realize" (Herron, Shaffer, and McDermott 2005, p. 33). While surveys of students' attitudes about their courses may provide a certain kind of useful feedback, they will not yield the information that is needed to modify instruction to improve students' learning. What is needed are assessments that are carefully linked to the ideas and skills being taught so that judgments about what students do or do not know can be made with a high degree of certainty and specificity. With this learning data in hand, instructors can begin to modify their courses and their teaching to respond to the needs of their students.

For its studies of middle and high school science textbooks, Project 2061 developed criteria for considering how well each book's assessment tasks aligned with the targeted ideas and how well those assessments measured students' understanding of those same ideas (Stern and Ahlgren 2002). Drawing on its textbook evaluations, Project 2061 has now articulated more fully a set of criteria and a procedure for analyzing and profiling assessment items for their alignment with content standards and for other characteristics that affect their usefulness in providing information about what students know about specific ideas. The procedure considers (1) whether the ideas in the content standard are *needed* to complete the assessment task successfully or if the task can be completed without them, and (2) whether those ideas are *enough by themselves* or if other ideas and skills are required. The procedure also involves analyzing assessment items for their comprehensibility; susceptibility to test-wise solution strategies; bias related to gender, class, race, and ethnicity; and appropriateness of the task context.

Project 2061's criteria and procedures are being used to study assessment items of all types—from selected-response items such as multiple-choice questions to more involved performance tasks—and to analyze items for both diagnostic and evaluative purposes. Although Project 2061's approach to assessment analysis does not deal with the psychometric implications of an item, it does help to articulate exactly what is being tested by a particular item, thus improving the validity of interpretations that can be made from performance results.

Using these analytical tools to screen items released from state, national, and international tests and to develop some completely new items, Project 2061 is creating an online bank of more than 300 science and mathematics assessment items for use in grades 6–10. Supported by a grant from the National Science Foundation, the collection will allow users to search for items that are well aligned to learning goals in *Benchmarks for Science Literacy, NSES,* and the content standards of nearly every state. Each item in the collection is also being reviewed for its suitability for use with a wide range of students, including English-language learners (DeBoer 2005).

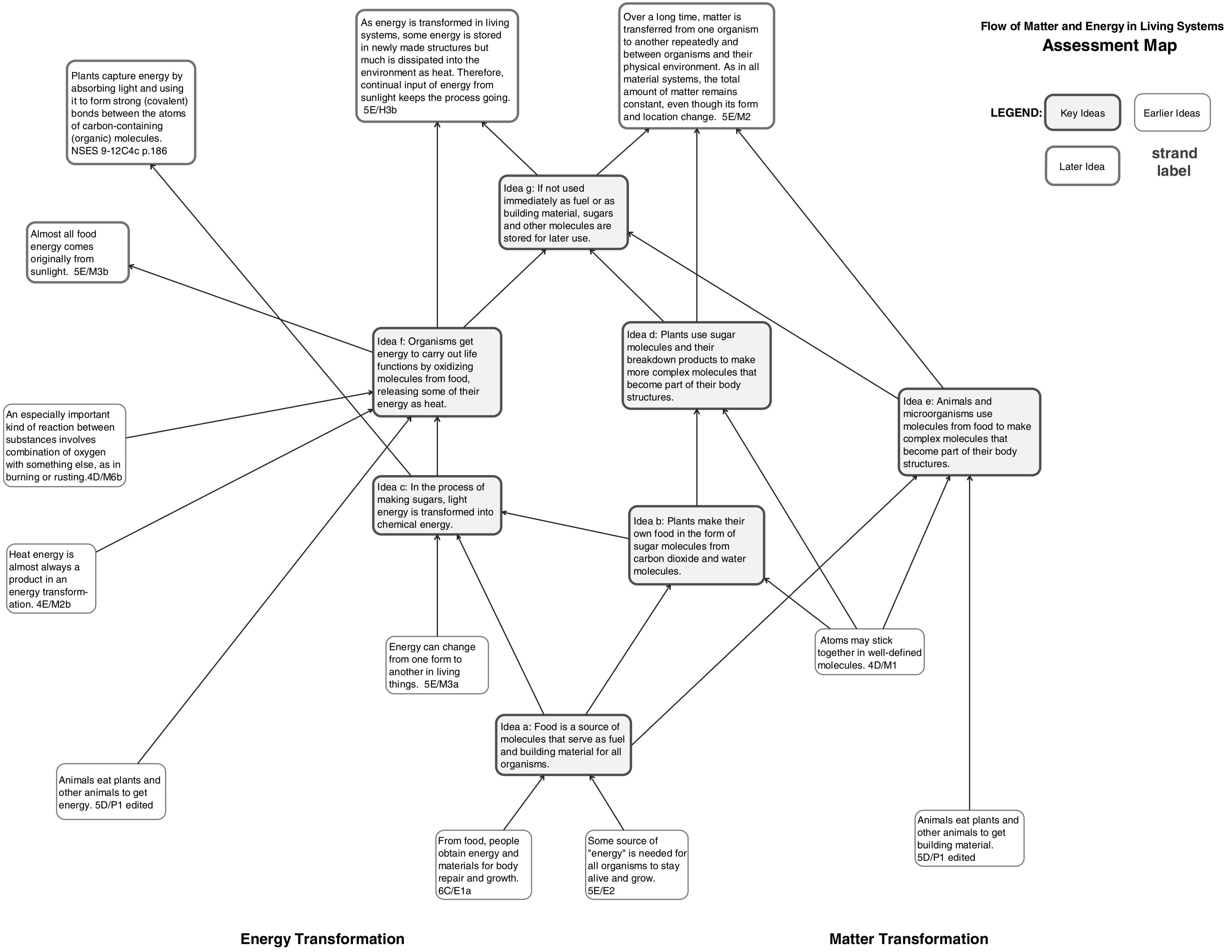
These high-quality items are likely to be of interest to college faculty who want to determine what their incoming students know prior to instruction. The items can also be used by faculty as models for developing or selecting test items that are aligned to the content they are teaching and responsive to the unique characteristics of their students. In the end, of course, the quality of any test—whether at the K–12 or college level—comes down to the specific tasks that students are asked to perform. We know that not every idea that is taught can be tested and that one item, or even one set of items, can never provide complete confidence that students understand or do not understand an idea. Nonetheless, every item should contribute some knowledge of what students do or do not understand.

To help guide decisions about what and how to test, Project 2061 has found that mapping the ideas and skills that are associated with a particular benchmark or standard can be a powerful tool for assessment design. Assessment maps can provide useful conceptual frameworks for creating single items or multi-item tests. In addition to specifying the ideas and skills targeted by a particular content standard or learning goal, an assessment map also identifies related ideas, common misconceptions, prerequisite ideas, and ideas that come later in the developmental progression. For each of the 16 science and mathematics topic areas covered by its online bank of assessment items, Project 2061 is creating an assessment map to display connections among ideas related to the relevant content standards (see Figure 32.4 for an example). The maps are adapted from those in Project 2061's *Atlas of Science Literacy* (2001a) and are consistent with the work on progress variables in learning by Wilson and Draney (1997).

Assessment maps give test developers a convenient visual boundary around the set of ideas they might want to test and allow them to choose assessment items that can yield diagnostic information about student learning, especially with respect to misconceptions and

Figure 32.4

Example of a Project 2061 Assessment Map



Plants capture energy by absorbing light and using it to form strong (covalent) bonds between the atoms of carbon-containing (organic) molecules. NSES 9-12C4c p.186

As energy is transformed in living systems, some energy is stored in newly made structures but much is dissipated into the environment as heat. Therefore, continual input of energy from sunlight keeps the process going. 5E/H3b

Over a long time, matter is transferred from one organism to another repeatedly and between organisms and their physical environment. As in all material systems, the total amount of matter remains constant, even though its form and location change. 5E/M2

Idea g: If not used immediately as fuel or as building material, sugars and other molecules are stored for later use.

Almost all food energy comes originally from sunlight. 5E/M3b

Idea f: Organisms get energy to carry out life functions by oxidizing molecules from food, releasing some of their energy as heat.

Idea d: Plants use sugar molecules and their breakdown products to make more complex molecules that become part of their body structures.

Idea e: Animals and microorganisms use molecules from food to make complex molecules that become part of their body structures.

An especially important kind of reaction between substances involves combination of oxygen with something else, as in burning or rusting.4D/M6b

Idea c: In the process of making sugars, light energy is transformed into chemical energy.

Idea b: Plants make their own food in the form of sugar molecules from carbon dioxide and water molecules.

Heat energy is almost always a product in an energy transform-ation. 4E/M2b

Energy can change from one form to another in living things. 5E/M3a

Atoms may stick together in well-defined molecules. 4D/M1

Idea a: Food is a source of molecules that serve as fuel and building material for all organisms.

Animals eat plants and other animals to get energy. 5D/P1 edited

Animals eat plants and other animals to get building material. 5D/P1 edited

From food, people obtain energy and materials for body repair and growth. 6C/E1a

Some source of "energy" is needed for all organisms to stay alive and grow. 5E/E2 prerequisite knowledge that pertain to specific ideas on the maps. For college-level courses, instructors can take a similar approach, developing assessment maps for particular units, projects, or an entire course. Tests built around assessment maps can provide important insights into students' thinking. For example, misconceptions shown on an assessment map can be used to develop "distractors" (wrong answer choices) for multiple-choice questions. How students respond to those questions can help instructors determine whether they need to address the misconceptions more directly through readings, discussions, or other classroom activities. Taking a more goals-based and learner-based approach to course design is an ongoing and dynamic process involving several cycles of revising, testing, and refining the key elements of the course.

Fostering a Climate for Reform

So far, this chapter has provided suggestions for reform of the college science curriculum based on K–12 reform efforts that have relied on Project 2061's *Science for All Americans* and *Benchmarks for Science Literacy* and the NRC's *National Science Education Standards*. We have called attention to lessons that can be learned from these efforts, but it is important to note that while curriculum reform is necessary, it is not sufficient to support and sustain improvements in undergraduate science education over the long term. The key is to consider all parts of the education system, knowing that reforms in each depend on and make possible reform in the others. Here we outline the kinds of systemic changes that are required and reflect on the opportunities for and obstacles to those changes.

It may be helpful to first consider how higher education fits into a systemic reform model from the K–12 perspective. In *Blueprints for Reform* (AAAS 1998) Project 2061 examined the role of higher education in the context of designing a K–12 curriculum that would ensure science literacy for all. The report identifies characteristics of higher-education institutions that make them particularly suited as advocates for education reform at the pre-college and college levels. Among the strengths that colleges and universities can build on is their freedom to innovate and an infrastructure for research that can be used to test and refine new approaches in pedagogy, materials development, and instructional technology and to "model the teachers-as-researcher role for their K-12 colleagues" (AAAS 1998, p. 222). *Blueprints* also acknowledges the need to situate reforms within a broader institutional context, beginning with leadership from presidents and provosts, as well as from deans and departments chairs, and extending to collaborations with K–12 educators and relationships with students and their parents.

Each college and university is different, of course, and a "one size fits all" approach to reform is as unlikely to succeed at the undergraduate level as it is at K–12. In its report *Beyond Bio 101*, the Howard Hughes Medical Institute (HHMI, n.d.) takes a far-reaching look at how various institutions are striving to transform their undergraduate biology programs to meet the diverse needs of students, faculty, higher-education institutions, and the increasingly interdisciplinary field of biology itself. Based on its review, HHMI found several factors that were associated with successful reform:

- Teaching that recognizes the personal bond between teacher and student; this is particularly important to the development of young scientists.
- Leadership at the departmental or programmatic level; this is essential in fostering the kinds of changes in attitudes, perceptions, and goals that are needed.

- Commitment to continuous and incremental change, paying attention to what works and building on successful experiences.
- Communities that foster and reward good teaching.

Although the report identifies several promising trends, it warns of the danger of mistaking innovation for lasting change, quoting from education analyst Sheila Tobias's book *Revitalizing Undergraduate Science* (1992):

> *What hinders students are the pace, the conflicting purposes of the courses (to, variously, provide an introduction or lay a foundation for a research career, or weed out the "unfit"); attitudes of their professors and fellow students; unexplained assumptions and conventions; exam design and grading practices; class size; the exclusive presentation of new material by means of lecture; and the absence of community—a host of variables that are not specifically addressed by most reforms.* (p. 18)

The problems identified by Tobias were some of the same problems impeding reform efforts at Towson University, according to Laurence Boucher, who was then dean of the university's College of Science and Mathematics. Reporting on his school's collaboration with Project 2061 to promote a more learner-focused approach to science and mathematics teaching, Boucher noted the change-resistant nature of higher education and the difficulty of institutionalizing reforms. Boucher's aim was to put into place reform strategies that would become part of the institution's culture of best practices. In addition to a variety of workshops and professional development programs for faculty, Boucher also organized a faculty team to analyze one of their introductory physical science courses and a biology course, which he describes as an "archetypal 'bad' course: crammed with material in an attempt at encyclopedic coverage that stresses the superficial learning of facts with cookbook laboratories." By taking a critical look at the courses, it was hoped that faculty would be motivated to make changes and that the improved courses would serve as models for improvement (Boucher, manuscript in preparation). Boucher's colleague Katherine Denniston agrees that university faculty need appropriate kinds of support, resources, and tools to carry out their reform efforts:

> *The creative effort of curriculum design and implementation requires time and the opportunity to collaborate with colleagues. They need seminars and workshops so they can learn what research shows about best practice in science classrooms. Institutions must consider these seminars and workshops to be an important part of the educators' workload, not events to be crowded into already-overbooked weekends and take time away from family. Finally, for university faculty, the scholarship of teaching must be rewarded at a level commensurate with the scholarship of discovery. When faculty have these kinds of support, standards-based reform efforts such as Project 2061 will have a much greater chance of affecting permanent change in our educational systems…. Until that day, those of us who have had the opportunity to engage in this type of work have the responsibility to share what we have learned with our colleagues. By encouraging university administrators and faculty to consider standards-based course and teaching assessment rather than the typical student and/or peer evaluations, we can facilitate reform while promoting change in the rewards structure at the university. In this way, we can change the system one small step at a time.*
> (Denniston, manuscript in preparation)

Conclusion

This chapter has described ways in which the learning goals established for K–12 students can have useful applications at the college level. It has also explored some of the implications that a goals-based and learner-based approach might have for undergraduate science courses, teaching, and assessment. Although K–12 goals, strategies, and resources can be adapted for use in higher education, it is essential to recognize that colleges and universities have a unique and powerful culture that is likely to overcome even the most vigorous reform efforts. Lasting change will require an equally robust infrastructure to support new ideas and practices.

References

Advisory Committee to the National Science Foundation Directorate for Education and Human Resources. 1996. *Shaping the future: New expectations for undergraduate education in science, mathematics, engineering, and technology*. NSF 96-139. Arlington, VA: National Science Foundation.

American Association for the Advancement of Science (AAAS). 1990a. *The liberal art of science: Agenda for action*. Washington, DC: AAAS.

American Association for the Advancement of Science (AAAS). 1990b. *Science for all Americans*. New York: Oxford University Press.

American Association for the Advancement of Science (AAAS). 1993. *Benchmarks for science literacy*. New York: Oxford University Press.

American Association for the Advancement of Science (AAAS). 1998. *Blueprints for reform: Science, mathematics, and technology education*. New York: Oxford University Press.

American Association for the Advancement of Science (AAAS). 2001a. *Atlas of science literacy*. Washington, DC: AAAS.

American Association for the Advancement of Science (AAAS). 2001b. *Designs for science literacy*. New York: Oxford University Press.

Berkheimer, G. D., C. W. Anderson, and S. T. Spees. 1990. *Using conceptual change research to reason about curriculum*. Research Series Paper No. 195. East Lansing: Michigan State University, Institute for Research on Teaching.

Boucher, L. J. Manuscript in preparation. Working with Project 2061 to change science and mathematics education in the academy. American Association for the Advancement of Science.

Bruner, J. S. 1995. On learning mathematics. *Mathematics Teacher* 88 (4): 330–335. (Reprint of paper presented at the meeting of the National Council of Teachers of Mathematics, Salt Lake City, UT, 1960)

Catley, K., R. Lehrer, and B. Reiser. 2004. *Tracing a prospective learning progression for developing understanding of evolution*. Paper commissioned by the National Academies Committee on Test Design for K-12 Science Achievement, 2005. Washington, DC: National Academy of Sciences. *www7.nationalacademies.org/bota/Evolution.pdf*

Commission on Behavioral and Social Sciences and Education. 2000. *How people learn: Brain, mind, experience, and school; expanded edition*. Washington, DC: National Academies Press. Also available online at *www.nap.edu*

DeBoer, G. E. 2005. Standard-izing test items. *Science Scope* 28 (4): 10–11.

Denniston, K. J. Manuscript in preparation. Evaluating a college biology course using Project 2061 tools. American Association for the Advancement of Science.

Denniston, K. J. n.d. Elements of course design: Biology 115: Biological Sciences I. (Unpublished manuscript written for American Association for the Advancement of Science Project 2061)

Driver, R., A. Squires, P. Rushworth, and V. Wood-Robinson. 1994. *Making sense of secondary science: Research into children's ideas*. London: Routledge.

Heller, P. 2001. Lessons learned in the CIPS curriculum project. Paper presented at the AAAS Conference on Developing Textbooks That Promote Science Literacy, Washington, DC. *www.project2061.org/events/meetings/textbook/literacy/heller.htm*

Henderleiter, J., R. Smart, J. Anderson, and O. Elian. 2001. How do organic chemistry students understand and apply hydrogen bonding? *Journal of Chemical Education* 78 (8): 1126–1130.

Heron, P. R. L., P. S. Shaffer, and L. C. McDermott. 2005. Research as a guide to improving student learning: An example from introductory physics. In *Invention and impact: Building excellence in undergraduate science, technology, engineering, and mathematics (STEM) education,* 33–37. Washington, DC: American Association for the Advancement of Science.

Howard Hughes Medical Institute (HHMI). n.d. *Beyond Bio 101: The transformation of undergraduate biology education. www.hhmi.org/BeyondBio10*

A jump-start for new science textbook development: Resources for developing curriculum materials that promote science literacy. 2004. *2061 Connections* (May). *www.project2061.org/publications/2061Connections/2004/2004-05a.htm*

Kirst, M. W., and M. Usdan. 2004. Thoughts on improving K–16 governance and policymaking. Paper presented at What Role Does Governance Play in K–16 Reform? symposium conducted at the meeting of the American Educational Research Association, San Diego, CA.

Michigan Science Education Resources Project. 1993. *Chemistry That Applies*. Lansing: Michigan Department of Education.

National Research Council (NRC). 1996. *National science education standards*. Washington, DC: National Academy Press.

National Research Council (NRC). 2003. *What is the influence of the* National Science Education Standards*? Reviewing the evidence, a workshop summary.* Washington, DC: National Academy Press.

Project Kaleidoscope. 2002. *Recommendations for action in support of undergraduate science, technology, engineering, and mathematics*. Washington, DC: Project Kaleidoscope.

Reiser, B., J. Krajcik, E. Moje, and R. Marx. 2003. Design strategies for developing science instructional materials. Paper presented at the annual meeting of the National Association for Research in Science Teaching, Philadelphia, PA. *http://hi-ce.org/iqwst/Papers/reiser_krajcik_NARST03.pdf*

Richardson, J. 2005. Concept inventories: Tools for uncovering STEM students' misconceptions. In *Invention and impact: Building excellence in undergraduate science, technology, engineering, and mathematics (STEM) education,* 19–25. Washington, DC: American Association for the Advancement of Science.

Roseman, J. E., and L. Stern. 2003. Toward ecology literacy: Contributions from Project 2061 science literacy reform tools. In *Understanding urban ecosystems: A new frontier for science and education,* eds. A. R. Berkowitz, C. H. Nilon, and K. S. Hollweg, 261–281. New York: Springer-Verlag.

Schmidt, W. H., H. A. Wang, and C. C. McKnight. 2005. Curriculum coherence: An examination of US mathematics and science content standards from an international perspective. *Journal of Curriculum Studies* 37 (5): 525–559.

Smith, C., M. Wiser, C. W. Anderson, J. Krajcik, and B. Coppola. 2004. *Implications of research on children's learning for assessment: Matter and atomic molecular theory.* Paper commissioned by the Committee on Test Design for K–12 Science Achievement. Washington, DC: National Academy of Sciences.

Stern, L., and A. Ahlgren. 2002. Analysis of students' assessments in middle school curriculum materials: Aiming precisely at benchmarks and standards. *Journal of Research in Science Teaching* 39 (9): 889–910.

Stern, L., and J. E. Roseman. 2001. Textbook alignment. *The Science Teacher* 68 (3): 52–56.

Tobias, S. 1992. *Revitalizing undergraduate science: Why some things work and most don't.* Tucson, AZ : Research Corporation.

Wiggins, G., and J. McTighe. 1998. *Understanding by design*. Alexandria, VA: Association for Supervision and Curriculum Development.

Wilson, M., and K. Draney. 1997. *Developing maps for student progress in the SEPUP assessment system*. BEAR Report Series, SA-97-2. Berkeley: University of California at Berkeley.