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Features

Approaches to Cell Biology Teaching: A Primer on Standards

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The first challenge in designing and teaching any course is to decide what to teach. Although some undergraduate and graduate instructors are infamous for teaching only their area of research or only their pet topic, most instructors are engaged in an ongoing struggle with the demons of course content: What should students learn? In how much depth should they learn it? At what age is it cognitively appropriate for them to learn it? What will students have encountered before? What will prepare them for future studies? Often, class time is the largest consideration, forcing instructors to confront the difficult task of prioritizing and choosing only the most essential concepts for a course. In addition, the goals for what students should learn drive not only what is taught, but also how it is taught. The considerations are complex in all teaching situations, regardless of topic area, student age, or educational setting.

At most colleges and universities, the process of selecting course content is an extremely local enterprise. Sometimes the decisions are made by a small group of faculty members, but most often they are made by a single professor with the responsibility of teaching the course. The idea that courses are articulated into a meaningful progression for undergraduates may be discussed among faculty members responsible for different courses; however, discussions across divisional boundaries—biology and chemistry, for example—are rarer. Almost unheard of is agreement across institutions of higher education about what should be taught in all introductory biology courses or all cell biology courses. This level of articulation and alignment across institutions would likely be considered not only an affront to the independent spirit of colleges and universities, but also an impediment to both faculty creativity and integration of new knowledge into course content.

This said, all the previously mentioned articulations—across grade levels, across educational institutions, across teachers, and across content areas—are now major driving forces in what is taught to students in K–12 schools. These articulations take the form of what are referred to as standards.

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Although most scientists have many definitions of the word standard—standard molecular weight markers on a gel, standard curves for interpreting unknown amounts of a substance in a sample, and the standard transmission in a car—many are not familiar with standards in K–12 education or aware of the pervasive influence of such standards on everything from curriculum development to testing.

WHAT ARE SCIENCE EDUCATION STANDARDS?

Webster's Third New International Dictionary defines the word standard as "something that is established by authority, custom, or general consent as a model or example to be followed, or a set of criteria." The recent development of standards in K–12 education is not unique to science education but pervades all K–12 disciplines, including mathematics, language arts, social studies, and even physical education (e.g., see National Council of Teachers of Mathematics [NCTM], 1989). In 1983, the rallying cry of *A Nation at Risk*, a report from the National Commission on Excellence in Education, painted a future in which the United States fell further and further behind other countries in technological advancement, economic prosperity, and world leadership as a result of an illiterate citizenry inadequately educated by K–12 schools. Driven by this gloomy projection, a movement began to establish what constitutes essential knowledge for literate U.S. citizens, especially in the fast-paced fields of science and technology. The formal beginning of a national standards in education movement occurred with the founding of the National Education Goals Panel in 1989 by (Sr.) President George Bush, the same year that the NCTM published its pioneering *Curriculum and Evaluation Standards for School Mathematics*, National Research Council, 1996.

Also in 1989, the American Association for the Advancement of Science's Project 2061 published *Science for All Americans*, outlining the essential knowledge in science required for all U.S. citizens to be scientifically literate upon high school graduation. However, how K–12 students would arrive at this knowledge was unclear until the publication of the two most influential national science standards documents to date: Project 2061's *Benchmarks for Science Literacy* published in 1993 and the National Research Council's *National Science Education Standards* (*NSES*) published in 1996. Developed independently, these two documents are aligned with each other in their approaches to science education reform. First, both are grounded in equity, asserting that the science knowledge outlined is essential for all students, not just future scientists and engineers. Second, both endorse an approach to science learning that is student centered, rooted in engaging students' natural scientific curiosity and making science education relevant to the science of everyday living. Third, both present detailed science content standards that outline what students should know, understand, and be able to do during different stages of their K–12 experiences. Last, both emerged as the result of extensive collaboration among hundreds of individuals from both scientific organizations and educational organizations, with particularly strong involvement by K–12 teachers, and are presented as evolving visions of science education.

In addition, the *NSES* pioneered a vision for how to achieve these science content standards for students. The *NSES* presented not only science content standards, but also science teaching standards that detail a shift in how science is taught toward more conceptual and integrated science learning, in which students are actively engaged in discovery and scientific inquiry (see Table 1). To support this transformation of science teaching in schools, the *NSES* also outlined standards for professional development for science teachers (what teachers need to experience to be able to teach science this way), science assessment standards (how science should be tested), and guidelines for comprehensive reforms of science education programs and systems (National Research Council, 1996).

A WINDOW INTO THE SCIENCE CONTENT STANDARDS: WHERE IS CELL BIOLOGY?

What do you think students in K–12 classrooms are or ought to be learning about cells? When do you think they might be learning these things? As a scientific community, we often consider our area of study either so crucial and fascinating that everyone should be learning about it from kindergarten, or of such immense complexity that only undergraduates or maybe advanced high school students could begin to understand the concepts. To explore more specifically what science content standards for K–12 teachers and students look like, let us examine one strand of science content—cell biology—across all grade levels. An examination of the science content standards in the *NSES* and the *Benchmarks* shows general agreement about what K–12 students should learn about cell

Table 1. Changes in emphases in science content standards[a]

Less emphasis on	More emphasis on
Changing emphases	
Knowing scientific facts and information	Understanding scientific concepts and developing inquiry abilities
Studying subject matter disciplines (physical, life, earth sciences) for their own sake	Learning subject matter disciplines in the context of inquiry, technology, science in personal and social perspectives, and history and nature of science
Separating science knowledge and science process	Integrating all aspects of science content
Covering many science topics	Studying a few fundamental science concepts
Implementing inquiry as a set of processes	Implementing inquiry as instructional strategies, abilities, and ideas to be learned
Changing emphases to promote inquiry	
Activities that demonstrate and verify science content	Activities that investigate and analyze science questions
Investigations confined to one class period	Investigations over extended time periods
Process skills out of context	Process skills in context
Emphasis on individual process skills such as observation or inference	Use of multiple process skills: manipulation, cognitive, procedural
Getting an answer	Using evidence and strategies for developing or revising an explanation
Science as exploration and experiment	Science as argument and explanation
Providing answers to questions about science content	Communicating science explanations
Individuals and groups of students analyzing and synthesizing data without defending a conclusion	Groups of students often analyzing and synthesizing data after defending conclusions
Doing few investigations to leave time to cover large amounts of content	Doing more investigations to develop understanding, ability, values of inquiry, and knowledge of science content
Concluding inquiries with the result of the experiment	Applying the results of experiments to scientific arguments and explanations
Management of materials and equipment	Management of ideas and information
Private communication of student ideas and conclusions to teacher	Public communication of student ideas and work to classmates

[a]From National Research Council. (1996). National Science Education Standards, Washington, DC: National Academies Press, p. 113. Reprinted with permission from National Science Education Standards. Copyright 1996 by the National Academy of Sciences. Courtesy of the National Academies Press, Washington, D.C.

biology and when they should learn it (see Tables 2 and 3). Note that the *Benchmarks* map science content standards into *four* grade-level spans—kindergarten to 2nd grade, 3rd to 5th grade, 6th to 8th grade, and 9th to 12th grade—and the *NSES* does so across *three* grade-level spans–kindergarten to 3rd grade, 4th to 8th grade, and 9th to 12th grade, although not all topics appear in all grade level spans.

In early elementary school, conceptual development in children is linked to the concrete world and the observable, and children operate in what biologist-turned–child psychologist Jean Piaget termed the concrete operational stage of cognitive development (Piaget, 1954). As such, the microscopic nature of cells and their usual invisibility to the naked eye makes them cognitively inaccessible to many younger students. In both the *Benchmarks* and the *NSES*, students are introduced to cells in upper elementary school, at around the 4th or 5th grade and between the ages of 9 and 11 yr. The *Benchmarks* propose that, prior to this, students study magnifiers and microscopes, which will lay the foundation for development of the concept of the cell by building student understanding of the tools of science that will enable them to observe cells in later grades.

As students move from upper elementary school to middle school, both documents focus on introducing students to the concept of a cell as "the fundamental unit of life" and explicitly state that "some living things consist of a single cell" and "other organisms, such as humans, are multicellular." In addition, both documents approach the introduction of the cell not from the structural and functional vantage point of the cell itself, but from the perspective of the organism. Cells are introduced as the smaller units within organisms that compose the various body tissues and organs and carry out the functions required for a living thing to survive.

Both documents emphasize that students in grades 9–12 (ages 14–18 yr) should understand that cells have specialized subcellular structures that underlie their many functions. These older students learn about the molecules of the cell and the role that these molecules play in cell functions—the gatekeeper role of the cell membrane, the storage of genetic information by DNA, and the many facets of proteins. In addition, these high school science standards introduce photosynthesis in plant cells, the role of differentiation in development, and the role of regulation in cell growth and division. Further details about cell biology learning at all grade levels are given in Tables 2 and 3.

The overarching functional approach to understanding cells found in the *NSES* and the *Benchmarks* moves away from the more traditional anatomic introduction to cells that is rooted in memorizing names of organelles followed by the requisite building of a cell model from clay or other materials. In fact, this functional view taken in the standards is intimately linked to a strong vision of how students should be learning science (see Table 1). So that students achieve conceptual understanding of cells, the *NSES* explicitly states that students' learning experiences should be relevant to everyday life, engage students' critical thinking skills, and whenever possible actively involve students in scientific investigations and discussions among themselves. One example of how students can learn cell biology in a more inquiry-oriented manner is the middle school curriculum unit *No Quick Fix* developed by staff and teachers in the School of Education at the College of William and Mary (1997). *No Quick Fix* uses the

Table 2. Cell Biology Concepts in the *National Science Education Standards*

Grades 5–8
Living systems at all levels of organization demonstrate the complementary nature of structure and function. Important levels of organization for structure and function include cells, organs, tissues, organ systems, whole organisms, and ecosystems.
All organisms are composed of cells—the fundamental unit of life. Most organisms are single cells; other organisms, including humans, are multicellular.
Cells carry on the many functions needed to sustain life. They grow and divide, which thereby produces more cells. This requires that they take in nutrients, which they use to provide energy for the work that cells do and to make the materials that a cell or an organism needs.
Specialized cells perform specialized functions in multicellular organisms. Groups of specialized cells cooperate to form a tissue, such as a muscle. Different tissues are in turn grouped to form larger functional units, called organs. Each type of cell, tissue, and organ has a distinct structure and set of functions that serve the organism as a whole.
Grades 9–12
Cells have particular structures that underlie their functions. Every cell is surrounded by a membrane that separates it from the outside world. Inside the cell is a concentrated mixture of thousands of different molecules which form a variety of specialized structures that carry out such cell functions as energy production, transport of molecules, waste disposal, synthesis of new molecules, and the storage of genetic material.
Most cell functions involve chemical reactions. Food molecules taken into cells react to provide the chemical constituents needed to synthesize other molecules. Both breakdown and synthesis are made possible by a large set of protein catalysts, called enzymes. The breakdown of some of the food molecules enables the cell to store energy in specific chemicals that are used to carry out the many functions of the cell.
Cells store and use information to guide their functions. The genetic information stored in DNA is used to direct the synthesis of the thousands of proteins that each cell requires.
Cell functions are regulated. Regulation occurs both through changes in the activity of the functions performed by proteins and through the selective expression of individual genes. This regulation allows cells to respond to their environment and to control and coordinate cell growth and division.
Plant cells contain chloroplasts, the site of photosynthesis. Plants and many microorganisms use solar energy to combine molecules of carbon dioxide and water into complex, energy-rich organic compounds and release oxygen to the environment. This process of photosynthesis provides a vital connection between the sun and the energy needs of living systems.
Cells can differentiate, and complex multicellular organisms are formed as a highly organized arrangement of differentiated cells. In the development of these multicellular organisms, the progeny from a single cell forms an embryo in which the cells multiply and differentiate to form the many specialized cells, tissues, and organs that compose the final organism. This differentiation is regulated through the expression of different genes.

Table 3. Cell Biology Concepts in the *Benchmarks for Science Literacy*

By the end of 2nd grade, students should know that . . .
Magnifiers help people see things that they could not see without magnifiers.
Most living things need water, food, and air.
By the end of 5th grade, students should know that . . .
Some living things consist of a single cell. Like familiar organisms, they need food, water, and air; a way to dispose of waste; and an environment they can live in.
Microscopes make it possible to see that living things are made mostly of cells. Some organisms are made of a collection of similar cells that benefit from cooperating. Some organisms' cells vary greatly in appearance and perform very different roles in the organism.
By the end of 8th grade, students should know that . . .
All living things are composed of cells, from just one to many millions, whose details are usually visible only through a microscope. Different body tissues and organs are made up of different kinds of cells. The cells in similar tissues and organs in other animals are similar to those in human beings but differ somewhat from cells found in plants.
Cells repeatedly divide to make more cells for growth and repair. Various organs and tissues function to serve the needs of cells for food, air, and waste removal.
Within cells, many of the basic functions of organisms—such as extracting energy from food and getting rid of waste—are carried out. The way in which cells function is similar in all living organisms.
About two-thirds of the weight of cells is accounted for by water, which gives cells many of their properties.
By the end of 12th grade, students should know that . . .
Every cell is covered by a membrane that controls what can enter and leave the cell. In all but primitive cells, a complex network of proteins provides organization and shape and, for animal cells, movement.
Within every cell are specialized parts for the transport of materials, energy transfer, protein building, waste disposal, information feedback, and even movement. In addition, most cells in multicellular organisms perform some special functions that others do not.
The work of the cell is carried out by the many different types of molecules it assembles, mostly proteins. Protein molecules are long, usually folded chains made from 20 kinds of amino acid molecules. The function of each protein molecule depends on its specific sequence of amino acids, and the shape that the chain takes is a consequence of attractions between the chain's parts.
The genetic information encoded in DNA molecules provides instructions for assembling protein molecules. The code used is virtually the same for all life forms. Before a cell divides, the instructions are duplicated so that each of the two new cells obtains all the information necessary for carrying on.
Complex interactions among the different kinds of molecules in the cell cause distinct cycles of activities, such as growth and division. Cell behavior can also be affected by molecules from other parts of the organism or even other organisms.
Gene mutation in a cell can result in uncontrolled cell division, called cancer. Exposure of cells to certain chemicals and radiation increases mutations and thus increases the chance of cancer.
Most cells function best within a narrow range of temperature and acidity. At very low temperatures, reaction rates are too slow. High temperatures and/or extremes of acidity can irreversibly change the structure of most protein molecules. Even small changes in acidity can alter the molecules and how they interact. Both single cells and multicellular organisms have molecules that help to keep the cells' acidity within a narrow range.
A living cell is composed of a small number of chemical elements, mainly carbon, hydrogen, nitrogen, oxygen, phosphorous, and sulfur. Carbon atoms can easily bond to several other carbon atoms in chains and rings to form large and complex molecules.

Adapted from *Benchmarks for Science Literacy*, American Association for the Advancement of Science (1993). Oxford University Press, New York, NY.

overarching concept of related systems—social communities, humans, human body systems, and cellular systems—to provide students with a framework for exploring the structures and functions of prokaryotic and eukaryotic cells. Instructional activities are contextualized in the story of an outbreak of tuberculosis (TB) in a fictionalized school district and an accompanying need to understand TB so that the wellness of the students and teachers in the community can be promoted. During exploration of the causes for, transmission of, treatment for, and prevention of the transmission of TB, students learn about bacterial cells and their life cycles and about eukaryotic cell structure and function in the context of the immune system. What is also distinctive about this unit is its problem-based instructional format. Students acquire essential cell biology content knowledge while solving an interdisciplinary, "real-world" problem, because they are asked to formulate a proposal for TB control measures and to present their proposal to the local school board. The information needed to resolve this complex problem is not given to the students in predigested form, and cell biology concepts are not presented in stand-alone, abstract contexts. Rather, teachers skillfully guide students in identifying their questions about TB, support them in discovering answers through both library research and laboratory experimentation, push them to critically evaluate collected information, and finally challenge students to propose a resolution. In the end, students model processes intrinsic to scientific investigation while, in an inquiry-oriented, problem-based approach, they build their understanding of basic cell biology concepts that spiral through the science content standards. Student understandings about cells learned in this way are linked to tangible real-world events and embedded in broader societal concerns.

BENEFITS AND CHALLENGES OF SCIENCE CONTENT STANDARDS

As a vision for the future of science education in the United States, the potential benefits of national science education standards are significant. Common goals for what students should be learning provide a map for districts, schools, and teachers to adapt these ideas to their local context. Standards can serve as a guide to the spiraling conceptual development of K–12 students, minimizing redundancy and promoting deeper student understandings. (For a visual representation of spiraling, see the *Atlas of Science Literacy* [American Association for the Advancement of Science, 2001]). Most important, the *NSES*'s proposed shift toward teaching science with more problem-based, inquiry-oriented instructional approaches holds the promise of engaging students in the exciting parts of science—inquiry, discovery, and construction of scientific explanations in a community of scientists—while building their critical and creative skills as well as their content knowledge.

However, new visions also bring new controversies and challenges. Local, state, and national debates about exactly what and how much students should learn at each grade level in science have been extensive and intense, and intellectual, financial, and political support for implementing the *NSES*'s vision of science education already varies dramatically across the nation. In some states, the adaptation of national science standards to local contexts has proceeded relatively smoothly, with a fair degree of consensus and a commitment, at least for the short term, to realizing this new vision. In these states, standards have been written that are variants of the national standards, and teachers are experiencing new kinds of professional development in which they are building their conceptual understanding through discovery, inquiry, and scientific discussion. In some cases, state-level tests are even being developed to measure what the national standards value—conceptual understanding and critical thinking, as opposed to recitation and memorization. However, even in these states with forward momentum, there are significant challenges to implementing the vision. First, there is an ongoing process of defining, refining, and negotiating what this new approach to science and teaching looks like, a process that involves not just a change in understanding by teachers, but also a major shift in classroom behaviors on the part of students and in the expectations of parents and administrators. In addition, these reform efforts are expensive and resource intensive, and they come at a time when schools and districts are already overburdened, struggling financially, and under accountability pressures to improve reading and math scores.

Conversely, in other states, it has been difficult to reach a consensus on a starting vision for science education, much less a plan for implementing this vision. In many of these states, there have been extensive debates about what a "rigorous science education" really is, about the amount and level of content detail that students should learn at each grade level, and about the extent to which an inquiry-oriented approach to science education is important. These debates are not solely academic and are shifting the development of state science standards, curricula, teacher professional development, and assessments, often in a direction that moves science education in these states away from the spirit of the national standards.

These challenges and controversies highlight perhaps the most important outcome of the development of national science standards: that they have successfully engaged a broad community of scientists and educators in deep discussions about how and what to teach the nation's young people about science. Without these standards, such a national conversation might not have occurred.

IMPLICATIONS OF K–12 SCIENCE STANDARDS FOR HIGHER EDUCATION

Although implementation of science education standards has just begun, we are now 6 yr past the original publication of the *NSES* and almost 10 yr past the arrival of the *Benchmarks*. Increasingly during the next decade, students graduating from K–12 systems might arrive at institutes of higher education with a more standards-based precollege experience, with deeper knowledge of both scientific inquiry and content. What implications, then, do K–12 science education standards have for teaching science at our nations' colleges and universities? How well do introductory cell biology and biology courses at your institution align and articulate with the K–12 science content standards in the *NSES* and the *Benchmarks*? with your own state and local science content standards? What is essential for a U.S. college graduate to know in life science, and how does this differ for undergraduate majors in science, education, or the humanities? If the vision of the *NSES* comes to fruition during the next decade, students will arrive at the doors of higher education with not only substantially improved backgrounds in science, but also dramatically different experiences in terms of how they have learned science and what they have come to expect pedagogically from their science teachers. Will their arrival at colleges and universities avail them of similar approaches to science teaching? To what extent is inquiry a key pedagogical approach in science courses at your institution? What are the standards for how science is taught at the undergraduate level and what are the standards for the professional development of undergraduate science teachers? We wonder what a *National Science Education Standards* for higher education might look like . . . .

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Links to Related Web Sites

American Association for the Advancement of Science, Project 2061. http://www.project2061.org/tools/benchol/bolframe.htm

College of William and Mary. No Quick Fox: A Problem-Based Unit. http://www.kendallhunt.com/college/cgebro.html

Investigating the Influence of Standards: A Framework for Research in Mathematics, Science, and Technology Education. http://www.nap.edu/books/030907276X/html/

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