THE TEACHING OF SCIENCE:

21st CENTURY PERSPECTIVES

RODGER W. BYBEE

NSTA press
National Science Teachers Association

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For
Sumner Clark Eakins
and his young friends in the class of 2024

They represent the generation that will benefit from teaching science with 21st-century perspectives.

Preface

Science teachers at all levels—elementary, middle, and high school—confront diverse issues and requirements, all of which can divert teachers' time and attention from the fundamental task of helping students learn science. In their need to focus on the immediate tasks, teachers ask for lessons that will get them through the day or week. Although they certainly sense the need, if not the obligation, to pause and ask essential questions, they seldom have the time for reflection: What science content and processes are important for students to learn? How can I organize experiences to facilitate student learning? How will I know what students have learned? What knowledge and skills do I have to have to help students learn? To be clear, these questions may have variations, but they center on the instructional core that all teachers recognize as fundamental to their work as professionals.

The content and themes of the chapters in this book may be used to reflect on issues basic to the teaching of science. The topics and discussions in the book lend themselves to "summer reading" or professional development discussions with colleagues. This book neither emphasizes nor presents activities for teaching. The themes mostly address why to teach science and what is important to teach. Answering the *why* and *what* questions contributes to constructive responses to the *how* questions. Where possible and appropriate, I have provided references and resources that will help science teachers with their daily, weekly, and yearly tasks as professionals.

I have been honored to present several major lectures at National Science Teachers Association (NSTA) meetings. The original titles as well as the lecture locations and dates are listed on the following page. My practice is to prepare a written essay for the lectures. In all but two cases, those essays have not been published. Upon rereading the lectures, I realized two things. First, I tried to present ideas about curriculum and instruction in a style appropriate for science teachers. Second, the lectures made connections between the past and future. The latter occurred because the lectures were named for individuals—Robert H.

Karplus, Paul F-Brandwein, and Robert H. Carleton—who have made significant contributions to science education and influenced my career.

In preparing the chapters for this book, I have maintained the themes set forth in the original lectures. Because the lectures were presented several years apart, I took the liberty to change the sequence and update the chapters by adding contemporary information, eliminating some redundancies, and adding resources and references. In addition, I moved to the prologue the personal introductions about the persons for whom the lectures were named.

The first chapter introduces the subsequent chapters with major themes and an emphasis for the book. I also set forth the themes of curriculum and instruction as they relate to science teachers.

NSTA Lectures
Original Titles, Locations, and Dates

Reflections on Curriculum and Instruction
The Robert H. Karplus Lecture
NSTA National Conference
San Diego, California
March 29, 2002

The Teaching of Science: Content, Coherence, and Congruence
The Paul F-Brandwein Lecture
NSTA National Conference
Philadelphia, Pennsylvania
March 29, 2003

Teaching Science and Fulfilling National Aspirations: The Critical Role of Curriculum Reform
Life Members Lecture
NSTA National Conference
St. Louis, Missouri
March 30, 2007

The Robert H. Carleton Lecture
NSTA National Conference
Boston, Massachusetts
March 28, 2008

Scientific Literacy and Environmental Issues: Insights from PISA 2006
The Paul F-Brandwein Lecture
NSTA National Conference
Boston, Massachusetts
March 29, 2008

The second chapter is based on my 2003 Paul F-Brandwein Lecture. In this chapter, I introduce Brandwein's original themes of Substance, Structure, and Style and connect these themes to contemporary Content, Curricular Coherence, and Congruence. The bases for these themes are national standards, research on learning, and the role of inquiry in science instruction.

To the directors of the Paul F-Brandwein Institute, my colleagues, and especially my friend for more than 30 years, John Padalino, I extend my appreciation for the opportunity to present the 2003 Paul F-Brandwein Lecture. I took it as a great honor to present a lecture in memory of Paul F-Brandwein—a great environmentalist and a great science teacher. On several occasions, I had the opportunity to talk with Paul F-Brandwein and always found him to be personable and understanding of a young professional who wanted to understand his views on science education, environmental education, and gifted students who had interests in scientific careers.

If I may add a personal note of acknowledgment, I have known and worked with John (Jack) Padalino since our days in graduate school at New York University. He, like Paul, is a great environmentalist and distinguished educator. For years he worked to see that inner-city students participated in environmental education experiences that many would not have had without his extraordinary efforts. Jack has constantly reminded me that science education is largely political and mostly local. This bit of wisdom has been helpful on numerous occasions, as my professional work has encompassed local, national, and international perspectives.

The third chapter is based on my 2002 Robert H. Karplus Lecture. The essay includes an introduction to the influence Karplus had on curriculum development and ideas that we used at BSCS. This chapter also includes a detailed discussion of the BSCS 5E Instructional Model and its origins from the Karplus learning cycle.

I truly appreciated the opportunity to reflect on curriculum and instruction in general and the contributions of Robert H. Karplus in particular. I was deeply honored, as 2002 marked 50 years since the initial work on the Science Curriculum Improvement Study (SCIS). I also was thankful for a chance to discuss a bit of the history of science education.

Although I did not realize it at the time, I began reflecting on curriculum and instruction in 1968 when I spent a memorable week visiting SCIS. This was the first time I met Bob Karplus. During the next 13 years, I had numerous opportunities to visit with Bob, attend his presentations, read his publications, and use materials that he and his colleagues developed, including the SCIS materials. It would be inappropriate to leave the impression that we had a deep and enduring friendship, but Robert Karplus did have a profound and lasting influence on my career as a science teacher, curriculum developer, and educator. His influence came less through personal interaction and more through his intellectual endeavors, specifically his reflections on curriculum and instruction.

The 2008 Robert H. Carleton Lecture provides the content for Chapter 4. The chapter centers on the themes of teaching science as inquiry. After a brief introduction to the history of inquiry in science education, I use the national standards as the basis for a detailed discussion of inquiry as learning outcomes and teaching strategies. The concluding sections discuss the role of inquiry and preparation of 21st-century skills.

I delivered a second Paul F-Brandwein Lecture in 2008. This lecture is the basis for the fifth and sixth chapters. In that lecture, I used the theme of scientific literacy to introduce the Program for International Student Assessment (PISA), in which science was emphasized in 2006. The specific discussion centers on environmental themes that were assessed in the 2006 PISA.

The opportunity to present the 2008 Paul F-Brandwein lecture left me with no small humility and great honor. I acknowledge all directors of the Paul F-Brandwein Institute, especially those I have known and worked with and admired for years: Keith Wheeler, Alan Sandler, Cheryl Charles, Marilyn DeWall, and William Hammond.

Chapters 7 and 8 are based on my 2007 Life Members Lecture, in which I address 21st-century issues and link ideas from PISA 2006 science to the contemporary need for curriculum reform. Presenting the Life Members Lecture had significant personal meaning for me because it represented my 40th anniversary as a member of NSTA. I used the occasion to talk about two themes that have been central in my career as a member of NSTA: The first theme centers on fulfilling national aspirations, and the second theme addresses the critical role of instructional materials and curriculum reform.

In the epilogue, I address the need for leadership and the responsibilities for continued reform in science education.

Like any author, I must acknowledge the fact that many individuals contributed to the themes and ideas expressed in this book. I have benefitted greatly from my recent work on the PISA and discussions with members of the Science Expert Group, and especially my colleague Barry McCrae from the Australian Council for Educational Research (ACER). Barry continually asked for clarification and a rationale for ideas that became part of the PISA 2000 science assessment. Many of those ideas are integral to the themes in this book.

These NSTA lectures were presented during my tenure as executive director of BSCS. Support and encouragement from Pam Van Scotter, Nancy Landes, Joe Taylor, and Janet Carlson were not only helpful but also vital, and I acknowledge their assistance.

Several colleagues are part of a special NSTA meeting. Discussions during these yearly meetings have broadened and deepened my understanding of science education. Here I acknowledge Mark St. John, Harold Pratt, and

David Heil for their understanding of the personal and professional lives of science educators.

There is a special note of appreciation for Kathryn Bess, who listened, questioned, and clarified ideas that became central to the lectures and this book. This book's emphasis on science teachers and teaching is due largely to Kathryn's wise counsel.

I thank Claire Reinburg of NSTA for her support from the beginning proposal to the final product and Wendy Rubin for her contributions and seeing this manuscript through final production.

Finally, my assistant, Byllee Simon, contributed in numerous ways to the final manuscript for NSTA. I continue to appreciate her interest in, contributions to, and support of my work.

During my career I have been thankful for numerous interactions with science teachers. Their wisdom and experience have both tempered some ideas and embellished others. I certainly thank them and extend my appreciation for their ideas. They are the central hope for helping students realize their future as citizens, some of whom will be scientists and engineers.

Rodger W. Bybee
Golden, Colorado
February 2010

Prologue
Connecting the Past and Future

In the preface, I mentioned the fact that I knew the individuals for whom the NSTA lectures were named—Paul F-Brandwein, Robert Carleton, and Robert Karplus—and who had a great influence on my career. As work on this book continued, I thought it important to provide readers with a brief introduction to these individuals. The following discussion and this book connect these 20th-century leaders to future generations of science teachers as they themselves become the 21st-century leaders.

Paul F-Brandwein: Scientist, Environmentalist, and Curriculum Designer

The Brandwein Lectures both acknowledge Paul F-Brandwein's long and distinguished career, including serving on the Steering Committee of the Biological Sciences Curriculum Study (BSCS) from the late 1950s into the 1960s. Paul F-Brandwein directed the Gifted Student Committee at BSCS and was responsible for initiating a program on student research problems. He felt deeply about giving students the opportunity to engage in scientific inquiry as a means to encourage their future careers as scientists.

Paul F-Brandwein played a key role in BSCS's early publications for gifted students. He was a member of the BSCS Steering Committee and the Gifted Committee from 1959 to 1962 and a member of the Special Student Committee from 1962 to 1963. I also would note that Harcourt Brace, the company for which Paul was a senior editor and an education consultant, published BSCS's *Biological Sciences: An Inquiry Into Life*, known as the BSCS "Yellow Version."

Brandwein had impressive credentials in addition to his position at Harcourt: consulting science editor to Science Research Associates; associate director of the Joint Council on Economic Education with special responsibility as director of its Conservation and Resource-Use Project; associate editor of NSTA's journal *The*

Science Teacher; and president of the Federation of Science Teachers of New York. He taught in New York City high schools for 15 years and was chairman of a science department for 10 of those years. Brandwein also had 15 years of college teaching experience, including positions at New York University, Teachers College, Columbia University, and Harvard University.

Among his publications before his work for BSCS were *The Gifted Student as Future Scientists*; *You and Science*; *The Physical World*; *Teaching High School Science: A Book of Methods*; *Teaching High School Science: A Sourcebook for the Biological Sciences*; and *Teaching High School Science: A Sourcebook for the Physical Sciences*.

A Biology Education for Gifted Students

Brandwein was especially perceptive in his observations about the gifted student, noting at a Steering Committee meeting that identifying the gifted student was one of the most important problems for science teachers. He said that we frequently confuse "brightness" with "giftedness." A bright student accepts what is presented by the instructor; the gifted student may question what is given to him by the teacher and may not fit into the classroom emotionally or otherwise. Dr. Anne Roe of the Graduate School of Education at Harvard University was a member of the BSCS committee and a colleague of Brandwein. She studied the intellectual and emotional characteristics of gifted students and found that most of them are dissatisfied with the present explanation of reality and continually search for more satisfying explanations (Grobman 1969). His concern with providing challenging science experiences for gifted students led Brandwein to propose a program of BSCS materials.

The Gifted Student Committee agreed to organize materials that could be used by high school science teachers to encourage the work of highly talented students, especially in biology. The plans called for assembling about 300 investigations that these students might conduct. The investigations were conceived as original research problems for which solutions were not yet available in the literature and were intended to take several years of work to accomplish. After the students completed their research investigations, they would write up their results and submit them to BSCS for editing; the results would then be returned to the student for approval and finally forwarded to an appropriate journal for publication under the student's name. The Gifted Student Committee planned to enlist the collaboration of biologists throughout the country in preparing brief outlines of research projects for these students (BSCS 1960).

During the 1960 Summer Writing Conference in Boulder, Colorado, six members of the Gifted Student Committee worked on the new materials. Members of that committee included Paul Brandwein; Hurbert Goodrich, Wesleyan University; Jerome Metzner, Bronx High School of Science; Richard Lewontin, University of Rochester; Evelyn Morholt, Fort Hamilton High School, Brooklyn, New York; and Walter Rosen, Marquette University.

Research Problems for Biology Students

The Gifted Student Committee selected and edited 100 proposed research problems from research biologists, and these were eventually published in a volume titled *Biological Investigations for Secondary School Students*. The book included a preface that oriented gifted students to the selection and use of a prospectus and a bibliography of general and specific references. The committee also planned to develop a means of evaluating the use of these proposed problems by participating schools.

In anticipation of teaching science as inquiry, a theme developed in this book, I quote from the introduction to *Biological Investigations for Secondary School Students*:

> *These one hundred ideas for investigation were developed to bring you the opportunity to gain experience in the art of investigation. You probably will not find "answers" to the problems they pose in textbooks, nor do we expect you will find a possible avenue to their solution in the references appended to each one. However, the careful thought and zealous work, the imaginativeness and inventiveness you will bring to the investigation, will yield you two or three years of exciting work. You may even be fortunate enough to discover a new fact, a new relationship, a new technique; you may be the first to know something no one before you has known. You may experience the thrill which comes to the scientist, the thrill of discovery, and more than that, you may have the joy of sharing your discovery with others.* (BSCS 1961)

In 1962, the activities of the BSCS Committee on the Gifted Student involved changing its name to the Committee on the Special Student to include students at both ends of the ability range. A subcommittee chaired by Evelyn Klinckmann of San Francisco College for Women defined unsuccessful learners to include the 20 to 30% of students taking high school biology who had difficulty with BSCS biology. At the 1963 Summer Writing Conference, the committee proposed producing materials for those students who had not been successful in field tests of BSCS programs.

By 1964, under Brandwein's leadership, the Committee on the Special Student had written three publications, including *Teaching High School Biology: A Guide to Working With Potential Biologists* (Brandwein et al. 1962). This volume was developed for teachers working with strong biology students. It contained material on the characteristics of the gifted student (with particular reference to science); strategies for encouraging the development of an art of investigation; promising practices in the teaching of students of high ability in biology as observed in U.S. classrooms; and an introduction to the use of the library as well as a bibliography on "giftedness." Additionally, two volumes of research problems in biology were prepared. Each of these paperback volumes had 40 investigations that were useful for originating problems for research on the school level (Grobman 1969).

A Conceptual Framework for BSCS

Paul F-Brandwein had significant influence on the conceptual framework used at BSCS. In a 1976 article titled "Reflections on the Early Days of BSCS," Bentley Glass had this to say after an introduction about organisms and the levels of organization used in the design of BSCS programs:

> *Especially, we agreed to select and emphasize a limited number of great biological concepts, or themes, that would run clearly throughout every phase of the treatment in every version, or program. The nine themes we chose, a procedure in which Paul Brandwein played a leading part, are so well known it is unnecessary to itemize them, except in the form of the diagram which provides our matrix of organizing ideas.* (Glass 1976, pp. 3–4)

You can see in this quotation the importance that Brandwein placed on major conceptual ideas, in this case for the discipline of biology. I thought this quotation especially appropriate because it shows Paul's leadership at BSCS and provides connections to other sections of this book. His ideas influenced the other founders and early development of BSCS. Indeed, his influence continues to this day and will do so into the future.

As a gifted teacher himself, Brandwein clearly had a major influence on BSCS programs for the exceptionally talented science student. He came to BSCS well aware of the limitations of the lecture and of existing textbooks and was determined to help transform science education. To quote Calvin Stillman,

> *The role of the warm mentor is fundamental in Paul's work. The younger person has to identify himself, and once he does so, the mentor is the strong person who helps the young one to find out [through original work] what it means to be a scientist. For Paul, science was the system of constructing a hypothesis and testing it carefully, with no sense of failure if the hypothesis turns out to be wrong.* (Stillman 1997)

There was a second aspect of Paul's career, conservation. His activity as a conservationist was lifelong; indeed, it has extended beyond his life in the form of property he and his wife, Mary, bequeathed (as the Rutgers Creek Wildlife Conservancy) to an organization committed to students, teachers, and scientists interested in the environment and natural systems. That conservancy has been administered through an affiliation with the Pocono Environmental Education Center at Dingman's Ferry, Pennsylvania. John Padalino directed the center until his retirement.

Robert H. Carleton: Science Educator, Administrator, and Education Leader

In the late 1960s, as a graduate student at the University of Northern Colorado, I met and had several opportunities to visit with Robert Carleton. He quietly listened to my questions, which I am sure were simple if not naïve, and talked about the role of the National Science Teachers Association (NSTA) in local, state, national, and international science education. Only later did I realize the depth and breadth of his leadership.

During his undergraduate and graduate studies in science education at two major universities, Carleton was elected to Phi Beta Kappa. For more than four decades, Robert Carleton contributed to science education as a high school teacher, university professor, and executive secretary of NSTA. He served as executive secretary of NSTA for 25 years. During his tenure as executive secretary of NSTA—one of the foremost leadership positions in the field of science teaching—Carleton demonstrated the unique abilities of creative and sound ideas combined with the energy and political wisdom to carry those ideas to fruition. Working harmoniously with diverse elected officers of NSTA, he was a model of national leadership.

In his years as NSTA's executive secretary (1948–1973), Robert Carleton participated in numerous national and international committees, conferences, and advisory groups concerned with supporting science teachers and advancing science education. He also was the author of more than a dozen textbooks in science, part of his many contributions to the teaching field during his career.

Robert H. Karplus: A Science Teacher and Education Leader

In the late 1950s and early 1960s, a number of scientists became actively involved in science education in general and curriculum development in particular. Some of the names may be familiar: Jerrold Zacharius, Glenn Seaborg, David Hawkins, Bentley Glass, Arnold Grobman, and John Moore. Robert Karplus joined the science education community when he became interested in elementary school science. This was in fact Bob's second career. His first career was in theoretical physics and included work at the Institute for Advanced Study in Princeton, New Jersey; Harvard; and the University of California, Berkeley. As a theoretical physicist, Karplus had a brilliant and exceptional career, which he left to take on the challenges of curricular reform in science education (Fuller 2002).

As a father of seven children, Bob's responsibility as a parent combined with his curiosity and interest in science naturally extended to schools. In 1958, Bob visited his daughter Beverly's second-grade classroom to teach several science lessons. Bob gave a physics lecture to second graders. You can only imagine the children's response. Karplus took this encounter seriously, as he wanted children to understand the wonders of science and appreciate the excitement of discovery that he had experienced as a scientist.

> *I cannot resist telling two other stories about Karplus—the learner as teacher. Robert Karplus placed the toy truck in front of a child. He rolled the truck slowly across the desk. "Did the truck move?" he asked. "No," replied the child.*
>
> *(It is difficult to learn the fundamental concepts of motion when an object that goes from one location to another does not move. Perhaps he had misunderstood. He moved the truck back to its starting position. Again, he slowly rolled the toy truck across the desk to a new location.)*
>
> *"Did the truck move?" he asked again. "No," the child replied once again. "Can you explain to me why you say the truck did not move?" Karplus asked. "It did not move," responded the child triumphantly. "You moved it!"* (Fuller 2002, p. 301)

Another classroom experience always touches the heart and brings a smile to any science teacher. Karplus believed it was important to see phenomena and interpret investigations from a scientific point of view. Karplus designed a series of activities to help children understand that many processes of change in a system eventually come to a balance point when the system reaches equilibrium. At the conclusion of his investigations, one boy announced to Professor Karplus, "I know something that will go on forever. You will keep on talking forever" (Karplus and Thier 1967). I can only imagine Bob, with that great smile and a twinkle in his eye, changed to a new topic.

Jerome Bruner paid a great tribute to Robert Karplus, the science teacher, when he had this to say about Bob:

> *His ideas about how to teach science were not only elegant but from the heart. He knew what it felt like "not to know," what it was like to be a "beginner." As a matter of temperament and principle, he knew that not knowing was the chronic condition not only of a student but of a real scientist. That is what made him a true teacher, a truly courteous teacher. What he knew was that science is not something that exists out there in nature, but that it is a tool in the mind of the knower-teacher and student alike. Getting to know something is an adventure in how to account for a great many things that you encounter in as simple and elegant a way as possible.* (Fuller 2002, p. 321)

During this period of initial work in science education (generally 1958–1963), Karplus worked with other University of California, Berkeley, faculty on the Elementary School Science Project (ESSP) and visited the Elementary Science Study (ESS). He also participated in a summer curriculum development for MINNEMAST, a mathematics and science program at the University of Minnesota, Minneapolis.

In the course of these experiences as a teacher and curriculum developer, Karplus pondered several insightful questions. First, how can one create learning experiences that achieve a connection between the pupil's intuitive attitudes and the concepts of the modern scientific point of view? Second, how can one determine what the children have learned? Third, how can one communicate with the teacher so that the teacher can in turn communicate with the pupils (Karplus and Thier 1967, p. 11)? Such questions led Karplus to a personal study of psychology, in particular, the work of Jean Piaget. Embedded in these questions are ideas that anticipate the contemporary science of learning and curriculum development by extension.

By 1963, Robert Karplus had the professional experience with science, students, and curriculum study; the personal time to reflect on fundamental questions about curriculum and instruction; and the opportunity to develop his ideas in the Science Curriculum Improvement Study (SCIS).

I truly appreciated the opportunities these lectures provided to reflect on the leadership and contributions of Paul F-Brandwein, Robert Carleton, and Robert Karplus. The ideas they shared about science concepts and processes, curriculum, instruction, assessment, professional development, and management of projects and organizations were formative at the time and continued to develop as I grew as a professional. The chapters in this book both honor their legacies and connect their ideas formed in the 20th century to 21st-century perspectives.

8

A Perspective on the Reform of Science Teaching

After the launch of Sputnik in October 1957, the United States responded to the Soviet Union by accelerating, broadening, and deepening efforts to reform science and technology education. Now our country is being challenged again. Our contemporary response again must include improving science education in general and, relative to themes in this book, science teaching in particular.

The U.S. response to Sputnik was unique to that time in history. So, too, must the contemporary response be unique. Now the primary goals are to sustain innovation by both scientists and engineers, create a deep technical workforce, and develop scientifically and technologically literate citizens for the 21st century. All of us—science teachers, teacher educators, policy makers, and the public—must ask and answer the Sisyphean question: What should citizens know, value, and be able to do in preparation for life and work in the 21st century?

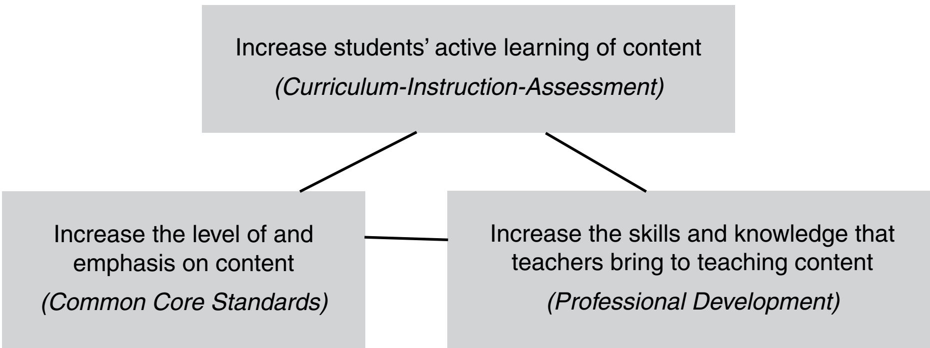
This chapter presents a perspective on reform. It begins with a brief review of the instructional core, then turns to a larger view of reform, one that includes broader questions of goals and progresses to the most fundamental area—classroom practices. After this overview of reform, I address practical questions of what must be done to improve science teaching and respond to the 21st-century goals—scientific literacy, a deep technical workforce, and a diverse scientific and engineering workforce.

Stay Focused on the Instructional Core

What is meant by *instructional core*? In the simplest form, the instructional core consists of the students, teacher, and learning outcomes. Of course, the learning process becomes more complex when you consider the backgrounds and diversity of students in any classroom, qualifications of the teachers, and the difficulty of learning conceptual ideas and the complex processes of scientific inquiry. Richard Elmore (2009) has pointed out that there are only three ways to improve student learning at a scale that makes a difference. First, you can increase the rigor and focus of content. Second, you can increase the level of students' learning of content. Third, you can increase teachers' knowledge and skill for teaching the content (see Figure 8.1).

Figure 8.1

The Instructional Core



Source: Elmore, R. 2009. Improving the instructional core. In *Instructional rounds in education: A network approach to improving teaching and learning*, ed. E. U. City, R. Elmore, S. Fiarman, and L. Teite. Cambridge, MA: Harvard Education Press.

Changing the Content

Increasing the level or focus of content is usually the goal of revising national, state, or local content or performance standards. The content standards may, for example, aim to change science content from facts to major conceptual ideas and core concepts in science. The focus might change from an exclusive emphasis on scientific knowledge to a balance of scientific knowledge and scientific literacy. Whatever the change in content, decisions about the content and performance standards are controlled by groups and processes such as national organizations, state committees, or local teams.

Engaging the Learner

In most classrooms, changing the level of student learning is influenced by the school or district curriculum, instructional materials, and the strategies and methods of science teaching that teachers use. Instructional materials may facilitate teachers' understanding and use of strategies that change the level of engagement and learning through the introductions of strategies based on contemporary understanding of how students learn science. The BSCS 5E Instructional Model serves as an example of an integrated instructional sequence that gives teachers and students time and opportunities to learn new, challenging science content and develop abilities for innovation. The design of instructional materials can help teachers understand and apply strategies that will engage students, but the participating teachers have to make changes to accommodate their unique schools, courses, and students.

Providing Professional Development

The third type of change in the instructional core is a unique and most powerful contribution to improving student learning at scale. Increasing the teacher's knowledge of students' learning, their inquiry-based teaching skills, and instructional model use can provide the basis for engaging students actively in learning. Professional development can use a unique, constructive, and opportunistic approach to the instructional core, which has the potential to influence student learning at a scale that eventually will be evident in assessments.

Changing One Element Requires Changes in Two Others

However, there is, as Shakespeare pointed out, a "rub." Increasing one of the three essential elements of the instructional core requires changes in the other two. The National Research Council (NRC), National Governors Association (NGA), and Council of Chief State School Officers (CCSSO) are developing new standards for science education. So, increasing teachers' knowledge and skills requires some understanding of those standards and the subsequent need to change and reform curricula to enhance student engagement. This fact suggests the need to help teachers and administrators recognize the required changes in school programs if they want to increase student achievement at scale.

To conclude, the education landscape is littered with strategies, projects, models, materials, and innovations that respond to continuing calls for reform and improvement of student learning. Let's stop and ask, What really counts for improvement? The answer is student achievement. Whether determined by a traditional end-of-course grade, state tests, the national report card, or international assessments, student achievement is the bottom line. So, one can ask, What can educators do to improve student achievement? A second fundamental question follows: What can we do to improve student achievement at a scale that makes a difference? The answer is clear and direct: Stay focused on the instructional core.

Understanding the Dimensions and Dynamics of Science Education

The Purpose of Science Education

The term *purpose* refers to various goal statements of what science teaching should achieve, such as scientific literacy for all learners. The strength of purpose statements lies in their widespread acceptance and agreement among science educators and their application to all components of science education—for example, classroom teaching, teacher education, curriculum development, and policy making at local, state, and national levels. Weaknesses of purpose statements exist in their ambiguity about the role of specific components of science education. For example, what does the purpose of achieving scientific literacy mean for an elementary grade teacher? A high school Earth science teacher? A science supervisor? A curriculum developer? A teacher educator? Clearly, the answers vary. Individuals need statements representing scientific literacy that are more concrete and directly related to various components of science education.

National statements about the purposes of science education support the vision that science education must accommodate all students. Specifically, national standards define the level of understanding and the abilities that all students—regardless of background, future aspirations, or interest in science—should develop. By their position as national standards, these policy documents embody the assumption that all students can learn science, or, to paraphrase an aphorism from an earlier era of reform, science can be taught effectively in some intellectually honest form to all students (Bruner 1960).

National standards encourage science teachers to provide opportunities for all students to learn science throughout their school years. They clearly and unequivocally advocate including those who traditionally have not received encouragement and opportunities to learn science.

Policies for Science Education

Policy statements are concrete translations of the purpose—achieving scientific literacy for all learners—for various components of science education. Documents that give direction and guidance but are not actual programs serve this purpose. Examples of policy documents include district syllabi for K–12 science; state frameworks; and national, state, and local standards. In the contemporary reform movement, several documents clarify policies for scientific literacy. *National Science Education Standards* (NRC 1996), *Benchmarks for Science Literacy* (AAAS 1993), and the *Science Framework for the 2009 National Assessment of Educational Progress* (NAGB 2009)—all of which have considerable overlap and consistency for the content—provide clear, detailed, and elaborate definitions of scientific literacy. They represent common ground for the content of science education (AAAS 1995). Science teachers should expect the new "common core" standards for science to build on and complement current standards.

Concerning the dimensions of scientific literacy, the Standards and Benchmarks present a balance of functional, conceptual, procedural, and multidimensional scientific literacy. They have, for example, reduced technical words and thus represent a significant first step toward less emphasis on scientific vocabulary and more emphasis on other dimensions of scientific literacy. The documents elaborate on conceptual and procedural dimensions of scientific literacy. Furthermore, the Standards include changes from prevalent views of scientific processes. The abilities of inquiry, for instance, extend beyond a limited emphasis on science processes, such as observation, inference, hypothesis, and experiment. The Standards on "Science as Inquiry" include the processes of science and give greater emphasis to cognitive abilities, such as using logic, evidence, and extant knowledge to construct explanations of natural phenomena. Finally, the policy documents include the human dimensions of science and technology, such as history, the nature of science, and science in personal and social perspectives.

Programs for Science Teaching

Science programs include the actual curriculum materials based on policy documents such as the Standards and Benchmarks. Science programs are unique to grade levels, disciplines, and aspects of science teaching and present a consistent, coordinated, and coherent approach to the science education of all students. Examples of science programs for secondary schools include the American Chemical Society's *ChemCom* and the new Biological Sciences Curriculum Study's *BSCS Science: An Inquiry Approach*.

School science programs may be developed by national organizations, or they may be developed by states or local school districts. Who develops the materials is not the defining characteristic of science programs. That schools, colleges, state agencies, and national organizations have programs aligned with national, state, and local policies is the important feature and requirement of standards-based reform in the 21st century.

Practices for the Teaching of Science

Practice refers to the specific processes of teaching science. The practices of science teaching include the personal dynamics between teachers and students and the interactions among students and assessments, educational technologies, laboratories, and myriad other science teaching strategies. The view of contemporary reform described here assumes that science teachers will implement classroom practices consistent with policies, programs, and the goal of achieving scientific literacy for all learners. Improving the practices in the classroom centers on the instructional core and the most individual, unique, and fundamental aspect of science education—the act of teaching students. From the perspective of science teachers, there should be little doubt about the need for local leadership and support for their work in contemporary reform.

Dynamics of Contemporary Reform

If achieving scientific literacy is the goal and science teachers understand the various domains and dimensions of scientific literacy, then it seems important to have a map of the reform territory to know your location, means of movement, direction of travel, and what lies ahead. We can use themes just outlined—purpose, policy, program, practice—for locating and clarifying different efforts in the geography of contemporary reform (see Tables 8.1 [pp. 146–147] and 8.2 [p. 148]).

Table 8.1

Dimensions of Contemporary Reform

Perspectives	**Time** (for actual change to occur)	**Scale** (number of individuals involved)	**Space** (scope and location of the change activity)	
Purpose Reforming goals Establishing priorities for goals Providing justification for goals	*1–2 years* To publish document	*Hundreds* Philosophers and educators who write about aims and goals of education	*National/Global* Publications and reports are disseminated widely	
Policy Establishing design criteria for programs Identifying criteria for instruction Developing frameworks for curriculum and instruction	*3–4 years* To develop frameworks and legislation	*Thousands* Policy analysts, legislators, supervisors, and reviewers	*National/State* Policies focus on specific areas	
Program Developing materials or adopting a program Implementing the program	*3–6 years* To develop a complete educational program	*Tens of Thousands* Developers, field-test teachers, students, textbook publishers, software developers	*Local/School* Adoption committees	
Practices Changing teaching strategies Adapting materials to unique needs of schools and students	*7–10 years* To complete implementation and staff development	*Millions* School personnel, public	*Classrooms* Individual teachers	

The left column in Table 8.1 summarizes the perspectives of purpose, policy, program, and practices. The top row includes six aspects of reform: time, scale, space, duration, materials, and agreement. You can review the table and develop a general sense of the dimensions and difficulties of the reform effort as you ask questions such as the following:

- How long does it take to form policies such as national standards or state frameworks?
- Once a new program is implemented, how long will it continue in a school system?

Duration (once change has occurred)	**Materials** (actual products of the activity)	**Agreement** (difficulty reaching agreement among participants)
Year New problems emerge and new goals and priorities are proposed	*Articles/Reports* Relatively short publications, reports, and articles	*Easy* Small number of reviewers and referees
Several Years Once in place, policies are not easily changed	*Book/Monograph* Longer statements of rationale, content, and other aspects of reform	*Difficult* Political negotiations, trade-offs, and revisions
Decades Once developed or adopted, programs last for extended periods	*Books/Courseware* Usually several books for students and teachers	*Very Difficult* Many factions, barriers, and requirements
Several Decades Individual teaching practices often last a professional lifetime.	*Complete System* Books plus materials, equipment, and support	*Extraordinarily Difficult* Unique needs, practices, and beliefs of individuals, schools, and communities

- Who is responsible for a particular effort, such as curriculum reform, policy formation, or classroom practices?
- How do all dimensions of the framework contribute to the whole of science education?
- How does the framework relate to systemic initiatives?

Table 8.2 (p. 148) describes other aspects of reform. Again, the left column includes the perspectives of purpose, policy, program, and practices. The top row includes risk, cost, constraints, responsibilities, and benefits and considers these in terms of school districts, school personnel, and students. The analysis presented in the figure indicates that purpose statements and policy documents, although essential, have minimal and moderate influence on reform, respectively. We are now approaching the phases where risk, cost, constraints, personal responsibilities, and benefits are all high or extremely high. Clearly, the science teaching community has significant challenges ahead.

Table 8.2

Cost, Risks, and Benefits of Contemporary Reform

Perspectives	Risk to Individual School Personnel	Cost in Financial Terms to School	Constraints Against Reform for School	Responsibility for Reform by School Personnel	Benefits to School Personnel and Students
Purpose Reforming goals Establishing priorities for goals	Minimal	Minimal	Minimal	Minimal	Minimal
Policy Establishing design criteria Identifying criteria for instruction Developing frameworks for curriculum and instruction	Moderate	Moderate	Moderate	Moderate	Moderate
Program Developing materials or adopting a program Implementing the program	High	High	High	High	High
Practices Changing teaching strategies Adapting materials to unique needs of schools and students	Extremely high	Extremely high	Extremely high	Extremely high	Extremely high

Perhaps more important than the specific cells, Tables 8.1 and 8.2 give an overall picture of the reform effort. If I placed a "you are here" label on this map, it would be the interface between policy and program. We have policies in the form of the Standards and Benchmarks. The next phases of reform will take longer; involve more individuals, materials, and equipment; move closer to schools and classrooms; and present more difficulties when it comes to reaching agreement and actually improving school science programs and changing instructional practices.

The nation needs a vision, a first tactical response, and a strategic plan for a decade of actions, all designed to reform science education to develop scientific literacy and sustain the U.S. position as a global leader. Although the need to change seems evident, the changes specifically implied for science and technology for kindergarten through grade 12 must be clarified and addressed. The next sections are based on an article titled "Do We Need Another Sputnik?" (Bybee 2007) and a report titled *A Decade of Action: Sustaining Global Competitiveness* (BSCS 2007).

Fostering Scientific Literacy

What Must We Do?

I begin with a recommendation that will facilitate reform by beginning with teachers and their standard request when asked to change: Where are the materials?

Develop a new generation of curriculum materials for scientific literacy. Specifications for the curriculum materials use the contexts and competencies from PISA 2006 Science, and the content builds on both national and international frameworks. Based on PISA 2006, Figure 8.2 (p. 150) presents a framework for the curriculum. Contexts for the curriculum are described in Table 8.3 (p. 151).

Content for the curriculum would be based on the *National Science Education Standards* (NRC 1996) and the *Benchmarks for Scientific Literacy* (AAAS 1993), and aligned with the *Science Assessment and Item Specifications for the 2009 National Assessment of Educational Progress* (National Assessment Governing Board 2005) and the new common core standards.

Support professional development of science teachers. Specific actions are recommended to achieve this goal. First, establish summer institutes that focus on building teachers' content and pedagogical knowledge and skills. There should be follow-up experiences during the academic year. Second, develop online communities to support all participating science teachers. These professional development programs should be concentrated and continuous, have an educational context, focus on content, and establish professional learning communities.

Figure 8.2

A Perspective for K–12 Scientific and Technological Literacy

Table 8.3

Contexts for the Science Curriculum

Context	Personal	Social	Global
Careers	Scientific research, engineering, technical, and teaching	Scientific research, medicine, engineering, information and communication technology	World health, economic progress, security
Health	Maintenance of health, accident prevention, nutrition	Control of disease and social transmission, nutrition, food choices, community health	Epidemics and spread of infectious diseases
Resources	Control of personal consumption of materials and energy	Maintenance of human populations, quality of life, security, production and distribution of food, energy supply	Renewable and nonrenewable energy, natural systems, population growth, sustainable use of species
Environment	Research on environmentally friendly behavior, use and disposal of materials	Research on population distribution, disposal of waste, environmental impact, local weather	Biodiversity, ecological sustainability, control of pollution, production and loss of soil
Hazards	Natural and human-induced hazards, decisions about housing	Rapid changes (earthquakes, severe weather), slow and progressive changes (coastal erosion, sedimentation), risk assessment	Climate change, impact of modern warfare
Research and Development	Interest in science and technology, science-based hobbies, sport and leisure activities, use of personal technology	Aerospace engineering, biotechnology, information and communications technology, pharmaceuticals	Exploration of space, transportation, agriculture, applications to resolve global problems

The professional development programs should provide enough initial time to establish a clear foundation for teaching and learning. In addition to an early concentration, the program should extend over a year (or more) and include continuous work on selecting curriculum materials and improving instruction. The educational context for the professional development programs should include curriculum—that is, content and pedagogy with a direct and purposeful meaning for science teachers. Core concepts for scientific literacy must be the programs' focus. Finally, the programs require the establishment of professional learning communities, with teams of teachers analyzing teaching, engaging in lesson study, reviewing content, and working on the implementation of curriculum materials.

Align certification and accreditation with contemporary priorities of scientific literacy. This recommendation uses the critical leverage of science teacher certification to facilitate reform of undergraduate teacher education programs. No discussion of improving science education escapes acknowledging the need to change teacher education. This includes changes in states' certification and national accreditation. In addition, federal support to colleges and universities that prepare significant numbers of future science teachers will be a major contribution to their reform. To this recommendation I add special support to colleges and universities with significant populations of Hispanic, African American, and Native American students so the institutions can recruit and prepare a greater diversity of science teachers.

Build district-level capacity for continuous improvement of programs for scientific literacy. Specific actions necessary for this priority include developing leaders, providing summer programs and assistance during the year, centering on critical leverage points such as selection of instructional materials, and designing programs so the district builds a sustainable infrastructure.

This priority connects to other priorities with the goal of sustaining the initial results attained through professional development, curriculum reform, and reform of undergraduate education. Although the federal costs will be high initially, by building district-level capacity one could anticipate reduced support in the long-term.

Explain to the public what this school science reform is about and why it will benefit their children and the country. One of the great insights from the Sputnik era was the fact that national leaders provided clear and compelling explanations of what the reform was and why it was important. Furthermore, there was continued support for science teachers and a national enthusiasm for reform.

A Vision and a Plan

As I have tried to make clear, current national aspirations center on economic and environmental rationales for education reform. Stated succinctly, the rationales state that our economic security depends on educating people for life and work in the 21st century. For the most part, the science education community has not made general connections to the economic rationale. Furthermore, there have been reports but no reform initiatives that represent a positive, constructive response to demands for an improved workforce and greater scientific literacy.

The vision for this reform centers on *content* aligned with science education policies such as the 2009 National Assessment of Educational Progress and frameworks for the international assessments PISA and TIMSS. The *contexts* for science programs range from personal to global and include categories such as careers, health, resources, environment, hazards, and research and development.

The *competencies* important for 21st-century science literacy build on the Secretary's Commission on Achieving Necessary Skills (SCANS) and specifically emphasize those skills and abilities that may be developed in school programs. Although numerous reports from business, industry, and government are not explicit about skills for the 21st century, recent workshops conducted by the National Research Council have described a set of 21st-century skills. Figure 8.3 presents a framework that includes the key features of these 21st-century skills.

Figure 8.3

Examples of 21st-Century Skills

Development of the following skills is intertwined with development of content knowledge related to technical jobs. Similarly, in science education, students may develop cognitive skills while engaged in study of specific science topics and concepts.

Adaptability: The ability and willingness to cope with uncertain, new, and rapidly changing conditions on the job, including responding effectively to emergencies or crisis situations and learning new tasks, technologies, and procedures. Adaptability also includes handling work stress; adapting to different personalities, communication styles, and cultures; and adapting physically to various indoor or outdoor work environments.

Complex communications and social skills: Skills in processing and interpreting both verbal and nonverbal information from others to respond appropriately. A skilled communicator is able to select key pieces of a complex idea to express in words and images to build shared understanding. Skilled communicators achieve positive outcomes with customers, subordinates, and superiors through social perceptiveness, persuasion, negotiation, instruction, and a personal orientation.

Nonroutine problem solving: A skilled problem solver uses expert thinking to examine a broad span of information, recognize patterns, and narrow the information to reach a diagnosis of the problem. Moving beyond diagnosis to a solution requires knowledge of how the information is linked conceptually and involves the ability to reflect on whether a problem-solving strategy is working and to switch to another strategy if the current strategy isn't working. Problem solving includes creativity to generate innovative solutions, integrate seemingly unrelated information, and entertain possibilities others may miss.

Self-management/self-development: Self-management skills include the ability to work remotely, in virtual teams; to work autonomously; and to be self-motivating and self-monitoring. One aspect of self-management involves the willingness and ability to acquire new information and skills related to work.

Systems thinking: The ability to understand how an entire system works, how an action, change, or malfunction in one part of the system affects the rest of the system—adopting a "big picture" perspective on work. Systems thinking includes judgment and decision making; systems analysis; and systems evaluation as well as abstract reasoning about how the different elements of a work process interact.

Competencies are in a central position as they represent the essential change in emphasis for curricular supplements and teaching strategies described in the next sections. These skills have been mentioned in prior chapters. They are summarized here as basic to proposed instructional materials.

How We Can Begin

This section presents a larger picture of how we can initiate and bring about the changes described in the last section to a scale that matters within the U.S. education system.

The science education community must plan a decade of action. Achieving higher levels of scientific literacy cannot be accomplished quickly; it will take a minimum of 10 years. Tables 8.4 and 8.5 present specifications for reform and phases for a decade of reform centering on improving scientific literacy in the United States.

Table 8.4

Specifications for Action

Unit of Change	Instructional Core
Time frame for change	10 years
Critical core of change	Teachers' knowledge and skills, curriculum for active learning, level of content and abilities
Components of change	Education policies, curriculum programs, teaching practices
Theory of action for change	Introduce curriculum model instructional units for reform and provide professional development based on those units. Changes in assessment would be introduced as complements to curriculum reform.

Table 8.5

A Decade of Action: Phases and Goals

Phase	Timeline	Goal
Initiating a response	2 years	Design, develop, and implement model instructional units.
Bringing the reform to scale	6 years	Change policies, programs, and practices at local, state, and national levels.
Sustaining the reform	2 years	Build capacity at the local level for continuous improvement of school science and technology programs.
Evaluating the reform	Continuous, with major evaluation in 10 years	Provide formative and summative data on the nature and results of the reform efforts.

A Decade of Action

This section presents a strategic plan for making the vision a reality. The plan will require a *Decade of Action*. I use *The Tipping Point* (Gladwell 2002) as the theory of action and identify school districts as the unit of change.

Initiating the Reform: Introducing Little Changes With Big Effects

The work for this phase will last two years. Beginning with a brief period of dialogue to form partnerships and establish coalitions of support, this phase very quickly turns to the funding and development of *model instructional units* for reform. The model instructional units use major sectors of the economy as the "topics" (e.g., aerospace, biotechnology, energy, hazard mitigation, health, and environmental quality) and emphasize themes such as careers and research and development.

Providing model instructional units, professional development, and exemplary assessments at the elementary, middle, and high school levels will have an effect on the system, develop understanding among school personnel, and increase support by policy makers and administrators. Furthermore, the units will provide a basis for answering the public's questions about what the changes involve and why they are important—especially for students.

Bringing the Reform to Scale: Systematic Changes That Make a Difference

Bringing the reform to scale will take six years. During this time, some work will continue on instructional materials developed in the first phase. After the initial phase, efforts to bring the reform to a significant scale would expand. Evaluations of teachers' responses and students' achievements, abilities, and attitudes would be reviewed and analyzed. These data would form the basis for revision of the original modules, development of new modules, and a compelling case statement for continued expansion of the reform. This is when the tipping points "connectors," "mavens," and "salespersons" of the reform begin major efforts to review and revise state policies and create new criteria for local and state adoptions of instructional materials. With revision of standards, states also would initiate changes in assessments. Publishers would begin developing new editions of core and supplemental programs. Through this entire period, professional development of science teachers would continue.

Districts begin the process of selecting and implementing materials as they become available. Professional development aligned with the new programs is ongoing. The central goal of this phase is to revise local, state, and national policies; develop new school science programs; and align teaching practices with the goals of the reform.

By the end of this phase, states would have new standards and assessments; new teacher certification requirements would be in place; new instructional materials for core and supplemental programs would be available; and the professional development of teachers would be aligned with the new priorities and would be ongoing. This phase likely would present the most difficulty, as business leaders, policy makers, and educators will directly confront resistance to change and criticism of the new initiatives and changes in policies, programs, and practices.

Sustaining the Reform: Building Local Capacity for a National Purpose

The work of this phase would be concentrated in the final two years of the decade. In the next phase, work will concentrate on building local capacity for ongoing improvement of science and technology education at the district level. These efforts concentrate on a phase-out of dependence on external funds for the reform efforts and phase-in of school districts' use of resources in response to the new advances in science and technology and implied changes for the school programs.

Evaluating the Reform: Monitoring and Adjusting to Change

Evaluation will involve continuous feedback about the work and changes in content and curriculum, teachers and teaching, and assessments and accountability. Clearly, there will be feedback during all phases. The feedback will inform judgments about the modules and issues associated with their implementation and the professional development of teachers.

Evaluations and feedback will be conducted and available at the school district, state, national, and even international levels. School districts and states will implement their own evaluations. Results from NAEP, TIMSS, and PISA also will provide results from national and international levels.

Concluding Discussion

We have broad consensus on the goal of achieving scientific literacy for all learners, and the Standards, Benchmarks, and new common core standards provide policies that clarify the content and dimensions of our goal. It should be clear that there are options and opportunities to improve science programs and teaching practices. We must all assume responsibility for confronting the next challenges as we move toward our goal of achieving scientific literacy for all learners.

Fulfilling national aspirations has long been a function of science teaching, and curriculum materials have been a central component that helped science teachers attain national priorities. The Sputnik era serves as a prime example of this observation.

Among the accomplishments of the Sputnik era, we have organizations such as BSCS, which have the history and reputation of addressing the complex challenges of designing and developing innovative curriculum materials. It is time to set aside the old idea that science teachers and school districts can develop curriculum materials for entire courses with a few weeks of summer work. I see this change as fundamental as we enter a new era of curriculum reform.

Business and industry have signaled the need for curriculum reform in science education. Priorities associated with the No Child Left Behind legislation centered on basic literacy and mathematics. Some of these priorities are being addressed. Science and technology must now become a new priority because the contributions from science will provide the basis for higher levels of achievement in the knowledge, values, skills, and abilities required for the 21st century. The latter represents the national aspirations for this era. Achieving workforce competencies will require more than single initiatives that center on isolated components of the educational system. Rather, achieving workforce competencies will take coherent and coordinated efforts distributed across the key components of education, and we can begin with curriculum materials designed for science teachers.

The United States faces large, complex problems that require radical responses. Fifty years ago, the Sputnik challenge galvanized the nation in a way every citizen could understand. We need a similar sense of urgency and mission today. Both the challenges and our nation's response must be understood by every citizen. The purposes are clear: maintaining the United States' position as a global economic presence and addressing issues associated with climate change and energy resources. Now we must address the need for curriculum reform so that science and technology education once again fulfill national aspirations.

Having stated these recommendations, I will note some important features. First, my recommendations center on critical leverage points to address immediate and long-term problems. Second, the direct implication for federal policy is financial support versus unfunded mandates, requests for cooperation, general recommendations to state and local governments, or appeals for support from business and industry. Third, priorities include multiple and coordinated efforts among, for example, the U.S. Department of Education, the National Science Foundation, the National Institutes of Health, and other agencies. Fourth, the initiatives should build on current research, such as *How Students Learn: Science in the Classroom* (Donovan and Bransford 2005), *America's Lab Report* (NRC 2006), and *Taking Science to School* (NRC 2007). Finally, policy makers can support these priorities from a nonpartisan perspective. It is in the United States' interest to achieve higher levels of scientific literacy.

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