Two Revolutions in K–8 Science Education

Today's science education, which teaches all students to do science and think like scientists, has depended on the involvement of scientists and their societies. It must continue to do so.

Ramon E. Lopez and Ted Schultz

Science is for *all* Americans" and "Science should be something students do, not something that is done to them"—these two slogans epitomize the two revolutions now taking place in American precollege science education. The first is a revolution in the goals of science education; the second, a revolution in the methods.

The scientific community has played key roles in both revolutions especially through efforts of the American Association for the Advancement of Science (AAAS), the National Academy of Sciences, and the National Science Foundation (NSF). Even the American Physical Society (APS), which traditionally has focused most of its concerns about education on the university, has been playing an active role in promoting systemic reform of science education in grades K–8 through its teacher–scientist alliance program.

What are these revolutions? Where did they come from? What has been the role of the scientific community? And what has APS been doing to support them? These are questions we shall try to answer.

New goal: Science is for *all* Americans

The idea that science education should be for all children, not just the best and brightest, reflects a recent, fundamental change in the relationship between science and American society. After World War II, there was a broad consensus that by advancing science, society as a whole would prosper. This idea was at the core of Vannevar Bush's seminal report *Science, The Endless Frontier*,[1] which laid out a social contract between science and society. Science would expand and thrive, and the results for society would be security and prosperity. The educational focus was on the undergraduate and graduate levels to produce more scientists and engineers. Precollege science education was barely mentioned.

As early as 1956, Jerrold Zacharias at MIT was already deeply concerned about science education. (See the PHYSICS TODAY articles "Setting New Directions in Physics Teaching: PSSC 30 Years Later" by Anthony P. French, September 1986, page 30 and "The Physicists Intervene" by Clifford Swartz, September 1991, page 22.) It was the launch of Sputnik in 1957 and the ensuing space race, however, that gave new urgency to the production of scientists and engineers and heightened the attention being paid to grades K–12. In this effort, Zacharias and other physicists, like MIT's Francis Friedman and Philip Morrison, and the University of California, Berkeley's Bob Karplus, played seminal roles (see figure 1). Also in 1961, the American Association of Physics Teachers (AAPT) began work to produce a new journal that would serve the needs of high-school teachers: *The Physics Teacher* was launched in 1963. Nevertheless, there was still no widely held belief that scientists should be involved in the education of children as part of their general professional duties, and K–12 science education was not a concern of APS.

In the 1980s and 1990s, with the fall of the Soviet Union and the globalization of many aspects of the world's increasingly technological economies, Zacharias's original vision was more widely shared. It became apparent that our nation's economic future would require a technologically competent and highly adaptable workforce. Problems facing our society at all levels were increasingly scientific and technological in nature. At the national level, challenges included global warming and acid rain; at the local level, pollution and a host of transportation problems needed solutions; and at the personal level, there was a wide range of health issues. To address these concerns effectively, Americans needed to be scientifically literate.

This realization produced a fundamental change in the consensus about science education: Science had to be not just for the best and the brightest, but for all. This idea was captured in the landmark book *Science for All Americans*,[2] produced by the AAAS, which laid out what a scientifically literate citizen should know and be able to do by the end of high school.

It was also becoming clear, because of the increasingly complex scientific and technological nature of problems citizens had to face, that science education should develop in students a whole set of intellectual habits and attitudes that might well be called scientific habits of thinking. That this goal is now an essential part of the consensus is confirmed repeatedly in APS's own institutes and workshops (see box 1 on page 46).

New methods: Children should *do* science

While the notion that children learn best when actively engaged was nothing new, the science curriculum projects of the late 1950s and the 1960s put this idea into practice. In 1956, under the leadership of Zacharias, Friedman, and Morrison (who was still at Cornell University), the Physical Science Study Committee was created. The ingenious and engaging materials PSSC produced had a big impact not only on high-school physics but also on biology and chemistry. In 1960, this group, joined by some nonphysicists (notably, David Hawkins), formed the Elementary Science Study, which developed materials for grades K–6 that embraced the life, Earth, and physical

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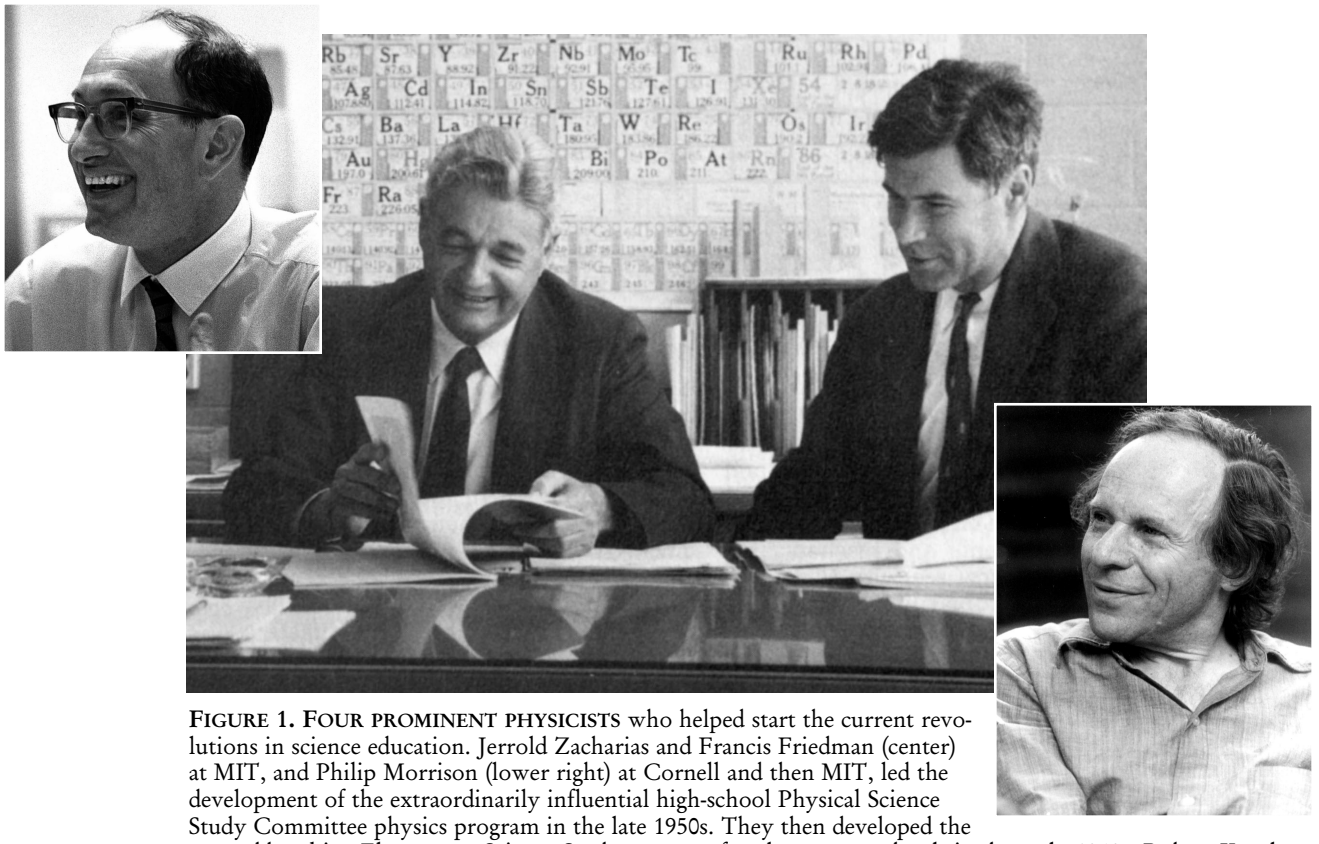

FIGURE 1. FOUR PROMINENT PHYSICISTS who helped start the current revolutions in science education. Jerrold Zacharias and Francis Friedman (center) at MIT, and Philip Morrison (lower right) at Cornell and then MIT, led the development of the extraordinarily influential high-school Physical Science Study Committee physics program in the late 1950s. They then developed the ground-breaking Elementary Science Study program for elementary schools in the early 1960s. Robert Karplus (upper left), a physicist at the University of California, Berkeley, developed the different but also influential Science Curriculum Improvement Study elementary science program at about the same time. (Zacharias and Friedman photo with permission from the MIT Museum; Morrison photo by Philip Daley, courtesy of AIP Emilio Segrè Visual Archives, Physics Today Collection; Karplus photo courtesy of the Karplus family; also to appear in *A Love of Discovery* by Robert G. Fuller, Kluwer Academic, in press.)

sciences. In 1963, Bob Karplus began the Science Curriculum Improvement Study, which developed additional materials.[3] These ESS and SCIS materials, whose development was supported by NSF, began the second revolution in American elementary science education.

Another critical development has been an explosion of knowledge in cognitive science about how people process information and learn. This knowledge has clarified our understanding of what is age-appropriate for the developing brain, but it has also collided with some traditional teaching practices and scientists' perceptions.

A clear example of this conflict is in astronomy, which has traditionally been taught in elementary grades because it excites children and because this excitement has been taken as evidence of learning. A number of studies, though, have demonstrated that, before the fifth grade, students generally have great difficulty understanding and consistently applying the idea of a round Earth.[4] If young students have difficulty understanding a round Earth, how can we expect them to understand basic astronomical principles? The remarkable film *A Private Universe*, produced by the education group at the Harvard–Smithsonian Center for Astrophysics, dramatically illustrates that early misconceptions persist: In interviews of Harvard graduates and faculty, most of them still had serious misconceptions about the origin of the seasons or the phases of the moon.[5]

Some of the best research on issues in teaching and learning has, in fact, been done by physicists (in physics departments) who study how students learn physics.[6] (See the PHYSICS TODAY articles "Learning and Instruction in Pre-college Physical Science" by Jose P. Mestre, September 1991, page 56 and "Teaching Physics: Figuring Out What Works" by Edward F. Redish and Richard N. Steinberg, January 1999, page 24.) One common conclusion of these investigations is that active engagement techniques are more effective than traditional, more didactic approaches to teaching science. The AAPT is now publishing, in supplementary issues of the *American Journal of Physics*, papers in the rapidly developing field of physics education research.

Curriculum materials and national standards

The scientific community has continued its involvement in the revolutions in science education by helping to develop good educational materials and to define standards for what science should be learned. Formal standards came after the development of some of the K–6 materials and are now affecting the development of middle-school materials.

In the 1980s, NSF funded several major projects to develop curriculum materials for grades K–6. These materials were based on the ESS and SCIS materials, which were demonstrated to be more effective for students than traditional methods.[7] They were designed by educators working with scientists, and went through a rigorous research and development cycle that included extensive and widespread field-testing.

As a result, three series of materials were commercially published in the late 1980s and the 1990s: *Full Option Science System* (FOSS; Delta Education), devel-

oped at the Lawrence Hall for Science (at the University of California, Berkeley), *Science and Technology for Children* (STC; Carolina Biological Supply Company), developed by the National Science Resources Center (a joint enterprise of the National Academy of Sciences and the Smithsonian Institution), and *Insights* (Kendall/Hunt), developed by the Education Development Center (where the original ESS program was developed). All are collections of self-contained "kits," large boxes with everything that is needed for the students to do the science and with abundant directions for teachers.

Roughly speaking, each series offers four kits for each of six or seven grade levels. Examples are kits on floating and sinking (see figure 2), measuring time, and the life cycle of butterflies. With each kit, children investigate a single subject for six to eight weeks. The investigations over this period build one upon another, so students get a deeper and deeper understanding of the science as they progress. Students develop the ability to think and behave like scientists as they make measurements, record and analyze data, draw and defend conclusions, and pose new questions. Scientists who observe classes that are using these materials are invariably excited to see children learning by doing. (See box 2 and figure 3 on page 48, both for more on specific projects done with the time-measuring kit.)

The scientific community also provided guidance as to what good science education should be. Following its *Science for All Americans* (1989), which set the goals, the AAAS, through its Project 2061, created *Benchmarks for Science Literacy* in 1993.[8] This volume answered the question: "What should students learn and when, in order that they have the knowledge and skills outlined in *Science for All Americans*?" NAS undertook a parallel effort and, in 1995, produced the *National Science Education Standards*.[9]

Benchmarks and the *NSES* were produced by literally thousands of people: teachers, teacher educators, researchers in science education, and scientists. The two volumes overlap by about 95%, but have important and helpful differences. The *NSES* provides standards not only for the teaching of students, but also for areas like teacher training and professional development, assessment, and the functioning of school systems to achieve these goals. *Benchmarks* includes standards for mathematics as well as for science.

Benchmarks and the *NSES* also share the same underlying philosophy:

▷ Science literacy for all is the vision.
▷ Real understanding, not factual recall, is the primary goal.
▷ Developing a desire to be lifelong learners in science is a second goal.
▷ Cognitive science provides a real and practical guide.

As embodiments of this philosophy, the *NSES* includes "science as inquiry" among the content areas students are to master, and originated the wonderful epigram "Science should be something students do, not something that is done to them."

Both *Benchmarks* and the *NSES* try to limit the total content. The Third International Mathematics and Science Study demonstrated that US textbooks in these subjects cover many more topics than do textbooks in Japan and Germany. Because teachers feel they need to cover most, if not all, of the material in the texts, a "mile-wide and inch-deep" approach has developed that has been widely criticized as detrimental. Nonetheless, the approach is difficult to dislodge. By decreasing the total amount of material to be covered, *Benchmarks* and the *NSES* seek to let students understand and retain more. Hence the slogan "less is more" applies.

Box 1. Are You Part of the Consensus?

What do you want students to know and be able to do as a result of their science education?" This question is asked of all participants at TSA institutes and workshops. Working in groups, they then draw up lists of answers. What would your list look like? Draw one up and compare it with the typical, verbatim list printed upside-down below.

When many such lists are compared, two things are noticeable. First, the lists created by educators, scientists, and business and community leaders are essentially indistinguishable. Second, "F=ma," "periodic table," and "DNA" appear on very few lists. While this could reflect the way the question is worded, it more likely reflects a widely-held desire that science education teach not just facts but also scientific habits of thinking. Subsequent discussion makes it clear that the participants assume that in order to think scientifically, students will need a command of real science facts—but the participants are asking for more than merely factual knowledge.

Curiosity—risk taking
Communicate learning
Think independently
Science is for everyone
Critical thinking
Observe the natural world
Less science anxiety
Okay to take risks—no wrong answers
Science is a process
Teamwork
Aware of opportunities/careers
Asking questions
Equity —"Open to everyone"
Problem solving
Appreciating mystery
Recording and reporting
Tell science from pseudoscience
Connections to all academic areas
Organization skills
Technology skills
Have fun

Science programs that are guided by these documents are generally referred to as "standards-based." The standards have also had a strong influence on the "science frameworks" that most states have developed in the last few years to guide science education locally. Many college programs try to prepare teachers based on these standards, but decisions on how science is to be taught are made at the district level.

The counter revolution

Although the consensus embodied in the two revolutions is widespread, it is not universal. Resistance comes from several sources:

First are those who dislike almost any change. "We've been doing it this way for years," they say. "Look how far it has gotten us. Why change? Besides, isn't this just another education fad—like new math?" Such resistance often comes from well-meaning parents. For them, science was tough, not fun. If their children don't have a textbook with lots of lists to memorize, they worry that the science is not "rigorous."

Second is the greatly increased emphasis in recent years on high-stakes testing in English and mathematics, where, for example, poor student performance can result in a state's taking over a school or school district. While no one wants to perpetuate badly performing schools, the result is that school systems are giving science a lower priority—they would rather focus on what is tested, despite increasing evidence that good science education greatly enhances students' writing, reading, and math skills.

A third source of resistance is the textbook publishers, for whom the present system is profitable. They produce beautiful, thick books in large numbers; states put those books on the "state adoption list"; and school districts buy them with state money. Why rock the boat when

FIGURE 2. FLOATING AND SINKING, a fifth-grade kit in the *Science and Technology for Children* series developed by the National Science Resources Center, includes basins, scales, cylinders and other objects in a variety of materials and sizes, and a host of other equipment. Using this kit, 24 children investigate the physics of floating and sinking; formulate Archimedes's Principle; develop the notion of a buoyant force; and build clay boats, attempting to maximize the boats' carrying capacity. This picture shows only a small fraction of the kit's contents. Also included are a teacher's manual, many student manuals, and a number of books at fifth-grade level on related topics. (Photograph by Ed Lee.)

things are going so well?

Fourth are those who reject many of the findings of cognitive science, for example the importance of material being age-appropriate. These folks were a major factor in the California standards battle in 1998. That is why California now expects the atomic theory of matter and the periodic table to be introduced in the *third grade*.

A fifth group, including many of the same people, believes that more is more: that the more facts a child is taught, the easier it is for the child to learn still more. This contrasts with the less-is-more belief underlying the standards—the more facts you try to teach a child, beyond a certain point, the less likely the child is to develop any real understanding.

Sustaining the revolutions

Except in a few scattered school districts, the revolutionary materials of the 1960s and 1970s disappeared as science education reverted to its traditional, didactic, just-the-facts approach. Why did these early programs fail? What have science educators learned?

In the early 1980s, the National Science Teachers Association identified a handful of districts that had sustained their exemplary, kit-based programs for years: Highline, Washington (near Seattle); Mesa, Arizona; Schaumberg, Illinois; and Fairfax County, Virginia. A study of these districts found they had five elements in common. The National Science Resources Center (NSRC), which was founded by Doug Lapp, the architect of the Fairfax County program, then started a series of National Leadership Institutes for school districts organized around the newly found commonalities, described much later, and in detail, in the book *Science for All Children*.[10] What are these five crucial elements?

School districts with successful programs buy the **best available materials**, which were ESS and SCIS in the 1960s and 1970s and are now the kits developed with NSF funding. After experience with these materials, most districts modify them to suit local needs. Scientists can provide valuable support in selecting the units most suitable to a district and in developing supplemental materials.

Teaching hands-on science requires lots of stuff. What does a teacher do when something breaks, is "borrowed," or is used up? Where can a teacher get more butterfly larvae? We don't ask surgeons to pick up gauze and sharp scalpels on their way to work, but we have expected teachers to do the equivalent. It doesn't work. If you want teachers to teach science, a science kit must arrive with all the materials in working order. School systems that have sustained hands-on programs over several years have established **science materials centers** to refurbish kits (see figure 4). When a unit is completed, everything goes back into the box, it is picked up, refurbished, and sent to the next teacher. Scientists and their employing institutions can contribute by helping make science materials centers efficient and cost effective.

Many teachers, especially elementary teachers, have an inadequate background in science, so they feel uncomfortable with the kits—or with any science for that matter. Most learned to teach the traditional way, so to them, student inquiry means a lot of noise and mess. Elementary teachers need to understand that the statement "I don't know, but maybe we can find out," is the starting point for all scientific inquiry. All teachers, including those new to a district or a grade level, need **ongoing professional development**. Scientists, both as content resources and (often unconscious) models of inquiry behavior, can make valuable contributions to the training of both teachers and the trainers of teachers.

A good program can be undone with a bad test. Today, we realize that schools need to develop different **assessment tools** for hands-on science. A fact-based, standardized test can cause teachers and administrators to resist the hands-on approach. Assessment must be aligned with the goals of the instruction. Teachers need to learn about new assessment techniques, and parents and school boards must be kept abreast of changes in grading. Scientists can help develop assessment tools, especially at the district and state levels.

To assure that the four elements just described are implemented and sustained, administrators and parents need to understand the nature of a reformed science program. **Sustained administrative support**, notwithstanding the typical rapid turnover of superintendents, is essential for implementing systemic changes in how science is taught. Also, because a hands-on, inquiry-centered approach is very different from the way most adults learned science, parents need to know why it is good to learn by doing. Scientists in a community can advocate and validate this kind of education.

FIGURE 3. A CLOCK ESCAPEMENT mechanism constructed with Tinkertoys® is the challenging activity that concludes the sixth-grade *Measuring Time* kit, part of the *Science and Technology for Children* series. With this kit, students spend six to eight weeks investigating water clocks, sundials (including the phases of the moon and some elements of planetary motion), and the dynamics of pendula. (Courtesy of the El Centro, California, Elementary School District.)

APS promotes systemic reform

In the last seven years, APS has jumped into the K–8 science education arena with its teacher–scientist alliance (TSA) program, which was modeled after the NSRC institutes. This is part of a recent tendency of APS to become involved in a wider range of activities, as described by Harry Lustig.[11]

The philosophy behind the TSA program is that really good science education will only occur in districts in which all five of the crucial elements are in place. Thus, APS decided to support systemic reform in those districts already on the way to implementing the crucial elements and to promote reform in those districts with good potential for implementing them. This was quite different from the activities of other societies, which were content to focus on some of the crucial elements by, for example, developing curriculum materials (American Chemical Society (ACS), Society of Automotive Engineers, and so forth) or providing professional development for teachers (ACS, American Institute of Physics, AAPT, and others). APS also chose to focus first on elementary schools (grades K–6), because that's where clear models for reform exist and where, according to strong, albeit anecdotal, evidence, many children lose interest in science. More recently, the focus has broadened to include middle schools (grades 6–8). In support of its goals of mobilizing and informing scientists and getting them involved at a strategic level in school district reform, TSA has operated a number of institutes and workshops.

The Five-Day Institutes for Lead Scientists are essentially short courses in science education reform. They have been held in Washington, DC, each January since 1995. Participants, mostly scientists and engineers, with a sprinkling of key educators from reforming districts, learn about the standards movement, the model for reform discussed previously, and the means of effecting change in schools. They also examine roles for scientists in supporting reform. Seven institutes have been conducted with a total of nearly 300 participants from more than 20 states. Many of those who have taken part in the institutes have become involved with the schools in their communities, in some cases taking leading roles in local reform efforts.

The Five-Day Regional Strategic Planning Institutes and Follow-ups have been designed for school-system teams comprising administrators, teachers, and scientists. The goal has been for these teams to draft the outline of a five-year strategic plan for implementing a district-wide reform of K–6 or K–8 science. Teams have been provided with examples of best practice and were allotted facilitated planning time. Institutes have been held each year in a different part of the country. Full regional institutes were held in the Northeast (with teams from Maine, Massachusetts, Rhode Island, and Connecticut), the Southeast (with teams from the Carolinas and Georgia), the San Diego area (with San Diego County and Imperial Valley teams, plus a few out-of-area teams from California's Bay Area, Colorado, and South Carolina), and Texas. A condensed, three-day institute for teams from Georgia was also held in connection with the APS centennial celebration. A total of 68 teams and more than 440 individuals have participated in the five institutes.

Roughly 18 months after each of these planning institutes, TSA has conducted the shorter (one- or two-day) follow-up institutes for the same teams. This has allowed them to review their progress, exchange ideas with other teams, and set new directions.

TSA also conducts two kinds of shorter workshops. The first is a one-day workshop to help educators and lead scientists in a given district recruit technical profession-

Box 2. Discovery in a Classroom

Two groups of sixth graders have been told to find out what affects the frequency of a pendulum. Each group makes a list of variables: length, mass, how far the pendulum is pulled aside, and so forth. They know about keeping all variables but one fixed, so they start investigating. They agree that making the pendulum longer decreases the frequency. They agree that pulling the pendulum further aside and giving it a push have similar but small effects. But one group finds a slight increase when they add a weight; the other, a slight decrease. They argue. They do it over, and watch each other. One student says it isn't easy to add some mass and keep everything else fixed. Another notes that one group added its mass above the first weight, while the other group added it below. They had changed the length! Could that be the problem? They set about again, this time trying to add mass without changing the length. The mystery is exciting for them. And what they learn about doing science they won't forget.

FIGURE 4. PACKED WITH SCIENCE activity materials, these boxes are some of the 3000 kits bound for the 127 elementary schools in Montgomery County, Maryland. After 8–10 weeks, the kits are collected by the Taylor Science Materials Center, where they are refurbished and then promptly sent out again. In a school year, each classroom teacher receives three such kits, which, together with supplementary hands-on activities, constitute the entire science program. Shown in the photo are Tom DuMars, the center's nationally renowned director, and an unidentified staff member. (Courtesy of William Mills, Montgomery County Public Schools photographer.)

als for the reform effort. The second is a three-hour workshop for PTA and business leaders, school board members and other community leaders; it provides information on the benefits of hands-on science and explores partnerships with scientists, businesses and educational institutions.

In a comprehensive independent study of the TSA program, many of the teams reported significant reform programs in various degrees of development, which, they almost always say, owe a great deal to team members' attendance at a TSA institute. In fact, North Carolina, with TSA support, is replicating the TSA institutes to effect systemic reform throughout the state.

Roles for individual scientists

The two revolutions have been driven in part by the scientific community, and systemic reform incorporating the five crucial elements has been the preferred goal of APS. Clearly, though, many roles are available for individual scientists, even in school districts that are not undergoing such reform.

Scientists can become involved by working directly with teachers, kids, school systems, or other stakeholders in the community. They can also mobilize resources—material and human—in their institutions. Contributions can be to any of the five crucial elements of reform. Many examples were researched and reported by RISE (Resources for Involving Scientists in Education) of the National Research Council and can be explored in some detail on the RISE Web site (www.nas.edu/rise).

Occasionally, a scientist with a deep commitment and a lot of imagination can successfully drive the change of an entire school system. Four of the many who accomplished this are Bruce Alberts, president of the National Academy of Sciences, who did it in the San Francisco city schools; Jerry Pine, a biophysicist at Caltech, who was central in making the Pasadena schools a model for reform that has influenced other districts throughout the country; John Wright, a chemist and former president of the University of Alabama at Huntsville, who started a program in Huntsville which has now spread to Birmingham and Nashville, Tennessee; and Bob DeHaan, a physicist turned cell biologist at Emory University who has driven change in the Atlanta public schools.

Science education for children now has the potential to be better than most of us would ever have imagined. We have a broad consensus on the goals, standards to guide the process, and a movement with a proven model to make it happen. The scientific community has been crucial in helping to achieve the goals, and individual scientists continue to be essential to the success of science education. There are plenty of opposing forces. And the inertia of the US educational system, with its almost 16 000 independent school districts, is enormous. Someone once remarked that changing the system was like moving a ten-ton marshmallow. Perhaps that's an understatement.

What will be accomplished in the long run is unclear, but the challenge of improving our children's science education is obvious.

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